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AMERICAN SOCIETY FOR TESTING AND MATERIALS
100 Barr Harbor Dr., West Conshohocken, PA 19428
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Standard Practice for Constant-Amplitude, Axial, Tension-Tension Cyclic Fatigue of Continuous Fiber-Reinforced Advanced Ceramics at Ambient Temperatures[1]

This standard is issued under the fixed designation C 1360; 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 (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 nonuniform or multiaxial stress states).

1.2 This practice applies primarily to advanced ceramic matrix composites with continuous fiber reinforcement: unidirectional (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 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 of Advanced Ceramics[2]

C 1275 Test Method for Monotonic Tensile Strength Testing of Continuous Fiber-Reinforced Advanced Ceramics with Solid Rectangular Cross-Section Specimens at Ambient Temperatures[2]

D 3479 Test Methods for Tension-Tension Fatigue of Oriented Fiber, Resin Matrix Composites[3]

D 3878 Terminology of High Modulus Reinforcing Fibers and Their Composites[3]

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

E 6 Terminology Relating to Methods of Mechanical Testing[4]

E 83 Practice for Verification and Classification of Extensometers[4]

E 337 Test Method for Measured Humidity with Psychrometer (Measurement of Wet-and Dry-Bulb Temperatures)[5]

E 380 Practice for Use of International System of Units (SI) (the Modernized Metric System)[6]

E 467 Practice for Verification of Constant Amplitude Dynamic Loads in an Axial Load Fatigue Testing Machine[6]

E 468 Practice for Presentation of Constant Amplitude Fatigue Test Results for Metallic Materials[6]

E 739 Practice for Statistical Analysis of Linear or Linearized Stress-Life (S-N) and Strain-Life (ε-N) Fatigue Data[6]

E 1012 Practice for Verification of Specimen Alignment Under Tensile Loading[4]

E 1150 Terminology Relating to Fatigue[4]

3. Terminology

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 C 1145, Terminology D 3878, Terminology E 6, and Terminology E 1150, respectively, apply to the terms used in this practice. Selected terms with definitions follow with the appropriate source given in parentheses. 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.)

[1] This practice is under the jurisdiction of ASTM Committee C–28 on Advanced Ceramics and is the direct responsibility of Subcommittee C28.07 on Ceramic Matrix Composites.

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

[3] *Annual Book of ASTM Standards*, Vol 15.03.

[4] *Annual Book of ASTM Standards*, Vol 03.01.

[5] *Annual Book of ASTM Standards*, Vol 07.02.

[6] *Annual Book of ASTM Standards*, Vol 14.01.

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 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 *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.

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.

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 E 1150.)

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

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, Nf 10^6– 10^7). (See Terminology E 1150.)

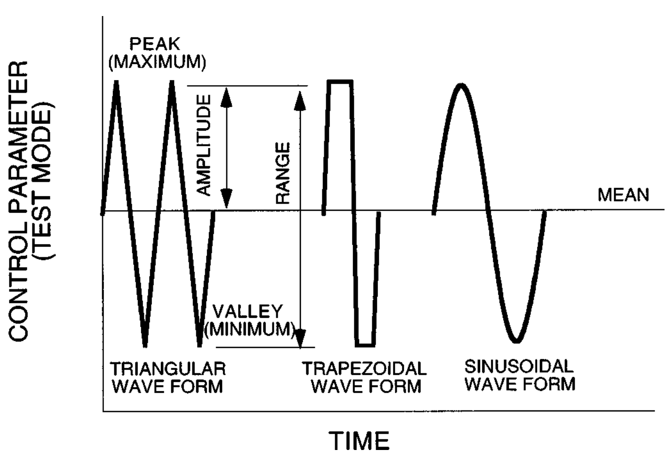

FIG. 1 Cyclic Fatigue Nomenclature and Wave Forms.

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.

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

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

3.2.12 *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.)

3.2.13 *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 1150):

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

and

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

3.2.14 *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 C 1275.)

3.2.14.1 *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).

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

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

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

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

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

3.2.19 *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 E 6.)

3.2.19.1 *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.

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

3.2.21 *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 1150 and Practice E 468.)

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

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

$= S_{max} - S_m = S_m - S_{min}$.

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

3.2.24 *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.

3.2.25 *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.)

3.2.26 *time to 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 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 [7] and STP 588 [8]. In addition, the strengths of the brittle matrices and fibers of CFCCs 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[7], STP 588[8], and Practice E 739. Studies to determine the influence of specimen volume or surface area on cyclic fatigue strength distributions for CFCCs have not been completed. 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 of material in the gage section of the 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 load (*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 specimen preparation or fabrication, volume percent of the reinforcement, orientation and stacking of the reinforcement, specimen conditioning, test environment, load 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 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

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[7] 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.

[8] *Manual on Statistical Planning and Analysis for Fatigue Experiments, ASTM STP 588,* ASTM, 1975.

its inherent resistance to fracture, the presence of flaws, or damage accumulation processes, or both. There can be significant damage in the CFCC 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 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 load ratio, R or A, can have a pronounced effect on the cyclic fatigue behavior of the material. A load ratio of $R = 1$ (that is, maximum equal to minimum) constitutes a constant load test with no fluctuation of load over time. A load 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 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” (that is, 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, 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 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 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 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 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 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 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 will normally constitute invalid tests. In addition, for face-loaded 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 E 4. 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 E 467.

6.2 *Gripping Devices*—Devices used to grip the test specimens may be of the types discussed in 6.2 of Test Method C 1275 as long as they meet the requirements of this practice and Test Method C 1275.

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 1275 as long as they meet the requirements of this practice and Test Method C 1275.

6.4 *Strain Measurement*—Determine strain by means of either a suitable extensometer or strain gages as discussed in Test Method C 1275. Extensometers shall satisfy Practice E 83, Class B-1 requirements and are recommended instead of strain