Designation: C 1273 – 95a (Reapproved 2000)

Standard Test Method for Tensile Strength of Monolithic Advanced Ceramics at Ambient Temperatures[1]

This standard is issued under the fixed designation C 1273; 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 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. In addition, specimen fabrication methods, testing modes (load, displacement, or strain control), testing rates (load 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 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.* Specific precautionary statements are given in Section 7.

2. Referenced Documents

2.1 *ASTM Standards:*

C 1145 Terminology of Advanced Ceramics[2]

C 1161 Test Method for Flexural Strength of Advanced Ceramics at Ambient Temperature[2]

C 1239 Practice for Reporting Uniaxial Strength Data and Estimating Weibull Distribution Parameters for Advanced Ceramics[2]

D 3379 Test Method for Tensile Strength and Young's Modulus for High-Modulus Single-Filament Materials[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 a Psychrometer (the Measurement of Wet- and Dry-Bulb Temperatures)[5]

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

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

2.2 *Military Handbook:*

MIL-HDBK-790 Fractography and Characterization of Fracture Origins in Advanced Structural Ceramics[7]

3. Terminology

3.1 Definitions—The definitions of terms relating to tensile testing appearing in Terminology E 6 apply to the terms used in this test method on tensile testing. The definitions of terms relating to advanced ceramics testing appearing in Terminology C 1145 apply to the terms used in this test method. Pertinent definitions as listed in Practice C 1239, Practice E 1012, Terminology C 1145, and Terminology E 6 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:

3.1.1 *advanced ceramic*—a highly engineered, high performance predominately nonmetallic, inorganic, ceramic material having specific functional attributes. (See Terminology C 1145.)

3.1.2 *axial strain*—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 devices

[1] This test method is under the jurisdiction of ASTM Committee C-28 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 15.03.

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

[5] *Annual Book of ASTM Standards*, Vol 11.03.

[6] *Annual Book of ASTM Standards*, Vol 14.02.

[7] Available from Standardization Documents Order Desk, Bldg. 4 Section D, 700 Robbins Ave., Philadelphia, PA 19111-5094, Attn: NPODS.

located at the mid length of the reduced section. (See Practice E 1012.)

3.1.3 *bending strain*—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.)

3.1.4 *breaking load*—the load at which fracture occurs. (See Terminology E 6.)

3.1.5 *fractography*—the analysis and characterization of patterns generated on the fracture surface of a test specimen. Fractography can be used to determine the nature and the location of the critical fracture origin causing catastrophic fracture in an advanced ceramic test specimen or component. (See Practice C 1239.)

3.1.6 *fracture origin*—that flaw (discontinuity) from which the strength-limiting crack emanates. (See Terminology C 1145.)

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

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

3.1.9 *tensile strength*,— S_u—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.)

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, monolithic advanced ceramic materials generally characterized by small grain sizes (<50 µm) and bulk densities near the theoretical density 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 of the flexure specimen limits the volume of material subjected to the maximum applied stress at fracture. 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 tensile test may be several times that of a single flexure specimen, the need to test a statistically significant number of tensile specimens is not obviated. Therefore, because of the probabilistic strength distributions of brittle materials such as advanced ceramics, a sufficient number of 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 C 1239 will affect the strength values. Therefore, strengths obtained using different recommended tensile 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 C 1239.

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 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 specimens fabricated to standardized dimensions from a particular material and/or selected portions 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.) 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 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 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 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, 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 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 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 stresses caused by bending.

6. Apparatus

6.1 *Testing Machines*—Machines used for tensile testing shall conform to the requirements of Practice E 4. The loads used in determining tensile strength shall be accurate within ±1 % at any load within the selected load range of the testing machine as defined in Practice E 4. 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 load 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 gripped section of the specimen. Line or point contacts and non-uniform pressure can produce Hertizan-type stresses leading to crack initiation and fracture of the 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 load applied by the test machine to the test specimen. Generally, these types of grip interfaces cause a load to be applied normal to the surface of the gripped section of the specimen. Transmission of the uniaxial load applied by the test machine is then accomplished by friction between the specimen and the grip faces. Thus, important aspects of active grip interfaces are uniform contact between the gripped section of the specimen and the grip faces and constant coefficient of friction over the grip/specimen interface.

6.2.2.1 For cylindrical specimens, a one-piece split-collet arrangement acts as the grip interface **(1, 2)**[8] as illustrated in Fig. 2. Generally, close tolerances are required for concentricity of both the grip and specimen diameters. In addition, the diameter of the gripped section of the specimen and the unclamped, open diameter of the grip faces must be within similarly close tolerances to promote uniform contact at the specimen/grip interface. Tolerances will vary depending on the exact configuration as shown in the appropriate specimen drawings.

6.2.2.2 For flat specimens, flat-face, 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 specimen must be within similarly close tolerances to promote uniform contact at the specimen/grip interface. Tolerances will vary depending on the exact configuration as shown in the appropriate specimen drawings.

6.2.3 *Passive Grip Interfaces*—Passive grip interfaces transmit the load applied by the test machine to the test specimen through a direct mechanical link. Generally, these mechanical links transmit the test loads to the specimen via geometrical features of the specimens such as button-head

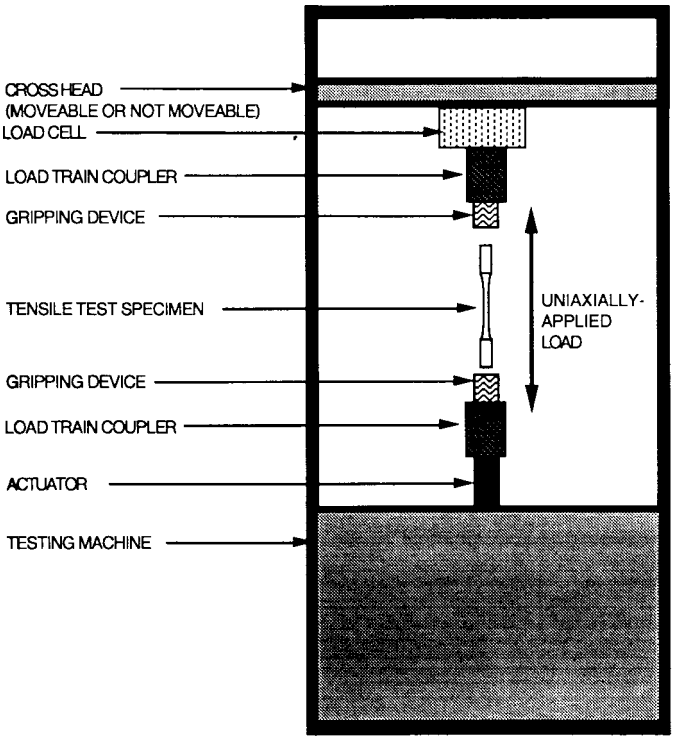


FIG. 1 Schematic Diagram of One Possible Apparatus for Conducting a Uniaxially-Loaded Tensile Test

[8] The boldface numbers given in parentheses refer to a list of references at the end of the text.

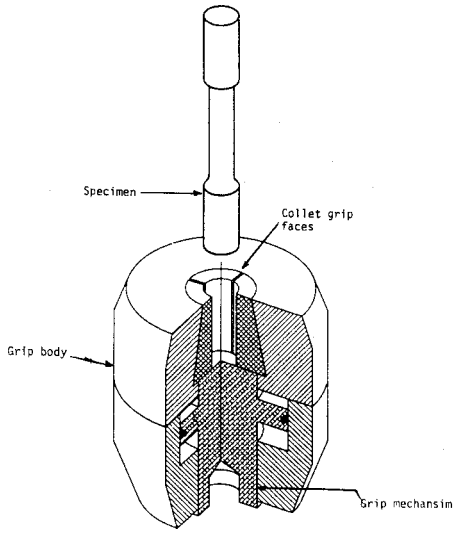


FIG. 2 Example of a Smooth, Split Collet Active Gripping System for Cylindrical Specimens

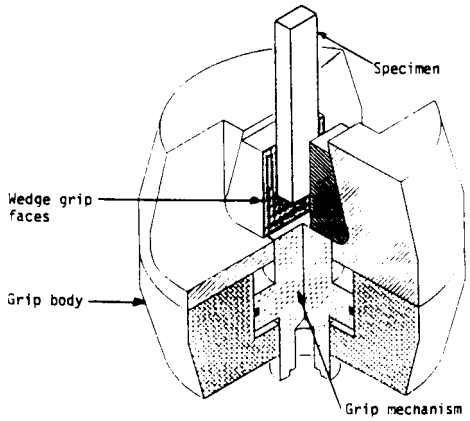


FIG. 3 Example of a Smooth, Wedge Active Gripping System for Flat Specimens

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 specimen and the grip faces.

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

6.2.3.2 For flat specimens, pins or pivots act as grip interfaces at either the shoulders of the specimen shank or at holes in the gripped specimen head **(4, 5, 6)**. Close tolerances are required of shoulder radii and grip interfaces to promote uniform contact along the entire specimen/grip interface as well as to provide for noneccentric 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 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 couplers does not automatically guarantee low bending in the gage section of the tensile specimen. Well-aligned fixed or self-aligning non fixed 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 specimen can add significantly to the final bending imposed in the gage section of the specimen.

6.3.1.1 Regardless of which type of coupler is used, alignment of the testing system must be verified as 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 must be used. Allowable bending requirements are discussed in 6.4. Tensile 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 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 specimens

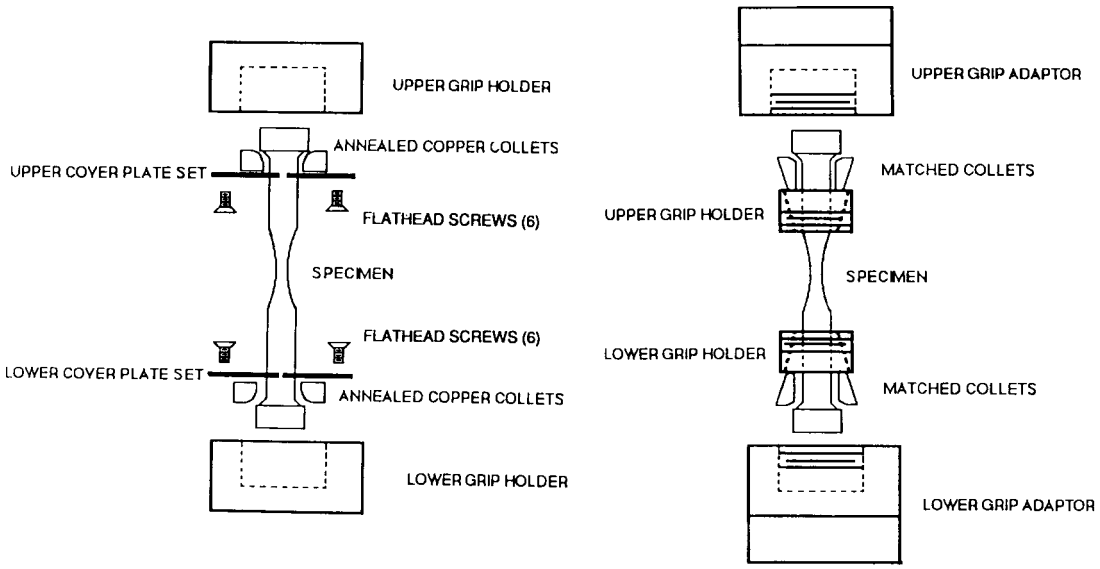


FIG. 4 Examples of Straight- and Tapered-Collet Passive Gripping Systems for Cylindrical Specimens (3)

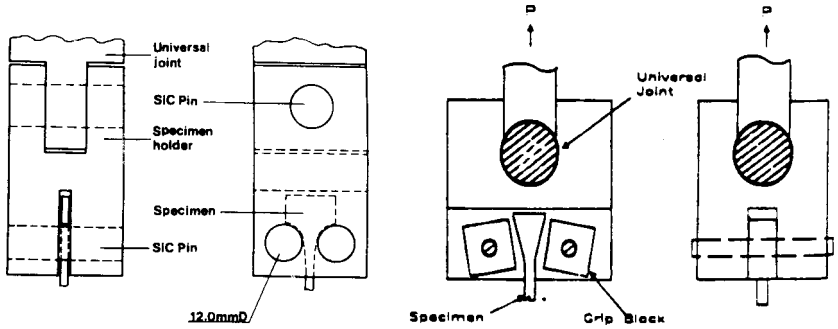


FIG. 5 Examples of Shoulder-Loaded, Passive Gripping Systems for Flat Specimens (4, 5)

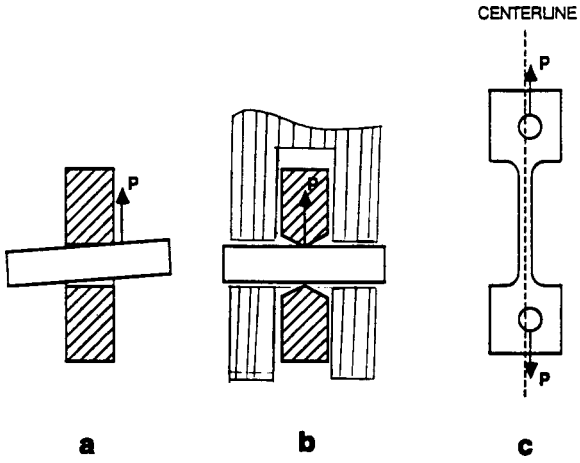


FIG. 6 Example of a Pin-Loaded, Passive Gripping System for Flat Specimens (16)

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 is conducted separately for each specimen and each test. Such devices **(7, 8)** 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 Load Train Couplers*— Non fixed 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, 7, 9, 10, 11)** of such devices. Examples of two such devices are shown in Fig. 7. Although non fixed load train couplers are intended to be self-aligning and thus eliminate the need to evaluate the bending in the 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

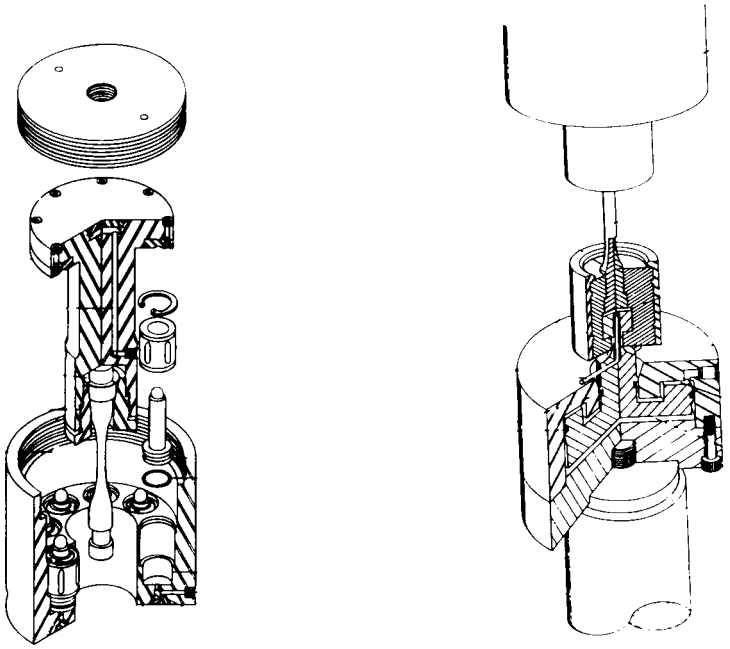


FIG. 7 Examples of Hydraulic, Self-Aligning, Non Fixed Load Train Couplers (9, 10)

of the strength distribution parameters (for example, Weibull modulus, $\hat{m}$, and characteristic strength, $\hat{\sigma}_0$) allowable percent bending as defined in Practice E 1012 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 specimens experienced the same level of bending and that Weibull modulus, $\hat{m}$, was constant. Thus, the maximum allowable percent bending at fracture for specimens tested under this test method shall not exceed five. However, it should be noted that unless all specimens are properly strain gaged and percent bending monitored until fracture, there will be no record of percent bending at fracture for each specimen. Therefore, the testing system shall be verified using the procedure detailed in the appendix such that percent bending does not exceed five at a mean strain equal to one half the anticipated strain at fracture. This verification shall be conducted at a minimum at the beginning and each 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 load 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 Practice E 4 and should have a minimum data acquisition rate of 10 Hz with a response of 50 Hz deemed more than sufficient.

6.5.1 Where strain or elongation of the gage section are also measured these values should be recorded either similarly to the load or as independent variables of load. 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

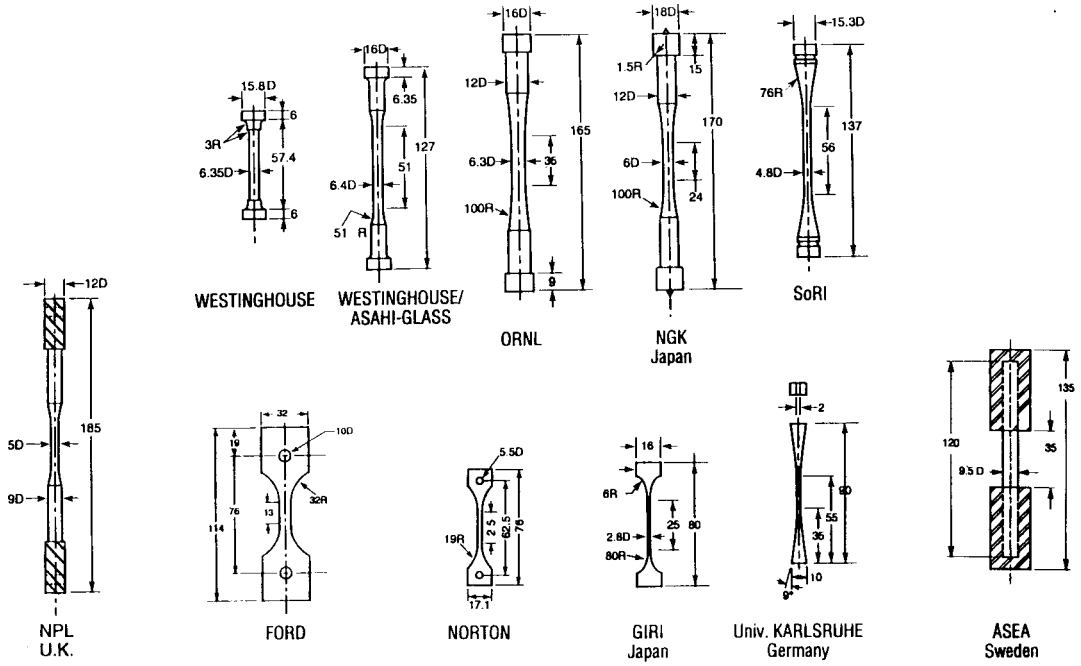
8.1 *Test Specimen Geometry*:

8.1.1 *General*—The geometry of tensile test specimen 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 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 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 specimen geometry.

8.1.1.1 Fig. 8 illustrates a range of tensile specimen geometries that have been applied to testing advanced ceramics. Note that Fig. 8 provides only a sampling of possible tensile 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 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 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 Specimens*— Cylindrical specimens are generally fabricated from rods of material and offer the potential of testing the largest volume of the various tensile specimens. In addition, the size of the 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 specimen fabrication, and the need to fabricate the specimen cylindrically usually requiring numerically controlled grinding machines, all of which may add substantially to the total cost per specimen. Gripped ends include various types of buttonheads **(3, 7 to 12)** as shown in Fig. 9, Fig. 10, and Fig. 11. In addition, straight shank geometries have been successfully used **(1, 2)** as shown in Fig. 12 and Fig. 13. Important tolerances for the cylindrical tensile specimens include concentricity and cylindricity that will vary depending on the exact configuration as shown in the appropriate specimen drawings.

8.1.3 *Flat Tensile Specimens*—Flat 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 specimen. Disadvantages include the relatively small volume of material tested and sensitivity of the 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. 14 and Fig. 15. In addition, pin-loaded gripped ends **(6)** have also been used successfully as shown in Fig. 16. It should be noted that gage sections of flat tensile 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 specimen it does avoid the problem of fractures initiating at corners of 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



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 Specimens Used for Advanced Ceramics

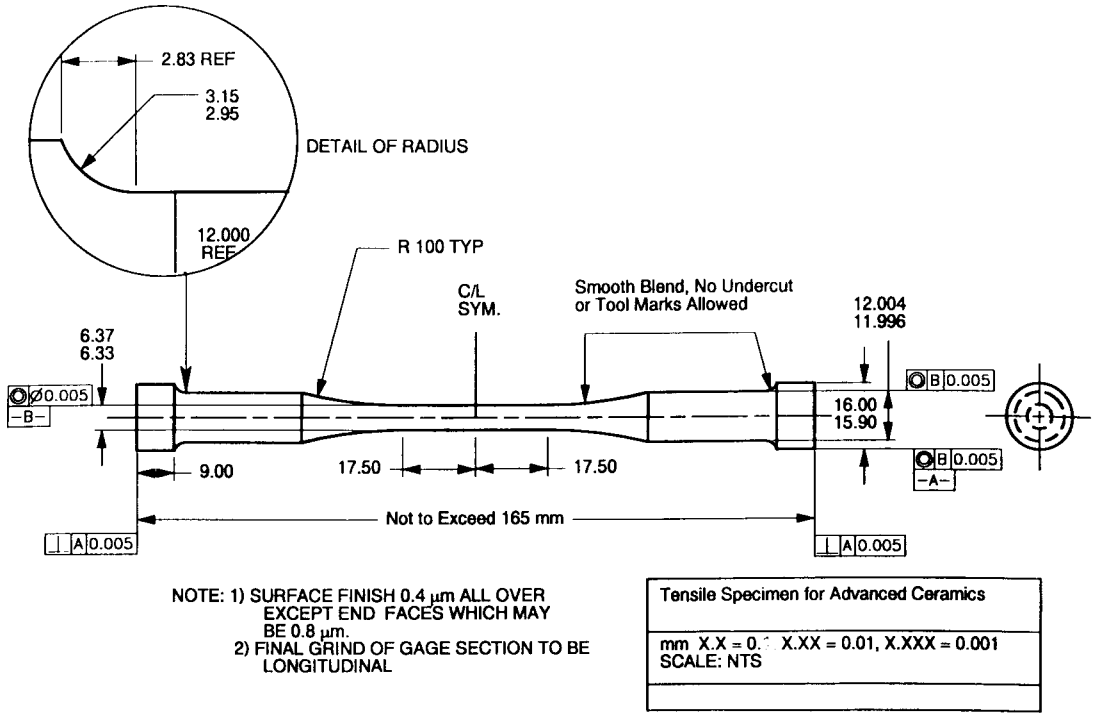


FIG. 9 Example of a Cylindrical Button-Head Tensile Specimen (3)

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 C 1161). Important tolerances for the flat tensile specimens include cylindricity of the gage section, parallelism of faces, and longitudinal alignment of load lines (pin hole centers or should loading points) all of which will vary depending on the exact configuration as shown in the appropriate specimen drawings.

8.2 *Specimen Preparation*:

8.2.1 Depending upon the intended application of the tensile

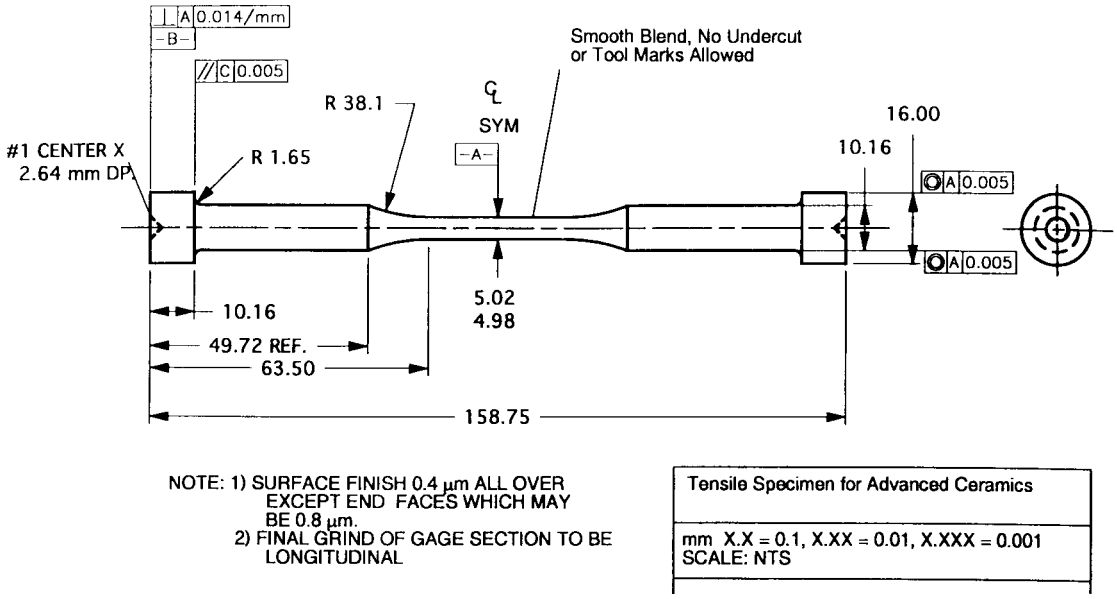


FIG. 10 Example of a Cylindrical, Button-Head Tensile Specimen (10)

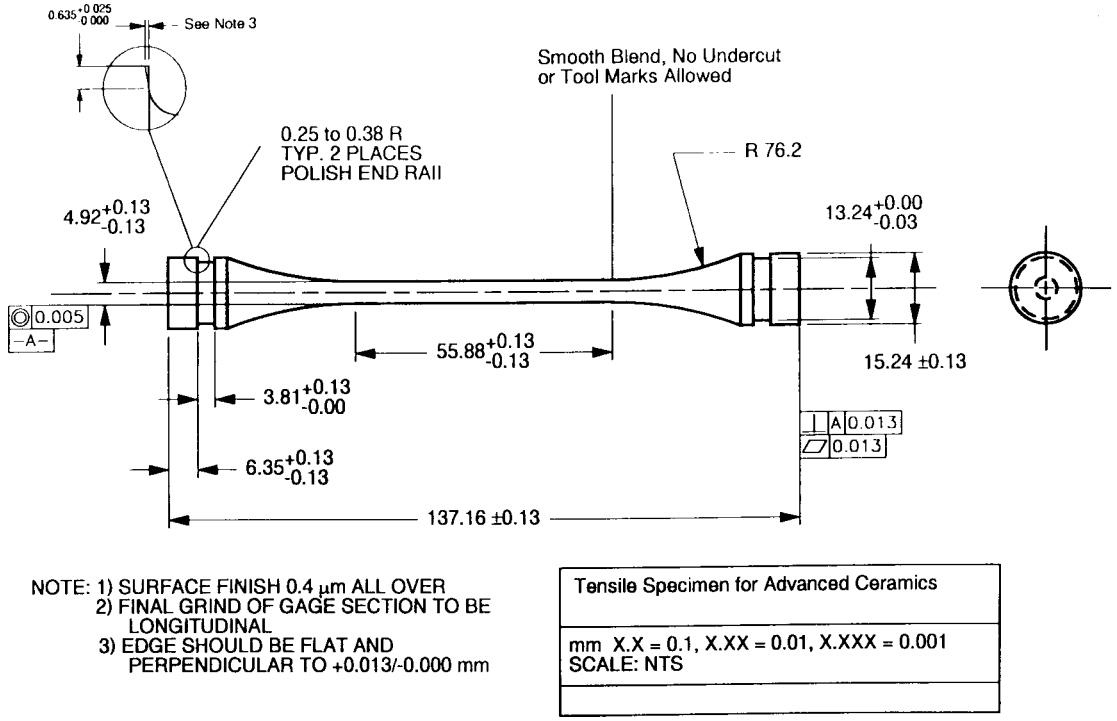


FIG. 11 Example of a Cylindrical, Button-Head Tensile Specimen (12)

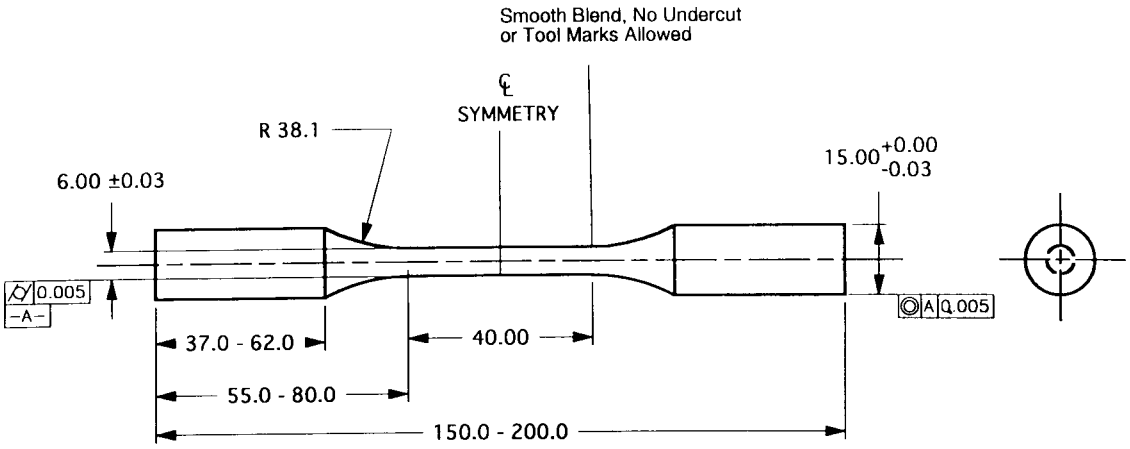
strength data, use one of the following specimen preparation procedures. Regardless of the preparation procedure used, sufficient details regarding the procedure must be reported to allow replication.

8.2.2 *As-Fabricated*—The tensile 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 part. No additional machining specifications are relevant. As-processed 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.

8.2.3 *Application-Matched Machining*— The tensile 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.

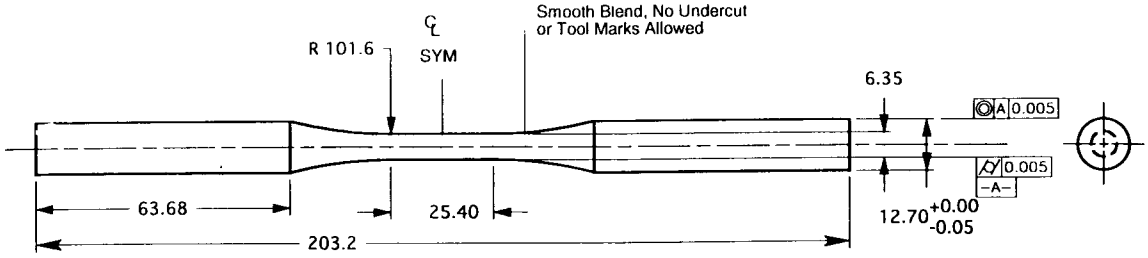
8.2.5 *Standard Procedure*—In instances where 8.2.2



NOTE: 1) SURFACE FINISH 0.4 μm ALL OVER EXCEPT END FACES WHICH MAY BE 0.8 μm.
2) FINAL GRIND OF GAGE SECTION TO BE LONGITUDINAL
3) TURNING CENTERS PERMITTED BOTH ENDS

Tensile Specimen for Advanced Ceramics
mm X.X = 0.1, X.XX = 0.01, X.XXX = 0.001 SCALE: NTS

FIG. 12 Example of a Cylindrical, Straight-Shank Tensile Specimen (8)



NOTE: 1) SURFACE FINISH 0.4 μm ALL OVER EXCEPT END FACES WHICH MAY BE 0.8 μm.
2) FINAL GRIND OF GAGE SECTION TO BE LONGITUDINAL

Tensile Specimen for Advanced Ceramics
mm X.X = 0.1, X.XX = 0.01, X.XXX = 0.001 SCALE: NTS

FIG. 13 Example of a Cylindrical, Straight-Shank Tensile Specimen (2)

through 8.2.4 are not appropriate, 8.2.5 should apply. The procedure in 8.2.5 (or as discussed in Test Method C 1161) 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.

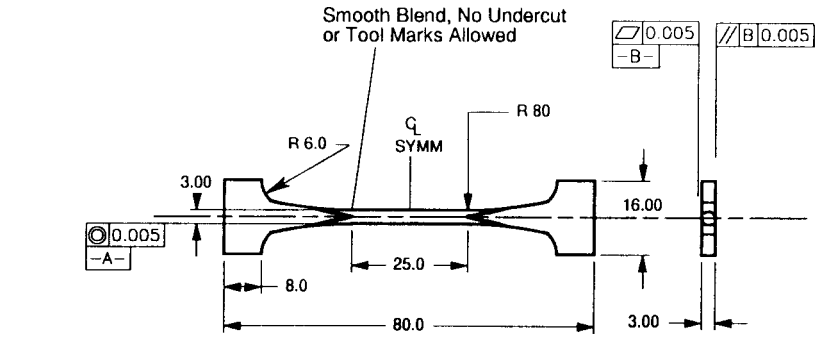
8.2.5.3 Edge finishing must be comparable to that applied to specimen surfaces. In particular, the direction of machining should be parallel to the longitudinal axis of the specimen.

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 μm 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.

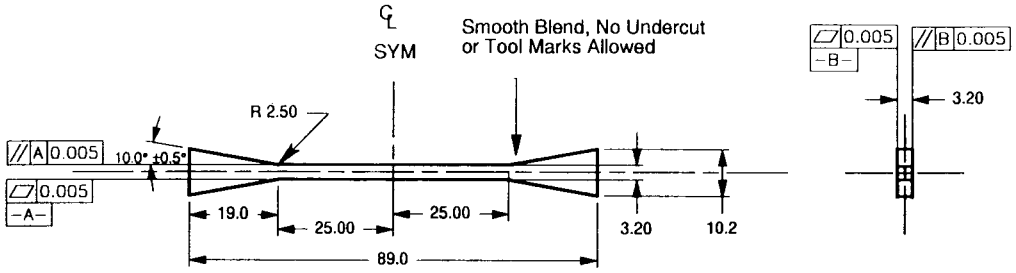
8.2.6 *Cylindrical Tensile Specimen Procedure*—Because of the axial symmetry of the button-head tensile specimen, fabrication of the specimens is generally conducted on a lathe-type apparatus. In many instances, the bulk of the material is removed in a circumferential grinding operation



NOTE: 1) SURFACE FINISH 0.4 μm ALL OVER EXCEPT END FACES WHICH MAY BE 0.8 μm.
2) FINAL GRIND OF GAGE SECTION TO BE LONGITUDINAL

Tensile Specimen for Advanced Ceramics
mm X.X = 0.1, X.XX = 0.01, X.XXX = 0.001 SCALE: NTS

FIG. 14 Example of a Flat, Shoulder-Loaded Tensile Specimen (4)



NOTE: 1) SURFACE FINISH 0.4 μm ALL OVER EXCEPT END FACES WHICH MAY BE 0.8 μm.
2) FINAL GRIND OF GAGE SECTION TO BE LONGITUDINAL

Tensile Specimen for Advanced Ceramics
mm X.X = 0.1, X.XX = 0.01, X.XXX = 0.001 SCALE: NTS

FIG. 15 Example of a Flat, Shoulder-Loaded Tensile Specimen (5)

with a final, longitudinal grinding operation performed in the gage section to assure 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 specimens.

8.2.6.1 Generally, computer numerical control (CNC) fabrication methods are necessary to obtain consistent specimens with the proper dimensions within the required tolerances. A necessary condition for this consistency is the complete fabrication of the specimen without removing it from the grinding apparatus, thereby avoiding the introduction of unacceptable tolerances into the finished 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, 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 = 0.2–0.4 μm) 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, 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 specimen to assure that any residual grinding marks are parallel to the applied stress.

Note: **Caution**—*Handling Precaution*—Extreme care should be exercised in storage and handling of finished specimens to avoid the introduction of random and severe flaws (for example, specimens impact or scratch against each other). It is therefore highly recommended that each specimen be stored in separate nonmetallic containers or in a nonmetallic

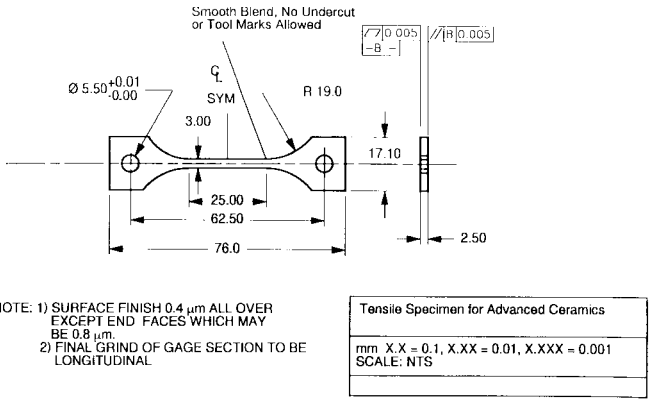


FIG. 16 Example of a Flat, Shoulder-Loaded Tensile Specimen (6)

container restricted from contact with other specimens by dividers. In addition, attention should be given to pre-test storage of specimens in controlled environments or desiccators to avoid unquantifiable environmental degradation of specimens prior to testing.

8.3 *Number of Test Specimens*—As noted in Practice C 1239, the total number of test specimens plays a significant role in the estimates of strength distribution parameters (for example, Weibull modulus, $\hat{m}$, and characteristic strength, $\hat{\sigma}_\theta$). 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 C 1239.

8.3.1 It is therefore impossible to state the actual number of 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 C 1239 requires the reporting of 90 % confidence bounds for Weibull modulus, $\hat{m}$, and characteristic strength, $\hat{\sigma}_\theta$ 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 $\hat{m}$, and $\hat{\sigma}_\theta$ for 5, 10, and 30 tests assuming a biased $\hat{m}$ of 10 and $\hat{\sigma}_\theta$ of 500 MPa for a single flaw population. As a rule of thumb a minimum of five tests can be conducted to determine an indication of material properties if material cost or specimen availability limit the number of tests to be conducted. A minimum of ten tests is required for the purposes of estimating a mean.

TABLE 1 Example of Upper and Lower 90 % Confidence Bounds for Weibull Parameter Estimates Assuming a Single Flaw Population[A]

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

[A] For a biased Weibull modulus, $\hat{m}$, of 10 and a characteristic strength, $\hat{\sigma}_\theta$, of 500 MPa.

9. Procedure

9.1 *Specimen Dimensions*—Determine the diameter or thickness and width of the gage section of each specimen to within 0.02 mm. Make measurements on at least three different cross sectional planes in the gage section. In the case of the cylindrical 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 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 specimens and specimen dimensions to ensure compliance with the drawing specifications. Generally, high resolution optical methods (for example, an optical comparator) or 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 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 B 1 of Practice E 83 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 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 specimen. Test modes may involve load, 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 *Load 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 load-controlled test, with load generally related directly to tensile stress in brittle linear elastic advanced ceramics, is the preferred test mode. Load 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. Load rate is calculated as:

$$\dot{P} = \frac{dP}{dt} = \dot{\sigma}A \tag{1}$$

where:

$\dot{P}$ = the required load rate in units of *N*/s,
P = the applied force in units of N,
t = time in units of *s*,
$\dot{\sigma}$ = the recommended (or desired stress rate) in units of MPa/s, and
A = the cross sectional area of the specimen gage section in units of mm^2.

The cross sectional area A is calculated as:

$$A = wb \text{ for rectangular cross sections} \tag{2}$$

or

$$A = \frac{\pi d^2}{4} \text{ for circular cross sections} \tag{3}$$

where:

w = the width of the gage section in units of mm,
b = the thickness of the gage section in units of mm, and
d = the diameter of the gage section in units of mm.

9.3.3 *Displacement Rate*—The size differences of each specimen geometry require a different loading rate for any given stress rate. Displacement mode is defined as the control of, or free-running displacement of, the test machine cross head. Thus, the displacement rate can be calculated as follows. Calculate $\dot{P}$ using the required (desired) stress rate as detailed in 9.3.2. Calculate the displacement rate as:

$$\delta = \frac{d\,\delta}{dt} = \left(\frac{1}{k_m} + \frac{1}{k_s}\right)\dot{P} \tag{4}$$

where:

δ = the required (desired) displacement rate of the cross head in units of mm/s,
δ = the cross-head displacement in units of mm,
k_m = he stiffness of the test machine and load train (including the specimen ends and the grip interfaces) in units of N/mm, and
k_s = the stiffness of the uniform gage section of the specimen in units of N/mm.

Note that $k_s$can be calculated as k_s= AE/L where A is the cross sectional area of the gage section, E is the elastic modulus of the test material, and L is the gripped length of the specimen. The stiffness, k_m, can be determined in accordance with Test Method D 3379 by measuring the load-displacement curves for various specimen lengths. The plot of k_m(slope of load-displacement curve) versus specimen length is then extrapolated to zero to find the actual machine stiffness. Alternatively, k_m can be estimated using the manufacturer's value for frame stiffness as a starting point and decreasing this value as necessary to account for various links in the load train.

9.3.4 *Strain Rate*—Strain is the independent variable in non linear analyses such as yielding. As such, strain rate is a method of controlling tests of deformation processes to avoid *runaway* (for example, uncontrolled, rapid failure) conditions. For the linear elastic behavior of most advanced ceramics at ambient temperatures, strain rate can be calculated directly from the required (desired) stress rate such that:

$$\dot{\epsilon} = \frac{d\epsilon}{dt} = \frac{\dot{\sigma}}{E} \tag{5}$$

where:

$\dot{\epsilon}$ = the strain rate in the specimen gage section in units of /s, and
ϵ = the strain in the specimen gage section.

Strain-controlled tests can be accomplished using an extensometer contacting the gage section of the specimen as the primary control transducer.

9.3.5 *Ramp Segments*—Normally, tests are conducted in a single ramp function at a single test rate from zero load to the maximum load at fracture. However, in some instances multiple ramp segments might be employed. In these cases, use a slow test rate to ramp from zero load to an intermediate load to allow time for deformation of collet material to critical radii

(for example, button-head fillets) in the test specimen. The final ramp segment of the test is conducted from the intermediate load to the maximum load at fracture at the required (desired) test rate. Report the type and time duration of the ramp.

9.4 *Conducting the Tensile Test*:

9.4.1 *Mounting the Specimen*—Each grip interface and specimen geometry described in Sections 6 and 8 will require a unique procedure for mounting the specimen in the load train. If special components (for example, annealed, copper collets) are required for each test, these should be identified and noted in the test report. Mark the specimen with an indelible marker as to the top and front (side facing the operator) in relation to the test machine. In the case of strain-gaged specimens, orient the specimen such that the "front" of the specimen and a unique strain gage (for example, Strain Gage 1 designated SG1) coincide.

9.4.2 *Preparations for Testing*—Set the test mode and test rate on the test machine. Preload the specimen to remove the "slack" from the load train. The amount of preload will depend on the material and tensile specimen geometry, and therefore must be determined and reported for each situation. If necessary, mount the extensometer on the specimen gage section and zero the output, or, attach the lead wires of the strain gages to the signal conditioner and zero the outputs. (Note that if strain gages are used to monitor bending, the strain gages should be zeroed with the specimen attached at only one end of the fixtures, that is, hanging free. This will ensure that bending due to the grip closure is factored into the measured bending.) Ready the autograph data acquisition systems for data logging.

9.4.3 *Conducting the Test*—Initiate the data acquisition. Initiate the test mode. After specimen fracture, disable the action of the test machine and the data collection of the data acquisition system. Measure the breaking load within ±1.0 % of the load range and note for the report. Carefully remove the specimen halves from the grip interfaces. Take care not to damage the fracture surfaces by preventing them from contact with each other or other objects. Place the specimen halves along with other fragments from the gage section into a suitable, non-metallic container for later analysis.

9.4.4 Determine the relative humidity in accordance with Test Method E 337.

9.4.5 *Post-Test Dimensions*—A measure of the gage section cross-sectional dimensions in accordance with 9.1 can be made and reported to 0.02 mm if the gage section has not been overly fragmented by the fracture process. If an exact measure of the gage section cross-sectional dimensions cannot be made due to fragmentation then use the average dimensions measured in 9.1.

9.4.5.1 Measure and report the fracture location relative to the midpoint of the gage section. The convention used should be that the midpoint of the gage section is 0 mm with positive (+) measurements toward the top of the specimen as tested (and marked) and negative (−) measurements toward the bottom of the specimen as tested (and marked).

9.4.5.2 Note that results from specimens fracturing outside the uniformly stressed gage section are not recommended for use in the direct calculation of a mean tensile strength at fracture for the entire test set. Results from specimens fracturing outside the gage section are considered anomalous and can be used only as censored tests (that is, specimens in which a tensile stress at least equal to that calculated by Eq. 6 was sustained in the uniform gage section before the test was prematurely terminated by a non-gage section fracture) as discussed in Practice C 1239 for the determination of estimates of the strength distribution parameters. From a conservative standpoint, when completing a required statistical sample (for example, n = 10) for purposes of average strength, test one replacement specimen for each specimen that fractures outside the gage section.

9.5 *Fractography*—Fractographic examination of each failed specimen is highly recommended to characterize the fracture origins. The strength of an advanced ceramic is often limited by discrete fracture origins in the material. Porosity, agglomerates, inclusions, and atypical large grains are examples of fracture origins within the volume of the material. Fracture origins on the surface of the specimen may be the result of contact stresses, impact events, or adverse environment. When the means are available, use fractographic methods to locate, identify, and classify the strength-limiting fracture origin in the advanced ceramic tensile test specimen. Moreover, for the purposes of estimating strength distribution parameters as detailed in Practice C 1239, each classification of fracture origins must be identified as a surface fracture origin or a volume fracture origin. Thus, several classifications of fracture origins may exist within the volumes or surface areas of the test specimens in a statistical sample. It should be clearly noted on the test report if a fractographic analysis is not performed. Fractography can be a subjective analytical method and the guidelines established in military handbook MIL-HDBK-790 should be used to establish objectivity.

10. Calculation

10.1 *Tensile Strength*—The standard formula for the tensile strength of a uniaxially loaded rod employs the uniaxial breaking load and the cross-sectional area of the uniform gage section:

$$S_u = \frac{P_{max}}{A} \tag{6}$$

where:

S_u = the tensile strength in units of MPa,
P_{max} = the breaking load in units of
A = the cross sectional area in units of mm^2.

Note that:

$$A = wb \text{ for rectangular cross sections} \tag{7}$$

or:

$$A = \frac{\pi d^2}{4} \text{ for circular cross sections} \tag{8}$$

where:

w = the average width of the gage section in units of mm as detailed in 9.1 and 9.1.1,
b = the average thickness of the gage section in units of mm as detailed in 9.1 and 9.1.1, and

d = the average diameter of the gage section in units of mm as detailed in 9.1 and 9.1.1.

10.1.1 Note that Eq. 6 represents the stress in the uniformly-stressed gage section but does not necessarily represent the stress acting directly upon the flaw that caused fracture. (In some instances, for example, for fracture mirror or fracture toughness calculations, the fracture stress must be corrected for fractures outside the gage length).

10.2 *Modulus of Elasticity*——If strain is measured in the uniform gage section of the specimen the modulus of elasticity (that is, ratio of stress to strain below the proportional limit) can be calculated as the slope of the least squares regression fit of the linear portion of the engineering stress-engineering strain curve. Engineering stress is defined as:

$$\sigma = \frac{P}{A} \tag{9}$$

where:
σ = the engineering stress in units of MPa,
P = the applied, uniaxial tensile load in units of N, and
A = the original cross sectional area in units of mm ^{2} as defined in Eq 7 and Eq 8.

Engineering strain is defined as:

$$\epsilon = \frac{(l - l_o)}{l_o} \tag{10}$$

where:
ϵ = the engineering strain,
l = the gage length (specimen or extensometer gage length) at any time in units of mm, and
l_o = the original gage length in units of mm.

For specimens that have been strain gaged, the appropriate strain values are obtained directly without measurement of gage section elongation.

10.3 *Fracture Strain in Tension*—The standard formula for the fracture strain in tension of a uniaxially loaded rod is calculated from the elongation at the breaking load and the original length of the uniform gage section:

$$\epsilon_f = \frac{(l_f - l_o)}{l_o} \tag{11}$$

where:
ϵ_f = the engineering strain at fracture,
l_f = the final length of the specimen gage section in units of mm, and
l_o = the original gage length of the specimen in units of mm.

For specimens that have been strain gaged, the appropriate strain values are obtained directly without measurement of gage section elongation.

10.4 *Mean, Standard Deviation, and Coefficient of Variation*——For each series of tests the mean, standard deviation, and coefficient of variation for each measured value can be calculated as follows:

$$Mean = \bar{X} = \frac{\sum_{i=1}^{n} X_i}{n} \tag{12}$$

$$Standard\ deviation = s.d. = \sqrt{\frac{\sum_{i=1}^{n} (X_i - \bar{X})^2}{n - 1}} \tag{13}$$

$$Coefficient\ of\ variation = V = \frac{100\ (s.d.)}{\bar{X}} \tag{14}$$

where:
X = the measured value, and
n = the number of valid tests.

11. Report

11.1 *Test Set*—Report the following information for the test set. Note any significant deviations from the procedures and requirements of this test method in the report:

11.1.1 Tensile test specimen geometry used (include engineering drawing),

11.1.2 Type and configuration of the test machine (include drawing or sketch if necessary). If a commercial test machine was used, the manufacturer and model number are sufficient for describing the test machine,

11.1.3 Type and configuration of grip interface used (include drawing or sketch if necessary). If a commercial grip interface was used, the manufacturer and model number are sufficient for describing the grip interface,

11.1.4 Type and configuration of load train couplers (include drawing or sketch if necessary). If a commercial load train coupler was used, the manufacturer and model number are sufficient for describing the coupler,

11.1.5 Number (n) of specimens tested validly (that is, fracture in the gage section). In addition, report total of number of specimens tested (n_T) to provide an indication of the expected success rate of the particular specimen geometry and test apparatus,

11.1.6 All relevant material data including vintage data or billet identification data. (Did all specimens come from one billet or processing run?) As a minimum, the date the material was manufactured must be reported. For noncommercial materials, the major constituents and their proportions should be reported as well as the primary processing route including green state and consolidation routes,

11.1.7 Description of the method of specimen preparation including all stages of machining,

11.1.8 Heat treatments, or pre-test exposures, if any, applied either to the as-processed material or to the as-fabricated specimen,

11.1.9 Test environment including relative humidity (see Test Method E 337), ambient temperature, and atmosphere (for example, ambient air, dry nitrogen, silicone oil, etc.),

11.1.10 Test mode (load, displacement, or strain control) and test rate (load rate, displacement rate, or strain rate). Calculated stress rate should also be reported if appropriate in units of MPa/s,

11.1.11 Percent bending and corresponding average strain in the specimen recorded during the verification as measured at the beginning and end of the test series,

11.1.12 Mean tensile strength ($\dot{S}_u$) and standard deviation (s.d.) and coefficient of variation (V).

11.1.13 Estimates of strength distribution parameters (for example, Weibull modulus, $\hat{m}$, and characteristic strength, $\hat{\sigma}_\theta$)

as well as appropriate confidence bounds may be calculated and reported in accordance with Practice C 1239.

11.1.14 Mean fracture strain ($\bar{\varepsilon}_f$) and standard deviation (s.d.) and coefficient of variation (V), if calculated, and

11.1.15 Mean elastic modulus (E) and standard deviation (s.d.) and coefficient of variation (V), if calculated.

11.2 *Individual Specimens*—Report the following information for each specimen tested. Note any significant deviations from the procedures and requirements of this test method in the report:

11.2.1 Pertinent overall specimen dimensions, if measured, such as total length, length of gage section, gripped section dimensions, etc. in units of mm,

11.2.2 Average surface roughness, if measured, of gage section measured in the longitudinal direction in units of µm,

11.2.3 Average cross sectional dimensions in units of mm,

11.2.4 Pre-load and breaking loads in units of N,

11.2.5 Calculated tensile strength at fracture in units of MPa,

11.2.6 Elastic modulus (if calculated) in units of MPa,

11.2.7 Fracture strain (if calculated),

11.2.8 Percent bending and average strain at fracture (if measured),

11.2.9 Fracture location relative to the gage section midpoint in units of mm (+ is toward the top of the specimen as marked and − is toward the bottom of the specimen as marked with 0 being the gage section midpoint), and

11.2.10 Type and location of fracture origin (flaw) relative to the front of the specimen as marked.

12. Precision and Bias

12.1 The tensile strength of an advanced ceramic is not a deterministic quantity but will vary from one specimen to another as well as from one type of geometry to another depending upon gage section volume or surface area **(13, 14)**. There will be an inherent statistical scatter in the results for finite statistical sample sizes (for example, 30 specimens). Weibull statistics can model this variability as discussed in Practice C 1239. This test method is intended so that the precision is high and the bias is low compared to the inherent variability of strength of the material.

12.2 An interlaboratory comparison of tensile strength values of an advanced silicon nitride was conducted. A number of laboratories tested a number of tensile specimens of an identical button-head cylindrical geometry over the course of a several month period. Grip interfaces and non fixed load train couplers of identical design were employed in all cases at the same load rates. Average percent bending across the gage section at fracture was ~2.5 (mean fracture strain of 2323 µε). Mean strengths varied by a maximum of 3.2 % and the Weibull modulus by 43 % (average of 12.9). The mean strength variation is well within the inherent scatter predicted for statistical sample size of 15 as shown in Ref **(14)**. However, the variation of the Weibull modulus falls outside the inherent scatter predicted for statistical sample size of 15 as shown in Ref **(13)**. This variation may have been due to the stress rate of the tests (11 MPa/s) being less than the minimum recommended in this test method.

12.3 For a material with a Weibull modulus of ten, estimates of the mean (or characteristic strength) for statistical sample size of 15 specimens will have a coefficient of variance of 4.8 %. The coefficient of variance for estimates of Weibull modulus is 26 %. For the same material with a Weibull modulus of ten, but with a statistical sample size of 30 specimens, estimates of the mean (or characteristic strength) have a coefficient of variance of 2.2 %. The coefficient of variance for estimates of Weibull modulus is 18 %.

13. Keywords

13.1 advanced ceramic; percent bending; tensile strength; tensile testing

APPENDIX

(Nonmandatory Information)

X1. VERIFICATION OF LOAD TRAIN ALIGNMENT

X1.1 *Purpose of Verification*—The purpose of this verification procedure is to demonstrate that the grip interface and load train couplers can be used by the test operator in such a way as to consistently meet the limit on percent bending as specified in Section 6. Thus, this verification procedure should involve no more care in setup than will be used in the routine testing of the actual tensile specimen. The bending under tensile load should be measured using verification (or actual) specimens of exactly the same design as that to be used for the tensile tests. For the verification purposes, strain gages should be applied as shown in Fig. X1.1. Verification measurements should be conducted at the beginning and end of a series of tests with a measurement at the midpoint of the series recommended, whenever the grip interfaces and load train couplers are installed on a different test machine, whenever a different operator is conducting a series of tests, or whenever damage or misalignment is suspected.

X1.2 *Verification Specimen*—The specimen used for verification must be machined very carefully with attention to all tolerances and concentricity requirements. Ideally the verification specimen should be of identical material to that being tested. However, if this is not possible or desired, an alternate material should be used with elastic modulus, elastic strain capability, and hardness similar to the test material. The specimen should be carefully inspected with an optical comparator before strain gages are attached to ensure that these requirements are met. After the strain gages are applied it will no longer be possible to meaningfully inspect the specimen, so

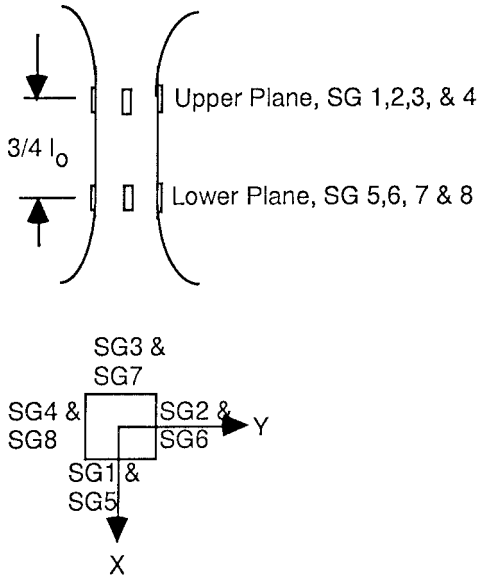


FIG. X1.1 Illustration of Strain Gage Placement on Gage Section Planes and Strain Gage Numbering

care should be exercised in handling and using it.

X1.2.1 For simplicity in applying this test method to test specimens with both circular and rectangular cross section gage sections, a minimum of eight foil resistance strain gages should be mounted on the verification specimen as shown in Fig. X1.1. Note that the strain gage planes should be separated by at least ¾ l_o where l_o is the length of the reduced or designated gage section. In addition, care must be taken to select the strain gage planes to be symmetrical about the longitudinal midpoint of the gage section. Avoid placing the strain gages closer than one strain gage length from geometrical features such as the transition radius from the gage section. These strain gages should be as narrow as possible to minimize strain averaging. Strain gages having active widths of 0.25 to 0.5 mm and active lengths of 1.0 to 2.5 mm are commercially available and are suitable for this purpose **(3)**. Four strain gages, equally spaced (90° apart) around the circumference of the gage section, should be mounted at each of two planes at either end of the gage section. These planes should be symmetrically located about the longitudinal midpoint of the gage section. Note that care should be taken to avoid placing the strain gages too near geometric transitions in the gage section which can cause strain concentrations and inaccurate measurements of the strain in the uniform gage section.

X1.3 *Verification Procedure*—Procedures for verifying alignment are described in detail in Practice E 1012. However, salient points for square and circular cross-sections are described here for emphasis. For rectangular cross-sections, especially when the thickness is too thin to strain gage all four sides, Practice E 1012 should be consulted for specific details.

X1.3.1 Connect the strain gages to the conditioning equipment and allow the strain gages to equilibrate under power for at least 30 min prior to conducting the verification tests. This will minimize drift during actual conduct of the verifications.

X1.3.2 Mount the top of the specimen in the grip interface.

X1.3.3 Zero the strain gages before mounting the bottom of the specimen in the grip interface. This will allow any bending due to the grips to be recorded.

X1.3.4 Mount the bottom of the specimen in the grip interface.

X1.3.5 Apply a sufficient load to the specimen to achieve an average strain of one half the anticipated fracture strain of the test material. Note that it is desirable to record the strain (and hence percent bending) as functions of the applied load to monitor any self alignment of the load train.

X1.3.6 Calculate percent bending as follows referring to Fig. X1.1 for the strain gage numbers. Percent bending at the upper plane of the gage section is calculated as follows.

$$PB_{upper} = \frac{\epsilon_b}{\epsilon_o} 100 \tag{X1.1}$$

$$\epsilon_b = \left[\left(\frac{\epsilon_1 - \epsilon_3}{2} \right)^2 + \left(\frac{\epsilon_2 - \epsilon_4}{2} \right)^2 \right]^{1/2} \tag{X1.2}$$

$$\epsilon_o \frac{\epsilon_1 + \epsilon_2 + \epsilon_3 + \epsilon_4}{4} \tag{X1.3}$$

where ϵ_1, ϵ_2, ϵ_3 and ϵ_4 are strain readings for strain gages located at the upper plane of the gage section. Note that strain gage readings are in units of strain and compressive strains are negative.

X1.3.7 The direction of the maximum bending strain on the upper plane is determined as follows:

$$\theta_{upper} = \arctan \left[\frac{\epsilon_{(next\ greatest\ of\ 1,\ 2,\ 3,\ 4)} - \epsilon_0}{\epsilon_{(greatest\ of\ 1,\ 2,\ 3,\ 4)} - \epsilon_0} \right] \tag{X1.4}$$

where θ_{upper} is measured from the strain gage with the greatest reading in the direction of the strain gage with the second greatest reading where counter clockwise is positive.

X1.3.8 Percent bending at the lower plane of the gage section is calculated as follows.

$$PB_{lower} = \frac{\epsilon_b}{\epsilon_o} 100 \tag{X1.5}$$

$$\epsilon_b = \left[\left(\frac{\epsilon_5 - \epsilon_6}{2} \right)^2 + \left(\frac{\epsilon_7 - \epsilon_8}{2} \right)^2 \right]^{1/2} \tag{X1.6}$$

$$\epsilon_o = \frac{\epsilon_5 + \epsilon_6 + \epsilon_7 + \epsilon_8}{4} \tag{X1.7}$$

where ϵ_5, ϵ_6, ϵ_7 and ϵ_8 are strain readings for strain gages located at the lower plane of the gage section. Note that strain gage readings are in units of strain and compressive strains are negative.

X1.3.9 The direction of the maximum bending strain on the lower plane is determined as follows:

$$\theta_{lower} = \arctan \left[\frac{\epsilon_{(next\ greatest\ of\ 5,\ 6,\ 7,\ 8)} - \epsilon_0}{\epsilon_{(greatest\ of\ 5,\ 6,\ 7,\ 8)} - \epsilon_0} \right] \tag{X1.8}$$

where θ_{lower} is measured from the strain gage with the greatest reading in the direction of the strain gage with the second greatest reading where counter clockwise is positive.

X1.3.10 Note that for the following comparisons, θ_{upper} and θ_{lower} may be adjusted to reference the same point on the circumference. Since strain gages 1 and 5 fall on the same longitudinal line around the circumference, for consistency these can be used as reference points for θ_{upper} and θ_{lower}, respectively. For example, on the upper plane, if strain gage 2 is the greatest measured strain with strain gage 3 being the next

greatest measured strain then the direction of the maximum bending strain with reference to strain gage 1 is $\theta_{upper} + 90°$ in the counterclockwise direction (that is, from strain gage 1 to 2). For uniform bending across the gage section with the specimen assuming a C-shape, $PB_{upper} \approx PB_{lower}$ and $|\theta_{upper} - \theta_{lower}| \approx 0°$. C-shape bending reflects angular misalignment of the grips. For non uniform bending across the gage section with the specimen assuming an S-shape, PB_{upper} may or not be equal to PB_{lower} and $|\theta_{upper} - \theta_{lower}| \approx 180°$. S-shape bending reflects eccentric misalignment of the grip centerlines. These general tendencies are shown in Fig. X1.2. Combinations of C and S shapes may exist where $|\theta_{upper} - \theta_{lower}|$ is some angle between 0 and 180°. In these cases the S-shape should first be eliminated by adjusting the concentricity of the grips such that the longitudinally aligned strain gages indicate approximately the same values (for example, $\epsilon_1 \approx \epsilon_5$, $\epsilon_2 \approx \epsilon_6$, etc.). More detailed discussions regarding bending and alignment are contained in Ref. **(15)**.

X1.3.11 The effect of the specimen warpage can be checked by rotating the specimen 90° about its longitudinal axis and performing the bending checks again. These checks can be repeated for subsequent 90° rotations until a 360° rotation of the specimen has been achieved. If similar results are obtained at each rotation then the degree of alignment can be considered representative of the load train and not indicative of the specimen. If load train alignment is within the specifications of 6.4, the maximum percent bending should be recorded and the tensile tests may be conducted. If the load train alignment is outside the specifications of 6.4 then the load train must be aligned or adjusted according to the specific procedures unique to the individual testing setup. This verification procedure shall then be repeated to confirm the achieved alignment.

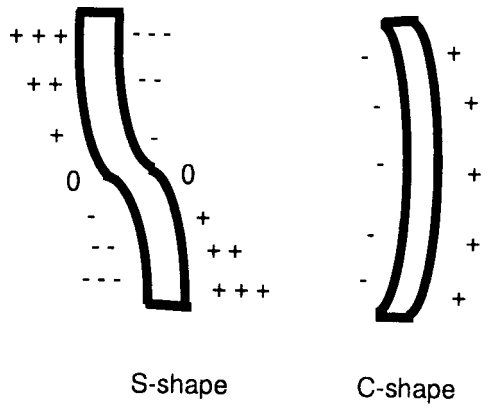


FIG. X1.2 S-Shape and C-Shape Bending of Tensile Specimen

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