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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, specimen fabrication methods, testing modes (load, 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 380 Standard for Use of International System of Units (SI) (the Modern Metric System)[5]

E 467 Practice for Verification of Constant Amplitude Dynamic Forcesin 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 1150 Definitions of Terms Relating to Fatigue[3]

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, Definitions E 1150, and Terminology E 6, respectively, apply to the terms used in this practice. Selected terms with definitions follow with the appropriate source given in parenthesis. Additional terms are also defined in 3.2.

3.2 *Definitions of Terms 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

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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.

strains measured at the surface on opposite sides of the longitudinal axis of symmetry of the 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 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 loads are equal. (See Definitions E 1150.)

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 Definitions E 1150.) 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 specimen sustains before failure of a specified nature occurs. (See Definitions E 1150.)

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 Definitions E 1150)

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 Definitions E 1150.)

3.2.9 *gage length, [L]*, *n*—the original length of that portion of the 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 Definitions E 1150):

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

and:

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

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

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

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

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

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

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

3.2.16 *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 Definitions E 1150 and Practice E 468.)

3.2.17 *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.

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

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

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

3.2.20 *tensile strength [FL^{-2}]*, *n*—the maximum tensile stress which a material is capable of sustaining. Tensile strength is calculated from the maximum load during a tension test carried to rupture and the original cross-sectional area of the specimen. (See Terminology E 6.)

3.2.21 *time to failure, tf [t]*, *n*—total elapsed time from test initiation to test termination required to reach the number of cycles to failure.

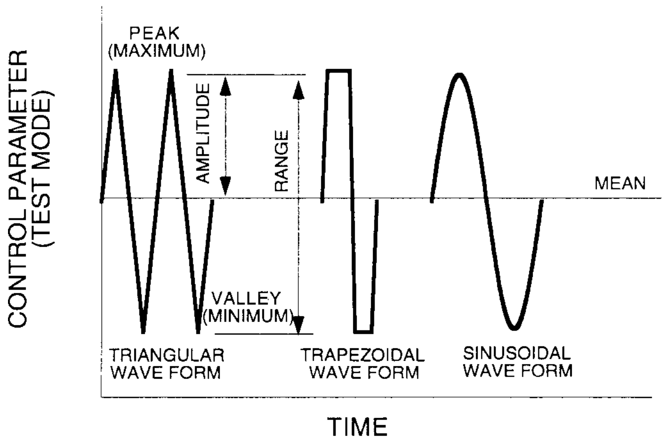

FIG. 1 Cyclic Fatigue Nomenclature and Wave Forms

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 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 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 load (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 specimen preparation or fabrication, specimen conditioning, test environment, load 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 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 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 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 loads (that is, loads 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 load ratio of R=1 (maximum equal to minimum) constitutes a constant load test with no fluctuation of load over time. A load 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 load 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) load 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

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

fatigue behavior (for example, cyclic fatigue limits, etc.). Machining damage introduced during 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 specimens in the as-processed condition (that is, it may not be allowable to machine the 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 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 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 specimen.

5.6 Fractures that initiate outside the uniformly stressed gage section of a 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 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 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 specimens are properly strain gaged and percent bending monitored during testing there will be no record of percent bending for each 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 (load, 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 load 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 specimen thereby affecting the cyclic fatigue life. If specimen heating is likely to occur or when there is doubt, monitor the 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