



Designation: **C1273—15 C1273 – 18**

# Standard Test Method for Tensile Strength of Monolithic Advanced Ceramics at Ambient Temperatures<sup>1</sup>

This standard is issued under the fixed designation C1273; 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 ( $\epsilon$ ) indicates an editorial change since the last revision or reapproval.

## 1. Scope

1.1 This test method covers the determination of tensile strength under uniaxial loading of monolithic advanced ceramics at ambient temperatures. This test method addresses, but is not restricted to, various suggested test specimen geometries as listed in the ~~appendix~~appendixes. 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, and data collection and reporting procedures are addressed. Note that tensile strength as used in this test method refers to the tensile strength obtained under uniaxial loading.

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

1.3 Values expressed in this test method are in accordance with the International System of Units (SI) and ~~SH0-02-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, health, and ~~health~~environmental practices and determine the applicability of regulatory limitations prior to use.* Specific precautionary statements are given in Section 7.

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:<sup>2</sup>

[C1145 Terminology of Advanced Ceramics](#)

[C1161 Test Method for Flexural Strength of Advanced Ceramics at Ambient Temperature](#)

[C1239 Practice for Reporting Uniaxial Strength Data and Estimating Weibull Distribution Parameters for Advanced Ceramics](#)

[C1322 Practice for Fractography and Characterization of Fracture Origins in Advanced Ceramics](#)

[D3379 Test Method for Tensile Strength and Young's Modulus for High-Modulus Single-Filament Materials](#)

[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 \(the Measurement of Wet- and Dry-Bulb Temperatures\)](#)

[E1012 Practice for Verification of Testing Frame and Specimen Alignment Under Tensile and Compressive Axial Force Application](#)

[SH0-02-IEEE/ASTM SI 10 American National Standard for Use of the International System of Units \(SI\): The Modern Metric System](#)  
[Metric Practice](#)

<sup>1</sup> This test method 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, 2015/July 1, 2018. Published September 2015/July 2018. Originally approved in 1994. Last previous edition approved in 2010/2015 as C1273 – 05 (2010)/C1273 – 15. DOI: 10.1520/C1273-15.10.1520/C1273-18.

<sup>2</sup> 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. Terminology

#### 3.1 Definitions:

3.1.1 The definitions of terms relating to tensile testing appearing in Terminology E6 apply to the terms used in this test method on tensile testing. The definitions of terms relating to advanced ceramics testing appearing in Terminology C1145 apply to the terms used in this test method. Pertinent definitions as listed in Practice C1239, Practice E1012, Terminology C1145, and Terminology E6 are shown in the following with the appropriate source given in parentheses. Additional terms used in conjunction with this test method are defined in the following:

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

3.1.3 *axial strain*—~~strain~~  $[LL^{-1}]$ ,  $n$ —the average of longitudinal strains measured at the surface on opposite sides of the longitudinal axis of symmetry of the specimen by two ~~strain-sensing~~ strain sensing devices located at the mid length of the reduced section. **E1012**

3.1.4 *bending strain*—~~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. **E1012**

3.1.5 *breaking force*—~~force~~  $[F]$ ,  $n$ —the force at which fracture occurs. **E6**

3.1.6 *fractography*—means and methods for characterizing a fractured specimen or component. **C1145**

3.1.7 *fracture origin*—the source from which brittle fracture commences. **C1145**

3.1.8 *percent bending*—the bending strain times 100 divided by the axial strain. **E1012**

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

3.1.10 *tensile strength*,—~~strength~~,  $S_u [FL^{-2}]$ ,  $n$ —~~the~~ 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 specimen. **E6**

### 4. Significance and Use

4.1 This test method may be used for material development, material comparison, quality assurance, characterization, and design data generation.

4.2 ~~High strength~~, High-strength, monolithic advanced ceramic materials generally characterized by small grain sizes (<50  $\mu\text{m}$ ) and bulk densities near the theoretical density are candidates for load-bearing structural applications requiring high degrees of wear and corrosion ~~resistance~~, resistance and high temperature strength. Although flexural test methods are commonly used to evaluate strength of advanced ceramics, the ~~non-uniform~~ nonuniform stress distribution of the flexure test specimen limits the volume of material subjected to the maximum applied stress at fracture. ~~Uniaxially-loaded~~ Uniaxially loaded tensile strength tests provide information on strength-limiting flaws from a greater volume of uniformly stressed material.

4.3 Although the volume or surface area of material subjected to a uniform tensile stress for a single ~~uniaxially-loaded~~ uniaxially loaded tensile test may be several times that of a single flexure test specimen, the need to test a statistically significant number of tensile test specimens is not obviated. Therefore, because of the probabilistic strength distributions of brittle materials such as advanced ceramics, a sufficient number of test specimens at each testing condition is required for statistical analysis and eventual design, with guidelines for sufficient numbers provided in this test method. Note that size-scaling effects as discussed in Practice C1239 will affect the strength values. Therefore, strengths obtained using different recommended tensile test specimens with different volumes or surface areas of material in the gage sections will be different due to these size differences. Resulting strength values can be scaled to an effective volume or surface area of unity as discussed in Practice C1239.

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~~ nonlinear stress-strain behavior which may develop as the result of testing mode, testing rate, processing or alloying effects, or environmental influences. These effects may be consequences of stress corrosion or subcritical (slow) crack growth, which can be minimized by testing at appropriately 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, or both, of a part may not totally represent the strength and deformation properties of the entire, full-size end product or its in-service behavior in different environments.

4.6 For quality control purposes, results derived from standardized tensile test specimens can be considered to be indicative of the response of the material from which they were taken for given primary processing conditions and post-processing heat treatments.

4.7 The tensile strength of a ceramic material is dependent on both its inherent resistance to fracture and the presence of flaws. Analysis of fracture surfaces and fractography, though beyond the scope of this test method, is highly recommended for all purposes, especially for design data.

5. Interferences

5.1 Test environment (vacuum, inert gas, ambient air, etc.) etc.), including moisture content (for example, relative humidity) 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 and testing rate. Testing to evaluate the maximum strength potential of a material should be conducted in inert environments or at sufficiently rapid testing rates, or both, so as to minimize slow crack growth effects. Conversely, testing can be conducted in environments and testing modes and rates representative of service conditions to evaluate material performance under use conditions. When testing is conducted in uncontrolled ambient air with the intent of evaluating maximum strength potential, relative humidity and temperature must be monitored and reported. Testing at humidity levels >65 % relative humidity (RH) is not recommended, and any deviations from this recommendation must be reported.

5.2 Surface preparation of test specimens can introduce fabrication flaws that may have pronounced effects on tensile strength. 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 increased 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 test methods of surface preparation do not exist. It should be understood that final machining steps may or may not negate machining damage introduced during the early coarse or intermediate machining. Thus, test specimen fabrication history may play an important role in the measured strength distributions and should be reported.

5.3 Bending in uniaxial tensile tests can cause or promote non-uniform nonuniform stress distributions with maximum stresses occurring at the test specimen surface leading to non-representative fractures originating at surfaces or near geometrical transitions. In addition, if strains or deformations are measured at surfaces where maximum or minimum stresses occur, bending may introduce over or under measurement of strains. Similarly, fracture from surface flaws may be accentuated or muted by the presence of the non-uniform nonuniform stresses caused by bending.

6. Apparatus

6.1 Testing Machines—Machines used for tensile testing shall conform to the requirements of Practices E4. The forces used in determining tensile strength shall be accurate to within ±1 % at any force within the selected force range of the testing machine as defined in Practices E4. 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 specimens. The brittle nature of advanced ceramics requires a uniform interface between the grip components and the

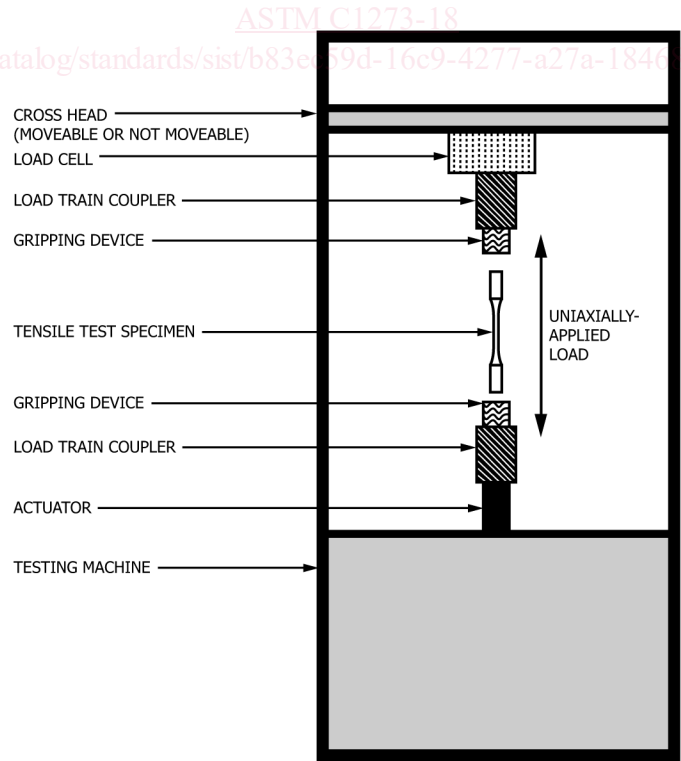


FIG. 1 Schematic Diagram of One Possible Apparatus for Conducting a Uniaxially-Loaded-Uniaxially Loaded Tensile Test

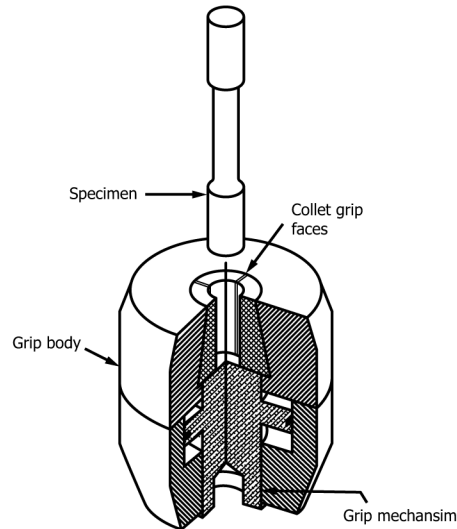


FIG. 2 Example of a Smooth, Split-Collet-Split-Collet Active Gripping System for Cylindrical Test Specimens

gripped section of the test specimen. Line or point contacts and ~~non-uniform~~ nonuniform pressure can produce Hertzian-type stresses, leading to crack initiation and fracture of the test specimen in the gripped section. Gripping devices can be classed generally as those employing active and those employing passive grip interfaces as discussed in the following sections.

6.2.2 *Active Grip Interfaces*—Active grip interfaces require a continuous application of a mechanical, hydraulic, or pneumatic force to transmit the force applied by the test machine to the test specimen. Generally, these types of grip interfaces cause a force to be applied normal to the surface of the gripped section of the test specimen. Transmission of the uniaxial force applied by the test machine is then accomplished by friction between the test specimen and the grip faces. Thus, important aspects of active grip interfaces are uniform contact between the gripped section of the test specimen and the grip faces and constant coefficient of friction over the grip/specimen interface.

6.2.2.1 For cylindrical test specimens, a one-piece split-collet arrangement acts as the grip interface (1, 2)<sup>3</sup> as illustrated in Fig. 2. Generally, close tolerances are required for concentricity of both the grip and test specimen diameters. In addition, the diameter of the gripped section of the test specimen and the unclamped, open diameter of the grip faces must be within similarly close tolerances to promote uniform contact at the test specimen/grip interface. Tolerances will vary depending on the exact configuration as shown in the appropriate test specimen drawings.

6.2.2.2 For flat test specimens, ~~flat-face, flat-faced,~~ wedge-grip faces act as the grip interface as illustrated in Fig. 3. Generally, close tolerances are required for the flatness and parallelism as well as wedge angle of the grip faces. In addition, the thickness, flatness, and parallelism of the gripped section of the test specimen must be within similarly close tolerances to promote uniform contact at the test specimen/grip interface. Tolerances will vary depending on the exact configuration as shown in the appropriate test specimen drawings.

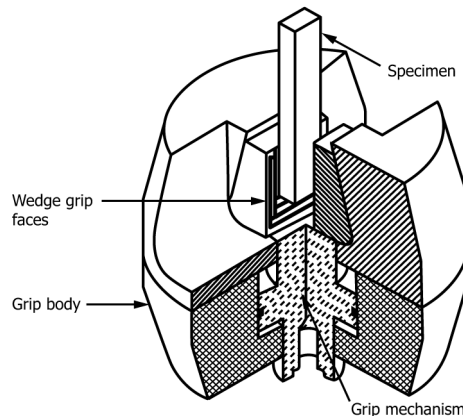


FIG. 3 Example of a Smooth, Wedge Active Gripping System for Flat Test Specimens

<sup>3</sup> The boldface numbers given in parentheses refer to a list of references at the end of the text.

6.2.3 *Passive Grip Interfaces*—Passive grip interfaces transmit the force applied by the test machine to the test specimen through a direct mechanical link. Generally, these mechanical links transmit the test forces to the test specimen via geometrical features of the test specimens such as button-head fillets, shank shoulders, or holes in the gripped head. Thus, the important aspect of passive grip interfaces is uniform contact between the gripped section of the test specimen and the grip faces.

6.2.3.1 For cylindrical test specimens, a ~~multi-piece split collet~~ *multi-piece, split-collet* arrangement acts as the grip interface at button-head fillets of the test specimen (3) as illustrated in Fig. 4. Because of the limited contact area at the test specimen/grip interface, soft, deformable collet materials may be used to conform to the exact geometry of the test specimen. In some cases, tapered collets may be used to transfer the axial force into the shank of the test specimen rather than into the button-head radius (3). Moderately close tolerances are required for concentricity of both the grip and test specimen diameters. In addition, tolerances on the collet height must be maintained to promote uniform ~~axial-loading~~ *axial loading* at the test specimen/grip interface. Tolerances will vary depending on the exact configuration as shown in the appropriate test specimen drawings.

6.2.3.2 For flat test specimens, pins or pivots act as grip interfaces at either the shoulders of the test specimen shank or at holes in the gripped test specimen head (44-6, 5, 6). Close tolerances are required of shoulder radii and grip interfaces to promote uniform contact along the entire test specimen/grip interface, as well as to provide for non-eccentric loading as shown in Fig. 5. Moderately close tolerances are required for longitudinal coincidence of the pin and hole centerlines as illustrated in Fig. 6.

6.3 *Load Train Couplers:*

6.3.1 *General*—Various types of devices (load train couplers) may be used to attach the active or passive grip interface assemblies to the testing machine. The load train couplers, in conjunction with the type of gripping device, play major roles in the alignment of the load train and thus subsequent bending imposed in the test specimen. Load train couplers can be classified as fixed and nonfixed as discussed in the following sections. Note that use of well-aligned fixed or self-aligning ~~non-fixed~~ *nonfixed* couplers does not automatically guarantee low bending in the gage section of the tensile test specimen. Well-aligned fixed or self-aligning ~~non-fixed~~ *nonfixed* couplers provide for well aligned load trains, but the type and operation of grip interfaces, as well as the as-fabricated dimensions of the tensile test specimen, can add significantly to the final bending imposed in the gage section of the test specimen.

6.3.1.1 Regardless of which type of coupler is used, alignment of the testing system must be verified ~~asat~~ *at* a minimum at the beginning and end of a test series. An additional verification of alignment is recommended, although not required, at the middle of the test series. Either a dummy or actual test specimen and the alignment verification procedures detailed in the ~~appendix~~ *appendixes* must be used. Allowable bending requirements are discussed in 6.4. Tensile test specimens used for alignment verification should be equipped with a recommended eight separate longitudinal strain gages to determine bending contributions from both eccentric and angular misalignment of the grip heads. (Although it is possible to use a minimum of six separate longitudinal strain gages for test specimens with circular cross sections, eight strain gages are recommended here for simplicity and consistency in describing the technique for both circular and rectangular cross sections). If dummy test specimens are used for alignment verification, they should have the same geometry and dimensions of the actual test specimens as well as the same mechanical properties (that is, elastic modulus, hardness, etc.) as the test material to ensure similar axial and bending stiffness characteristics as the actual test specimen and material.

6.3.2 *Fixed Load Train Couplers*—Fixed couplers may incorporate devices that require either a one-time, pre-test alignment adjustment of the load train which remains constant for all subsequent tests or an *in-situ*, pre-test alignment of the load train that

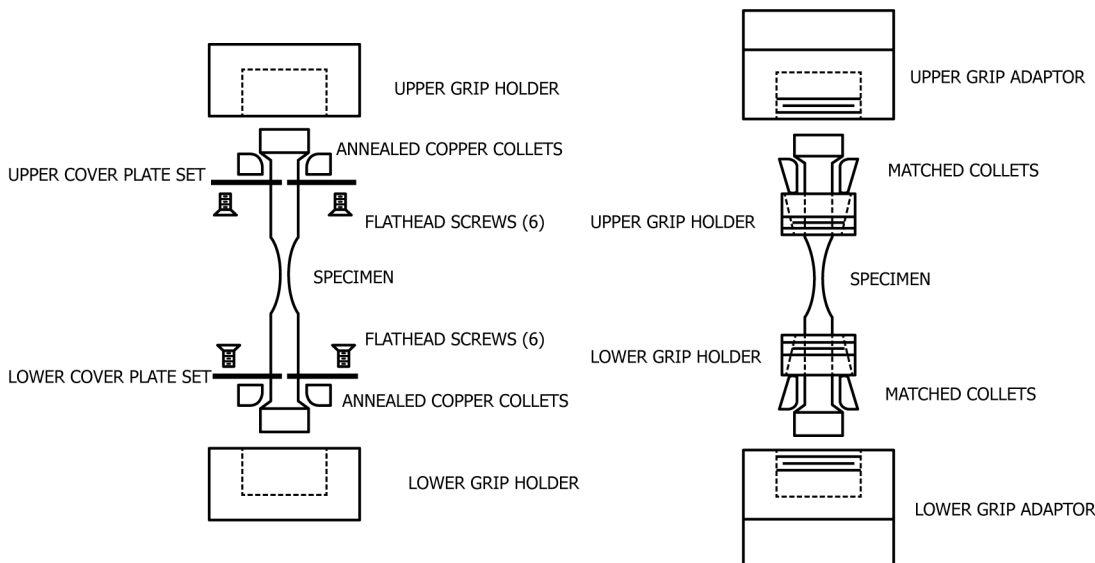


FIG. 4 Examples of Straight- and Tapered-Collet Passive Gripping Systems for Cylindrical Test Specimens (3)

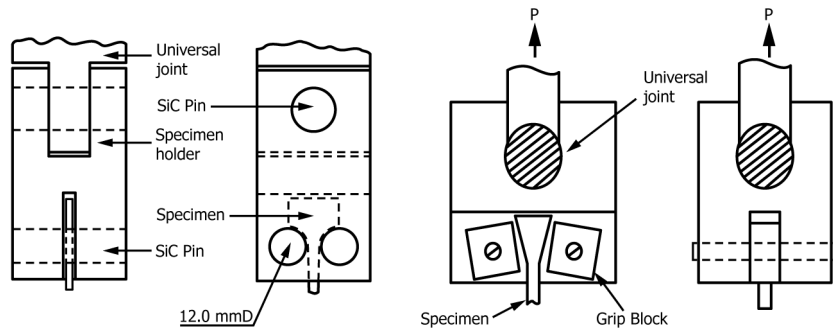


FIG. 5 Examples of Shoulder-Loaded, Passive Gripping Systems for Flat Test Specimens (4, 5)

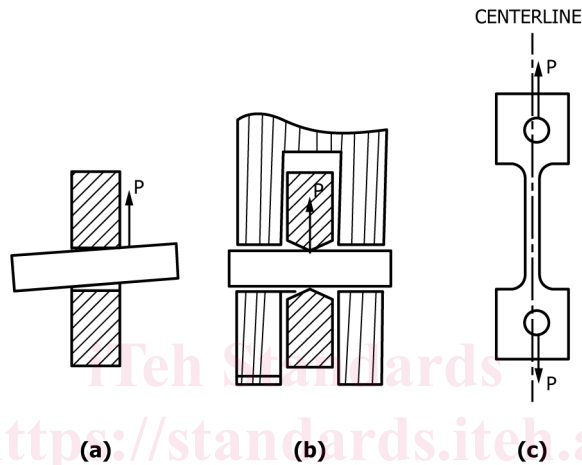


FIG. 6 Example of a Pin-Loaded, Passive Gripping System for Flat Test Specimens (7)

is conducted separately for each test specimen and each test. Such devices (8, 9) usually employ angularity and concentricity adjusters to accommodate inherent load train misalignments. Regardless of which method is used, alignment verification must be performed as discussed in 6.3.1.1.

6.3.3 ~~Non-Fixed~~ Nonfixed Load Train Couplers—~~Non fixed~~ Nonfixed couplers may incorporate devices that promote self-alignment of the load train during the movement of the crosshead or actuator. Generally, such devices rely upon freely moving linkages to eliminate applied moments as the load train components are loaded. Knife edges, universal joints, hydraulic couplers, or air bearings are examples (4, 8, 10-12, 11, 12) of such devices. Examples of two such devices are shown in Fig. 7. Although ~~non-fixed~~ nonfixed load train couplers are intended to be self-aligning and thus eliminate the need to evaluate the bending in the test specimen for each test, the operation of the couplers must be verified as discussed in 6.3.1.1.

6.4 Allowable Bending—Analytical and empirical studies (3) have concluded that for negligible effects on the estimates of the strength distribution parameters (for example, Weibull modulus,  $m^{\wedge}$ , and characteristic strength,  $\sigma_0^{\wedge}$ ), allowable percent bending as defined in Practice E1012 should not exceed five. These conclusions (3) assume that tensile strength fractures are due to fracture origins in the volume of the material, all tensile test specimens experienced the same level of bending, and that Weibull modulus,  $m^{\wedge}$ , was constant. Thus, the maximum allowable percent bending at fracture for test specimens tested under this test method shall not exceed five. However, it should be noted that unless all test specimens are properly strain gaged and percent bending monitored until fracture, there will be no record of percent bending at fracture for each test specimen. Therefore, the testing system shall be verified using the procedure detailed in the ~~appendix~~ appendixes such that percent bending does not exceed five at a mean strain equal to ~~one-half~~ one-half the anticipated strain at fracture. This verification shall be conducted at a minimum at the beginning and ~~each~~ end of each test series as recommended in previous sections. An additional verification of alignment is recommended, although not required, at the middle of the test series.

6.5 Data Acquisition—At the minimum, an autographic record of applied force versus time should be obtained. 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, an analog chart recorder or plotter should be used 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 within 1 % for total testing system, including readout unit, as specified in Practices E4 and should have a minimum data acquisition rate of 10 Hz, with a response of ~~50 Hz~~ 50 Hz deemed more than sufficient.

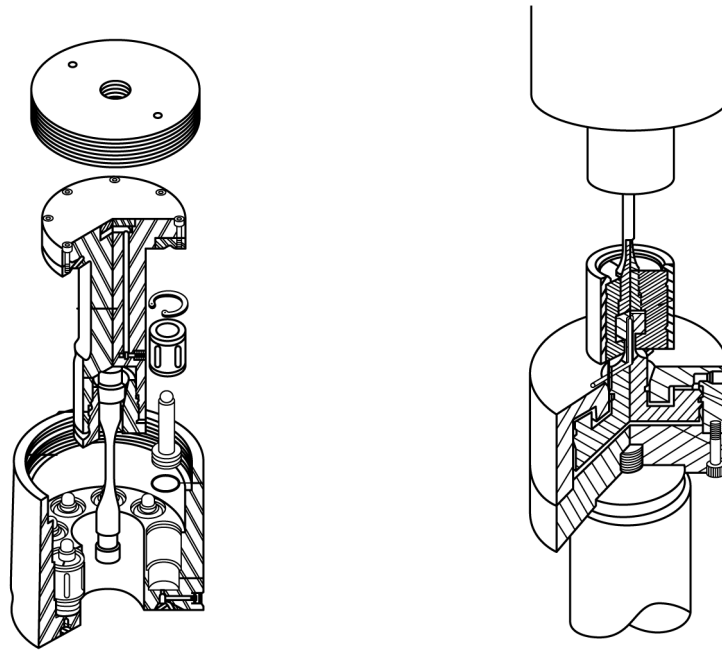


FIG. 7 Examples of Hydraulic, Self-Aligning, Non-Fixed-Nonfixed Load Train Couplers (10, 11)

6.5.1 Where strain or elongation of the gage section are also measured, these values should be recorded either similarly to the force or as independent variables of force. Cross-head displacement of the test machine may also be recorded but should not be used to define displacement or strain in the gage section, especially when self-aligning couplers are used in the load train.

6.6 *Dimension-Measuring Devices*—Micrometers and other devices used for measuring linear dimensions should be accurate and precise to at least one-half the smallest unit to which the individual dimension is required to be measured. For the purposes of this test method, cross-sectional dimensions should be measured to within 0.02 mm, requiring dimension measuring devices with accuracies of 0.01 mm.

## 7. Precaution

7.1 During the conduct of this test method, the possibility of flying fragments of broken test material is quite high. 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 later fractographic reconstruction and analysis is highly recommended.

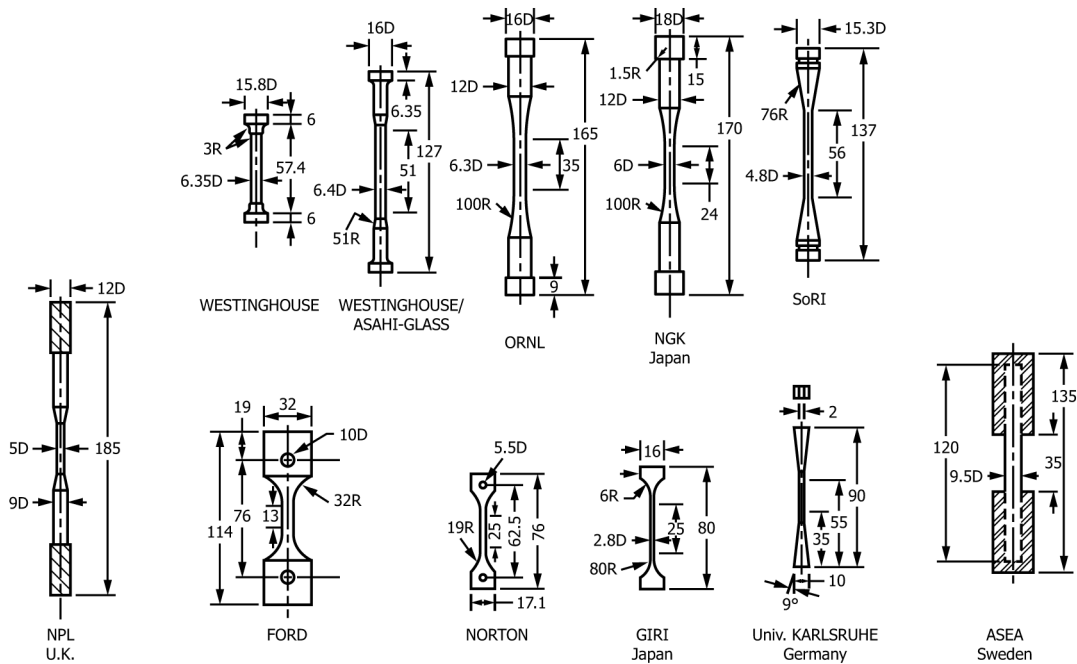
## 8. Test Specimens

### 8.1 Test Specimen Geometry:

8.1.1 *General*—The geometry of tensile test specimens is dependent on the ultimate use of the tensile strength data. For example, if the tensile strength of an as-fabricated component is required, the dimensions of the resulting tensile test specimen may reflect the thickness, width, and length restrictions of the component. If it is desired to evaluate the effects of inherent flaw distributions for a particular material manufactured from a particular processing route, then the size of the test specimen and resulting gage section will reflect the desired volume to be sampled. In addition, grip interfaces and load train couplers as discussed in Section 6 will influence the final design of the test specimen geometry.

8.1.1.1 Fig. 8 illustrates a range of tensile test specimen geometries that have been applied to testing advanced ceramics. Note that Fig. 8 provides only a sampling of possible tensile test specimens for ceramics and by no means purports to represent all possible configurations past or present. The following subsections discuss the more common, and thus proven, of these test specimen geometries, although any geometry is acceptable if it meets the gripping and bending requirements of this test method. If deviations from the recommended geometries are made, a stress analysis of the test specimen should be conducted to ensure that stress concentrations that could lead to undesired fractures outside the gage section do not exist.

8.1.2 *Cylindrical Tensile Test Specimens*—Cylindrical test specimens are generally fabricated from rods of material and offer the potential of testing the largest volume of the various tensile test specimens. In addition, the size of the test specimen lends itself to more readily evaluating the mechanical behavior of a material for engineering purposes. Disadvantages include the relatively large amount of material required for the starting billet, the large amount of material which must be removed during test specimen fabrication, and the need to fabricate the test specimen cylindrically usually requiring numerically controlled grinding machines, all of which may add substantially to the total cost per test specimen. Gripped ends include various types of button-heads (3, 8-13)



NOTE 1—All dimensions are in mm.

NOTE 2—Acronyms: NPL, U.K. = National Physical Laboratory, United Kingdom; ORNL = Oak Ridge National Laboratory; NGK = NGK Insulators; SoRI = Southern Research Institute; ASEA = ASEA-Ceram; NIST = National Institute of Standards and Technology; GIRI = Government Industrial Research Institute.

FIG. 8 Examples of Variety of Tensile Test Specimens Used for Advanced Ceramics

as shown in Fig. X2.1, Figs. X2.1-X2.3, Fig. X2.2, and Fig. X2.3. In addition, straight-shank straight-shank geometries have been successfully used (1, 2) as shown in Fig. X2.4, Figs. X2.4 and X2.5 and Fig. X2.5. Important tolerances for the cylindrical tensile test specimens include concentricity and cylindricity that will vary depending on the exact configuration as shown in the appropriate test specimen drawings.

8.1.3 Flat Tensile Test Specimens—Flat tensile specimens are generally fabricated from plates or blocks of material and offer the potential for ease of material procurement, ease of fabrication, and subsequent lower cost per test specimen. Disadvantages include the relatively small volume of material tested and sensitivity of the test specimen to small dimensional tolerances or disturbances in the load train. Gripped ends include various types of shoulder-loaded shanks (4, 5) as shown in Fig. X2.6, Figs. X2.6 and X2.7 and Fig. X2.7. In addition, pin-loaded gripped ends (6) have also been used successfully as shown in Fig. X2.8. It should be noted that gage sections of flat tensile test specimens for strength measurements are sometimes cylindrical. While this type of gage section adds to the difficulty of fabrication and therefore cost of the flat tensile test specimen, it does avoid the problem of fractures initiating at corners of non-cylindrical non-cylindrical gage sections. Corner fractures may be initiated by stress concentrations due to the elastic constraint of the corners but are more generally initiated by damage (chipping, etc.) that can be treated by chamfering the corners similar to that recommended for rectangular cross section bars used for flexure tests (see Test Method C1161). Important tolerances for the flat tensile test specimens include cylindricity of the gage section, parallelism of faces, and longitudinal alignment of load lines (pin hole (pinhole centers or shoulder loading points) points), all of which will vary depending on the exact configuration as shown in the appropriate test specimen drawings.

## 8.2 Test Specimen Preparation:

8.2.1 Depending upon the intended application of the tensile strength data, use one of the following test specimen preparation procedures. Regardless of the preparation procedure used, sufficient details regarding the procedure must be reported to allow replication.

8.2.2 As-Fabricated—The tensile test specimen should simulate the surface/edge conditions and processing route of an application where no machining is used; for example, as-cast, sintered, or injection molded injection-molded part. No additional machining specifications are relevant. As-processed test specimens might possess rough surface textures and non-parallel edges, and as such may cause excessive misalignment and/or be prone to non-gage section fractures, fractures, or both.

8.2.3 Application-Matched Machining—The tensile test specimen should have the same surface/edge preparation as that given to the component. Unless the process is proprietary, the report should be specific about the stages of material removal, wheel grits, wheel bonding, amount of material removed per pass, and type of coolant used.



8.2.4 *Customary Practices*—In instances where a customary machining procedure has been developed that is completely satisfactory for a class of materials (that is, it induces no unwanted surface/subsurface damage or residual stresses), this procedure should be used.

8.2.5 *Standard Procedure*—In instances where ~~8.2.28.2.2 – 8.2.4~~ through ~~8.2.4~~ are not appropriate, 8.2.5 should apply. The procedure in 8.2.5 (or as discussed in Test Method C1161) should serve as minimum requirements, and a more stringent procedure may be necessary.

8.2.5.1 Do all grinding or cutting with an ample supply of appropriate filtered coolant to keep the workpiece and grinding wheel constantly flooded and particles flushed. Do grinding in at least two stages, ranging from coarse to fine rate of material removal. All cutting can be done in one stage appropriate for the depth of cut.

8.2.5.2 Stock removal rate should not exceed 0.03 mm per pass to the last 0.06 mm. Final finishing should be performed with diamond tools that have between 320 and 600 grit. No less than 0.06 mm per face should be removed during the final finishing phase, and at a rate not more than 0.002 mm per pass. Remove equal stock from each face where applicable.

8.2.5.3 Edge finishing must be comparable to that applied to test specimen surfaces. In particular, the direction of machining should be parallel to the longitudinal axis of the test specimen.

8.2.5.4 Materials with low fracture toughness and a greater susceptibility to grinding damage may require finer grinding wheels at very low removal rates.

8.2.5.5 Generally, surface finishes on the order of average roughnesses,  $R_a$ , of 0.2 to 0.4  $\mu\text{m}$  are recommended to minimize surface fractures related to surface roughness. However, in some cases the final surface finish may not be as important as the route of fabrication due to the generation of subsurface damage during the fabrication process.

8.2.5.6 Geometric features such as holes, button-head radiuses, or transition radiuses require just as stringent attention to fabrication detail as that paid to gage section. Therefore, the minimum requirements outlined here should be applied to these geometric features as well as to the gage section.

8.2.6 *Cylindrical Tensile Test Specimen Procedure*—Because of the axial symmetry of the button-head tensile test specimen, fabrication of the test specimens is generally conducted on a lathe-type apparatus. In many instances, the bulk of the material is removed in a circumferential grinding operation with a ~~final, final~~ longitudinal grinding operation performed in the gage section to ~~assure~~ensure that any residual grinding marks are parallel to the applied stress. Beyond those guidelines given here, Ref. (3) provides more specific details of recommended fabrication methods for cylindrical tensile test specimens.

8.2.6.1 Generally, computer numerical control (CNC) fabrication methods are necessary to obtain consistent test specimens with the proper dimensions within the required tolerances. A necessary condition for this consistency is the complete fabrication of the test specimen without removing it from the grinding apparatus, thereby avoiding the introduction of unacceptable tolerances into the finished test specimen.

8.2.6.2 Formed, resinoid-bonded, diamond-impregnated wheels (minimum 320 grit in a resinoid bond) are necessary to both fabricate critical shapes (for example, button-head radius) and to minimize grinding vibrations and subsurface damage in the test material. The formed, resin-bonded wheels require periodic dressing and shaping (truing), that can be done dynamically within the test ~~machine, machine~~ to maintain the cutting and dimensional integrity.

8.2.6.3 The most serious concern is not necessarily the surface finish (on the order of  $R_a = 0.2\text{--}0.4 \mu\text{m}$ ) that is a result of the final machining steps. Instead, the subsurface damage is critically important although this damage is not readily observed or ~~measured, measured~~ and, therefore, must be inferred as the result of the grinding history. More details of this aspect have been discussed elsewhere (3). In all cases, the final grinding operation (“spark out”) performed in the gage section is to be along the longitudinal axis of the test specimen to ~~assure~~ensure that any residual grinding marks are parallel to the applied stress. (**Warning—Handling Precaution**—Extreme care should be exercised in storage and handling of finished test specimens to avoid the introduction of random and severe flaws (for example, test specimens impact or scratch against each other). It is therefore highly recommended that each test specimen be stored in separate nonmetallic containers or in a nonmetallic container restricted from contact with other test specimens by dividers. In addition, attention should be given to pre-test storage of test specimens in controlled environments or desiccators to avoid unquantifiable environmental degradation of test specimens prior to testing.)

8.3 *Number of Test Specimens*—As noted in Practice C1239, the total number of test specimens plays a significant role in the estimates of strength distribution parameters (for example, Weibull modulus,  $m^{\wedge}$ , and characteristic strength,  $\sigma^{\wedge}_0$ ). Initially, the uncertainty associated with parameter estimates decreases significantly as the number of test specimens increases. However, a point of diminishing returns is reached when the cost of performing additional tensile strength tests may not be justified. This suggests that a practical number of tensile strength tests should be performed to obtain a desired level of confidence associated with a parameter estimate. The number of test specimens needed depends on the precision required in the resulting parameter estimate. Additional details concerning the determination of the strength distribution parameters are provided in Practice C1239.

8.3.1 It is therefore impossible to state the actual number of test specimens required under this test method, since the number of test specimens needed depends on the precision required in the resulting parameter estimate and thus depends on the unique requirements of each application. Practice C1239 requires the reporting of 90 % confidence bounds for Weibull modulus,  $m^{\wedge}$ , and characteristic strength,  $\sigma^{\wedge}_0$ , when a single flaw population is responsible for strength distributions. As an illustrative example, Table 1 shows the upper and lower 90 % confidence bounds for  $m^{\wedge}$ ; and  $\sigma^{\wedge}_0$  for 5, ~~10, five, ten,~~ and 30 tests assuming a biased  $m^{\wedge}$  of 10 and  $\sigma^{\wedge}_0$  of 500 MPa for a single flaw population. As a rule of thumb, a minimum of five tests can be conducted to determine an

**TABLE 1 Example of Upper and Lower 90 % Confidence Bounds for Weibull Parameter Estimates Assuming a Single Flaw Population<sup>A</sup>**

Number of test specimens, $n$	$m^{\wedge}_{upper}$	$m^{\wedge}_{lower}$	$(\sigma^{\wedge}_{\theta})_{upper}$	$(\sigma^{\wedge}_{\theta})_{lower}$
5	14.6	3.6	566	448
10	13.5	5.5	534	469
30	12.2	7.5	517	483

<sup>A</sup> For a biased Weibull modulus,  $m^{\wedge}$ , of 10 and a characteristic strength,  $\sigma^{\wedge}_{\theta}$ , of 500 MPa.

indication of material properties if material cost or test specimen availability limit the number of tests to be conducted. A minimum of ten tests is required for the purposes of estimating a mean.

## 9. Procedure

9.1 *Test Specimen Dimensions*—Determine the diameter or thickness and width of the gage section of each test specimen to within 0.02 mm. Make measurements on at least three different ~~cross-sectional~~ cross-sectional planes in the gage section. In the case of the cylindrical test specimens, two measurements (90° apart) should be made on each plane. To avoid damage in the critical gage section area, it is recommended that these measurements be made either optically (for example, an optical comparator) or mechanically using a flat, anvil-type micrometer. In either case, the resolution of the instrument must be as specified in 6.6. Exercise extreme caution to prevent damage to the test specimen gage section. Ball-tipped or sharp anvil micrometers are not recommended because localized cracking may be induced. Record the measured dimensions and locations of the measurements and report for use in the calculation of the tensile stress at fracture. Use the average of the multiple measurements in the stress calculations.

9.1.1 Alternatively, to avoid damage to the gage section, post-fracture measurements of the gage section dimensions can be made using procedures described in 9.1. Note that in some cases, the fracture process can severely fragment the gage section in the immediate vicinity of the fracture, thus making post-fracture measurements of dimensions difficult. In these cases, it is advisable to follow the procedures outlined in 9.1 for pretest measurements to ensure reliable measurements.

9.1.2 It is advisable to conduct periodic, if not 100 %, inspection/measurements of all test specimens and test specimen dimensions to ensure compliance with the drawing specifications. Generally, ~~high-resolution~~ high-resolution optical methods (for example, an optical comparator) or ~~high-resolution~~ high-resolution digital point contact methods (for example, coordinate measurement machine) are satisfactory as long as the equipment meets the specification in 6.6. Note that the frequency of gage section fractures and bending in the gage section are dependent on maintaining proper overall test specimen dimensions within the required tolerances.

9.1.3 Measure surface finish to quantify the surface condition. Such methods as contacting profilometry can be used to determine surface roughness parallel to the tensile axis. When quantified, report surface roughness.

9.2 *Strain Measurements*—Although strain measurement techniques are not required in this test method, their use is highly recommended. In particular, multiple axial strain gages or dual axial extensometers conforming to Class B1 of Practice E83 can be used to monitor bending for each test. In addition, appropriate strain measurements can be used to determine elastic constants in the linear region of the ~~stress-strain~~ stress-strain curves and can serve to indicate underlying fracture mechanisms manifested as nonlinear stress-strain behavior.

9.2.1 When contacting extensometers are employed, exercise extreme care so as not to damage the surface of the gage section. Similarly, preparation of the surface for application of resistance strain gages should avoid the use of abrasive techniques that can locally increase surface roughness, possibly promoting surface-related fractures.

### 9.3 Test Modes and Rates:

9.3.1 *General*—Test modes and rates can have distinct and strong influences on the fracture behavior of advanced ceramics, even at ambient temperatures, depending on test environment or condition of the test specimen. Test modes may involve force, displacement, or strain control. Recommended rates of testing are intended to be sufficiently rapid to obtain the maximum possible tensile strength at fracture of the material. However, rates other than those recommended here may be used to evaluate rate effects. In all cases, the test mode and rate must be reported.

9.3.2 *Force Rate*—For most advanced ceramics exhibiting linear elastic behavior, fracture is attributed to a weakest-link fracture mechanism generally attributed to stress-controlled fracture from Griffith-like flaws. Therefore, a force-controlled test, with force generally related directly to tensile stress in brittle linear elastic advanced ceramics, is the preferred test mode. Force rate can be directly related to stress rate, thus simplifying data analysis. Stress rates >35 to 50 MPa/s are recommended to reduce the influence of environmental effects and thus obtain the greatest value of ultimate tensile strength. Alternatively, select stress rates to produce final fracture in 5 to 10 s to minimize environmental effects when testing in ambient air. Some materials may not be as sensitive to stress rate and less rapid stress rates may be employed in these situations. Force rate is calculated as: