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Standard Test Method for Monotonic Tensile Strength Testing of Continuous Fiber-Reinforced Advanced Ceramics With Solid Rectangular Cross-Section Test Specimens at Elevated Temperatures[1]

This standard is issued under the fixed designation C1359; 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 test method covers the determination of tensile strength including stress-strain behavior under monotonic uniaxial loading of continuous fiber-reinforced advanced ceramics at elevated temperatures. This test method addresses, but is not restricted to, various suggested test specimen geometries as listed in the appendix. In addition, test specimen fabrication methods, testing modes (force, displacement, or strain control), testing rates (force rate, stress rate, displacement rate, or strain rate), allowable bending, temperature control, temperature gradients, and data collection and reporting procedures are addressed. Tensile strength as used in this test method refers to the tensile strength obtained under monotonic uniaxial loading where monotonic refers to a continuous nonstop test rate with no reversals from test initiation to final fracture.

1.2 This test method 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 test method may also be used with glass (amorphous) matrix composites with 1-D, 2-D, 3-D and other multi-directional continuous fiber reinforcements. This test method does not directly address discontinuous fiber-reinforced, whisker-reinforced, or particulate-reinforced ceramics, although the test 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 SI10-02 IEEE/ASTM SI 10 .

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.* Refer to Section 7 for specific precautions.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

C1145 Terminology of Advanced Ceramics
D3878 Terminology for Composite Materials
E4 Practices for Force Verification of Testing Machines
E6 Terminology Relating to Methods of Mechanical Testing
E21 Test Methods for Elevated Temperature Tension Tests of Metallic Materials
E83 Practice for Verification and Classification of Extensometer Systems
E220 Test Method for Calibration of Thermocouples By Comparison Techniques
E337 Test Method for Measuring Humidity with a Psychrometer (the Measurement of Wet- and Dry-Bulb Temperatures)
E1012 Practice for Verification of Test Frame and Specimen Alignment Under Tensile and Compressive Axial Force Application
SI10-02 IEEE/ASTM SI 10 American National Standard for Use of the International System of Units (SI): The Modern Metric System

3. Terminology

3.1 *Definitions:*

3.1.1 Definitions of terms relating to tensile testing, advanced ceramics, fiber-reinforced composites as they appear in Terminology E6, Terminology C1145, and Terminology D3878, respectively, apply to the terms used in this test method. Pertinent definitions are shown in the following with the appropriate source given in parentheses. Additional terms used in conjunction with this test method are defined in 3.2.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *advanced ceramic*, *n*—highly engineered, high-performance predominately nonmetallic, inorganic, ceramic material having specific functional attributes. **C1145**

3.2.2 *axial strain* $[LL^{-1}]$, *n*—average longitudinal strains measured at the surface on opposite sides of the longitudinal

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

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

axis of symmetry of the specimen by two strain-sensing devices located at the mid length of the reduced section. **E1012**

3.2.3 *bending strain [LL^{-1}]*, *n*—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. **E1012**

3.2.4 *breaking force [F]*, *n*—force at which fracture occurs. **E6**

3.2.5 *ceramic matrix composite*, *n*—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.

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

3.2.7 *fracture strength [FL^{-2}]*, *n*—tensile stress that the material sustains at the instant of fracture. Fracture strength is calculated from the force at fracture during a tension test carried to rupture and the original cross-sectional area of the specimen. **E6**

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

3.2.8 *gage length [L]*, *n*—original length of that portion of the specimen over which strain or change of length is determined. **E6**

3.2.9 *matrix-cracking stress [FL^{-2}]*, *n*—applied tensile stress at which the matrix cracks into a series of roughly parallel blocks normal to the tensile stress.

3.2.9.1 *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 which 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 (elastic limit) curve.

3.2.10 *modulus of elasticity [FL^{-2}]*, *n*—ratio of stress to corresponding strain below the proportional limit. **E6**

3.2.11 *modulus of resilience [FLL^{-3}]*, *n*—strain energy per unit volume required to elastically stress the material from zero to the proportional limit indicating the ability of the material to absorb energy when deformed elastically and return it when unloaded.

3.2.12 *modulus of toughness [FLL^{-3}]*, *n*—strain energy per unit volume required to stress the material from zero to final fracture indicating the ability of the material to absorb energy beyond the elastic range (that is, damage tolerance of the material).

3.2.12.1 *Discussion*—The modulus of toughness can also be referred to as the cumulative damage energy and as such is regarded as an indication of the ability of the material to sustain damage rather than as a material property. Fracture mechanics methods for the characterization of CFCCs have not been developed. The determination of the modulus of toughness as provided in this test method for the characterization of the cumulative damage process in CFCCs may become obsolete when fracture mechanics methods for CFCCs become available.

3.2.13 *proportional limit stress [FL^{-2}]*, *n*—greatest stress which a material is capable of sustaining without any deviation from proportionality of stress to strain (Hooke's law). **E6**

3.2.13.1 *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, the procedure and sensitivity of the test equipment shall be specified.

3.2.14 *percent bending*, *n*—bending strain times 100 divided by the axial strain. **E1012**

3.2.15 *slow crack growth (SCG)*, *n*—subcritical crack growth (extension) which may result from, but is not restricted to, such mechanisms as environmentally-assisted stress corrosion or diffusive crack growth. **C1145**

3.2.16 *tensile strength [FL^{-2}]*, *n*—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 specimen. **E6**

4. Significance and Use

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

4.3 Unlike monolithic advanced ceramics that fracture catastrophically from a single dominant flaw, CFCCs generally experience ′graceful′ (that is, non-catastrophic, ductile-like stress-strain behavior) fracture from a cumulative damage process. Therefore, the volume of material subjected to a uniform tensile stress for a single uniaxially-loaded tensile test may not be as significant a factor in determining the ultimate strengths of CFCCs. However, the need to test a statistically significant number of tensile test specimens is not obviated. Therefore, because of the probabilistic nature of the strengths of the brittle fibers and matrices of CFCCs, a sufficient number of test specimens at each testing condition is required for statistical analysis and design. Studies to determine the influence of test specimen volume or surface area on strength distributions for CFCCs have not been completed. It should be noted that tensile strengths obtained using different recommended tensile test specimen geometries with different volumes of material in the gage sections may be different due to these volume differences.

4.4 Tensile tests provide information on the strength and deformation of materials under uniaxial tensile stresses. Uniform stress states are required to effectively evaluate any non-linear stress-strain behavior that may develop as the result of cumulative damage processes (for example, matrix cracking, matrix/fiber debonding, fiber fracture, delamination, and so forth) that may be influenced by testing mode, testing rate, effects of processing or combinations of constituent materials, environmental influences, or elevated temperatures. Some of these effects may be consequences of stress corrosion or sub critical (slow) crack growth that can be minimized by testing at sufficiently rapid rates as outlined in this test method.

4.5 The results of tensile tests of test specimens fabricated to standardized dimensions from a particular material or selected portions of a part, or both, may not totally represent the strength and deformation properties of the entire, full-size end product or its in-service behavior in different environments or various elevated temperatures.

4.6 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 the particular primary processing conditions and post-processing heat treatments.

4.7 The tensile behavior and strength of a CFCC are dependent on its inherent resistance to fracture, the presence of flaws, or damage accumulation processes, or both. Analysis of fracture surfaces and fractography, though beyond the scope of this test method, 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 tensile strength. In particular, the behavior of materials susceptible to slow crack growth fracture will be strongly influenced by test environment, testing rate, and elevated temperature of the test. 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. Monitor and report relative humidity (RH) and temperature when testing is conducted in uncontrolled ambient air with the intent of evaluating maximum strength potential. Testing at humidity levels >65 % RH is not recommended.

5.2 Surface preparation of test specimens, although normally not considered a major concern in CFCCs, can introduce fabrication flaws which may have pronounced effects on tensile mechanical properties and behavior (for example, shape and level of the resulting stress-strain curve, tensile strength and strain, proportional limit stress and strain, and so forth). 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, increase frequency 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 test specimens in the as-processed condition (that is, it may not be possible to machine the test specimen faces without compromising the in-plane fiber architecture). Final machining steps may, or may not negate machining damage introduced during the initial machining. Therefore, report test specimen fabrication history since it may play an important role in the measured strength distributions.

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

5.4 Fractures that initiate outside the uniformly-stressed gage section of a test specimen may be due to factors such as stress concentrations or geometrical transitions, extraneous stresses introduced by gripping, or strength-limiting features in the microstructure of the test specimen. Such non-gage section fractures will normally constitute invalid tests. In addition, for face-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 initiate fracture in the vicinity of the grips.

6. Apparatus

6.1 *Testing Machines*—Machines used for tensile testing shall conform to Practices E4. As defined in Practices E4, forces used in determining tensile strength shall be accurate within ±1 % at any force within the selected force range of the testing machine. A schematic showing pertinent features of the tensile testing apparatus is shown in Fig. 1.

6.2 *Gripping Devices:*

6.2.1 *General*—Various types of gripping devices may be used to transmit the measured force applied by the testing machine to the test specimen. The brittle nature of the matrices of CFCCs requires a uniform interface between the grip components and the gripped section of the test specimen. Line or point contacts and non-uniform pressure can produce