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Standard Test Method for Hoop Tensile Strength of Continuous Fiber-Reinforced Advanced Ceramic Composite Tubular Test Specimens at Ambient Temperature Using Elastomeric Inserts[1]

This standard is issued under the fixed designation C1819; 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 the hoop tensile strength including stress-strain response of continuous fiber-reinforced advanced ceramic tubes subjected to an internal pressure produced by the expansion of an elastomeric insert undergoing monotonic uniaxial loading at ambient temperature. This type of test configuration is sometimes referred to as an overhung tube. This test method is specific to tube geometries, because flaw populations, fiber architecture and specimen geometry factors are often distinctly different in composite tubes, as compared to flat plates.

1.2 In the test method a composite tube/cylinder with a defined gage section and a known wall thickness is loaded via internal pressurization from the radial expansion of an elastomeric insert (located midway inside the tube) that is longitudinally compressed from either end by pushrods. The elastomeric insert expands under the uniaxial compressive loading of the pushrods and exerts a uniform radial pressure on the inside of the tube. The resulting hoop stress-strain response of the composite tube is recorded until failure of the tube. The hoop tensile strength and the hoop fracture strength are determined from the resulting maximum pressure and the pressure at fracture, respectively. The hoop tensile strains, the hoop proportional limit stress, and the modulus of elasticity in the hoop direction are determined from the stress-strain data. Note that hoop tensile strength as used in this test method refers to the tensile strength in the hoop direction from the induced pressure of a monotonic, uniaxially-loaded elastomeric insert where monotonic refers to a continuous nonstop test rate without reversals from test initiation to final fracture.

1.3 This test method applies primarily to advanced ceramic matrix composite tubes with continuous fiber reinforcement: uni-directional (1-D, filament wound and tape lay-up), bidirectional (2-D, fabric/tape lay-up and weave), and tridirectional (3-D, braid and weave). These types of ceramic matrix composites can be composed of a wide range of ceramic fibers (oxide, graphite, carbide, nitride, and other compositions) in a wide range of crystalline and amorphous ceramic matrix compositions (oxide, carbide, nitride, carbon, graphite, and other compositions).

1.4 This test method does not directly address discontinuous fiber-reinforced, whisker-reinforced or particulate-reinforced ceramics, although the test methods detailed here may be equally applicable to these composites.

1.5 The test method is applicable to a range of test specimen tube geometries based on a non dimensional parameter that includes composite material property and tube radius. Lengths of the composite tube, push rods and elastomeric insert are determined from this non dimensional parameter so as to provide a gage length with uniform, internal, radial pressure. A wide range of combinations of material properties, tube radii, wall thicknesses, tube lengths and insert lengths are possible.

1.5.1 This test method is specific to ambient temperature testing. Elevated temperature testing requires high temperature furnaces and heating devices with temperature control and measurement systems and temperature-capable grips and loading fixtures, which are not addressed in this test standard.

1.6 This test method addresses tubular test specimen geometries, test specimen methods, testing rates (force rate, induced pressure rate, displacement rate, or strain rate), and data collection and reporting procedures in the following sections.

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

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1.7 Values expressed in this test method are in accordance with the International System of Units (SI).

1.8 *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 hazard statements are given in Section 8 and Note 1.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

C1145 Terminology of Advanced Ceramics
C1239 Practice for Reporting Uniaxial Strength Data and Estimating Weibull Distribution Parameters for Advanced Ceramics
D3878 Terminology for Composite 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
E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods
E337 Test Method for Measuring Humidity with a Psychrometer (the Measurement of Wet- and Dry-Bulb Temperatures)
E380 Practice for Use of the International System of Units (SI) (the Modernized Metric System) (Withdrawn 1997)[3]
E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method
E1012 Practice for Verification of Testing Frame and Specimen Alignment Under Tensile and Compressive Axial Force Application
SI10-02 IEEE/ASTM SI 10 American National Standard for Use of the International System of Units (SI): The Modern Metric System

3. Terminology

3.1 *Definitions:*

3.1.1 The definitions of terms relating to hoop tensile strength testing appearing in Terminology E6 apply to the terms used in this test method. The definitions of terms relating to advanced ceramics appearing in Terminology C1145 apply to the terms used in this test method. The definitions of terms relating to fiber reinforced composites appearing in Terminology D3878 apply to the terms used in this test method. Pertinent definitions as listed in Practice E1012, Terminology C1145, Terminology D3878, 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, n*—a highly engineered, high performance predominantly nonmetallic, inorganic, ceramic material having specific functional attributes. (See Terminology C1145.)

3.1.3 *breaking force, n*—the force at which fracture occurs. (See Terminology E6.)

3.1.4 *ceramic matrix composite (CMC), n*—a material consisting of two or more materials (insoluble in one another), in which the major, continuous component (matrix component) is a ceramic, while the secondary component/s (reinforcing component) may be ceramic, glass-ceramic, glass, metal or organic in nature. These components are combined on a macroscale to form a useful engineering material possessing certain properties or behavior not possessed by the individual constituents.

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

3.1.6 *gage length, n*—the original length of that portion of the specimen over which strain or change of length is determined. (See Terminology E6.)

3.1.7 *hoop tensile strength, n*—the maximum tensile component of hoop stress which a material is capable of sustaining. Hoop tensile strength is calculated from the maximum internal pressure induced in a tubular test specimen.

3.1.8 *matrix-cracking stress, n*—the applied tensile stress at which the matrix cracks into a series of roughly parallel blocks normal to the tensile stress.

3.1.8.1 *Discussion*—In some cases, the matrix cracking stress may be indicated on the stress-strain curve by deviation from linearity (proportional limit) or incremental drops in the stress with increasing strain. In other cases, especially with materials which do not possess a linear region of the stress-strain curve, the matrix cracking stress may be indicated as the first stress at which a permanent offset strain is detected in the during unloading (elastic limit).

3.1.9 *modulus of elasticity, n*—the ratio of stress to corresponding strain below the proportional limit. (See Terminology E6.)

3.1.10 *modulus of resilience, n*—strain energy per unit volume required to elastically stress the material from zero to the proportional limit indicating the ability of the material to absorb energy when deformed elastically and return it when unloaded.

3.1.11 *modulus of toughness, n*—strain energy per unit volume required to stress the material from zero to final fracture indicating the ability of the material to absorb energy beyond the elastic range (that is, damage tolerance of the material).

3.1.11.1 *Discussion*—The modulus of toughness can also be referred to as the cumulative damage energy and as such is regarded as an indication of the ability of the material to sustain damage rather than as a material property. Fracture mechanics

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

[3] The last approved version of this historical standard is referenced on www.astm.org.

methods for the characterization of CMCs have not been developed. The determination of the modulus of toughness as provided in this test method for the characterization of the cumulative damage process in CMCs may become obsolete when fracture mechanics methods for CMCs become available.

3.1.12 *proportional limit stress, n*—the greatest stress that a material is capable of sustaining without any deviation from proportionality of stress to strain (Hooke's law).

3.1.12.1 *Discussion*—Many experiments have shown that values observed for the proportional limit vary greatly with the sensitivity and accuracy of the testing equipment, eccentricity of loading, the scale to which the stress-strain diagram is plotted, and other factors. When determination of proportional limit is required, the procedure and sensitivity of the test equipment should be specified. (See Terminology E6.)

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

4. Summary of Test Method

4.1 In the test method a composite tube/cylinder with a defined gage section and a known wall thickness is loaded by the radial expansion an elastomeric insert (located midway inside the tube) that is compressed longitudinally between pushrods. The elastomericinsert expands under the uniaxial compressive loading of the pushrods and exerts a uniform radial pressure on the inside of the tube. The resulting hoop stress-strain response of the composite tube is recorded until failure of the tube. The hoop tensile strength and the hoop fracture strength are determined from the resulting maximum pressure and the pressure at fracture. The hoop tensile strains, the hoop proportional limit stress, and the modulus of elasticity in the hoop direction are determined from the stress-strain data.

4.2 Hoop tensile strength as used in this test method refers to the tensile strength in the hoop direction from the induced pressure of a monotonic, uniaxially-loaded elastomeric insert where monotonic refers to a continuous test rate with no reversals.

4.3 The test method is applicable to a range of test specimen tube geometries based on a non dimensional parameter that includes composite material property and tube radius. Lengths of the composite tube, push rods and elastomericinsert are determined from this non dimensional parameter so as to provide a gage length with uniform, internal, radial pressure. A wide range of combinations of material properties, tube radii, wall thicknesses, tube lengths and insert lengths are possible.

5. Significance and Use

5.1 This test method (a.k.a., overhung tube method) may be used for material development, material comparison, material screening, material down selection and quality assurance. This test method is not recommended for material characterization, design data generation and/or material model verification/validation.

5.2 Continuous fiber-reinforced ceramic composites (CFCC) are composed of continuous ceramic-fiber directional (1-D, 2-D, and 3-D) reinforcements in a fine grain-sized (<50 μm) ceramic matrix with controlled porosity. Often these composites have an engineered thin (0.1 to 10 μm) interface coating on the fibers to produce crack deflection and fiber pull-out.

5.3 CFCC components have a distinctive and synergistic combination of material properties, interface coatings, porosity control, composite architecture (1-D, 2-D, and 3-D), and geometric shape that are generally inseparable. Prediction of the mechanical performance of CFCC tubes (particularly with braid and 3-D weave architectures) cannot be made by applying measured properties from flat CFCC plates to the design of tubes. In particular tubular components comprised of CMCs material form a unique synergistic combination of material and geometric shape that are generally inseparable. In other words, prediction of mechanical performance of CMC tubes generally cannot be made by using properties measured from flat plates. Strength tests of internally-pressurized, CMC tubes provide information on mechanical behavior and strength for a multiaxially-stressed material.

5.4 Unlike monolithic advanced ceramics which fracture catastrophically from a single dominant flaw, CMCs generally experience "graceful" fracture from a cumulative damage process. Therefore, while the volume of material subjected to a uniform hoop tensile stress for a single uniformly pressurized tube test may be a significant factor for determining matrix cracking stress, this same volume may not be as significant a factor in determining the ultimate strength of a CMC. However, the probabilistic nature of the strength distributions of the brittle matrices of CMCs requires a statistically significant number of test specimens for statistical analysis and design. Studies to determine the exact influence of test specimen volume on strength distributions for CMCs have not been completed. It should be noted that hoop tensile strengths obtained using different recommended test specimens with different volumes of material in the gage sections may be different due to these volume effects.

5.5 Hoop tensile strength tests provide information on the strength and deformation of materials under biaxial stresses induced from internal pressurization of tubes. Non-uniform stress states are inherent in these types of tests and subsequent evaluation of any non-linear stress-strain behavior must take into account the unsymmetric behavior of the CMC under biaxial stressing. This non-linear behavior which may develop as the result of cumulative damage processes (for example, matrix cracking, matrix/fiber debonding, fiber fracture, delamination, etc.) which may be influenced by testing mode, testing rate, processing or alloying effects, or environmental influences. Some of these effects may be consequences of stress corrosion or subcritical (slow) crack growth that can be minimized by testing at sufficiently rapid rates as outlined in this test method.

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

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

5.8 The hoop tensile stress behavior and strength of a CMC are dependent on its inherent resistance to fracture, the presence of flaws, or damage accumulation processes, or both. Analysis of fracture surfaces and fractography, though beyond the scope of this test method, is highly recommended.

6. Interferences

6.1 Test environment (vacuum, inert gas, ambient air, etc.) including moisture content (for example, relative humidity) may have an influence on the measured hoop 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.

6.2 Surface preparation of test specimens, although normally not considered a major concern in CMCs, can introduce fabrication flaws that may have pronounced effects on hoop tensile stress mechanical properties and behavior (for example, shape and level of the resulting stress-strain curve, hoop tensile strength and strain, proportional limit stress and strain, etc.). Machining damage introduced during test specimen preparation can be either a random interfering factor in the determination of ultimate strength of pristine material (i.e., 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 initial machining. Thus, test specimen fabrication history may play an important role in the measured strength distributions and should be reported. In addition, the nature of fabrication used for certain composites (for example, chemical vapor infiltration or hot pressing) may require the testing of test specimens in the as-processed condition (that is, it may not be possible to machine the test specimen faces).

6.3 Internally-pressurized tests of CMC tubes can produce biaxial and triaxial stress distributions with maximum and minimum stresses occurring at the test specimen surface leading to fractures originating at surfaces or near geometrical transitions. In addition, if deformations or strains are measured at surfaces where maximum or minimum stresses occur, bending may introduce over or under measurement of strains depending on the location of the strain-measuring device on the specimen. Similarly, fracture from surface flaws may be accentuated or suppressed by the presence of the non-uniform stresses caused by bending.

6.4 Friction between the insert and the rough and/or unlubricated inner surface of tubular test specimen can produce compressive stresses on the inner bore of the tube that will reduce that hoop stress in the tube. In addition, this friction will accentuate axial bending stress.

6.5 Fractures that initiate outside the gage section of a test specimen may be due to factors such as stress concentrations or geometrical transitions, extraneous stresses introduced by fixtures/load apparatuses or strength-limiting features in the microstructure of the specimen. Such non-gage section fractures will usually constitute invalid tests.

7. Apparatus

7.1 *Testing Machines*—Machines used for applying uniaxial forces to elastomeric inserts for hoop tensile strength testing shall conform to the requirements of Practice E4. The axial force used in inducing the internal pressure shall be accurate within ±1 % at any force within the selected force range of the testing machine as defined in Practice E4. A schematic showing pertinent features of the hoop tensile strength testing apparatus is shown in Fig. 1.

7.2 *Fixtures:*

7.2.1 *General*—Compression loading fixtures are generally composed of two parts: *(1)* basic steel test machine grips (for example, hydraulically-loaded v-grips) attached to the test machine and *(2)* push rods that are held rigidly in the test machine grips and act as the interface between the grips and elastomeric insert. A schematic drawing of such a fixture and a test specimen is shown in Fig. 2. A figure showing an actual test setup is shown in Fig. 3. Another variation of the compression loading fixture can use *(1)* compression platens attached to the test machine and *(2)* push rods that are held against the platens in the test machine and act as the interface between the platens and elastomeric insert.

7.2.2 With insert testing, the only 'connection' between the pressurizing 'machinery' and the tube under test is a trapped film of high pressure lubricant (Fig. 2). Tests have shown that this lubricant film retains a constant thickness during testing to the maximum pressure (**1**). The objective is to transmit the applied force from the push rod through the lubricant film to the inner wall of the tube under test. However, evidence indicates that the insert behaves as a hydraulic fluid also up to longitudinal compressions of at least 5 % strain.

7.2.3 *Inserts*—Typically, commercial insert material are used because of the wide range of hardnesses available. The "correct" hardness is chosen by determining the insert force and related pressure at failure of the CMC tubular test specimen.

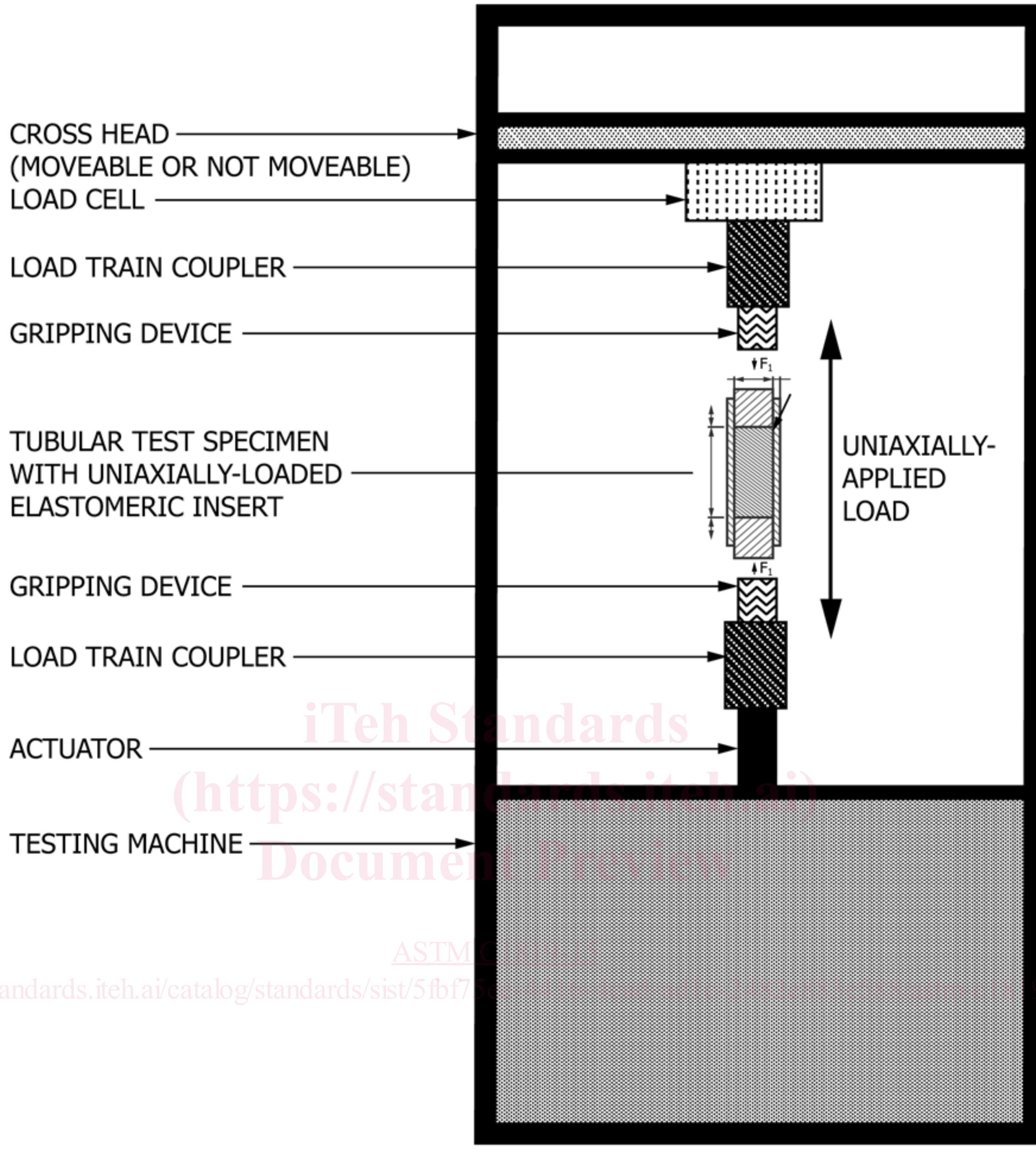

FIG. 1 Schematic Diagram of One Possible Apparatus for Applying a Uniaxial Force to an Elastomeric Insert for Conducting a Internally Pressurized Hoop Strength Test of a CMC Tube

NOTE 1—Common insert materials include urethane (such as Du Pont Adiprene™) or neoprene (**1**) mainly because of the wide range of hardnesses commercially available. Other inert materials successfully employed included silicon rubber such as Dow Corning Silastic™.

7.2.3.1 Inserts can be machined from a pre-cast block or cast "in place" (i.e., inside the tubular test specimen). However, a final grinding to finished size on diameter and length is essential so that end surfaces are perpendicular to diameter.

7.2.3.2 Insert length is chosen based on tubular test specimen dimensions and test material properties. The insert takes up only the central portion of the tube for two reasons: *(1)* tube ends act a guide for the push rods and *(2)* when correctly dimensioned per the requirement of this test method, the unpressurized tube ends can be made such that the stresses in the end surfaces during testing are negligible.

7.2.3.3 Previous studies (**1**)[4] have shown that pressurized length of the tube, L, and hence initial length of the insert should be:

$$L \geq 9/\beta$$
and
$$\beta = \sqrt[4]{\frac{3(1 - \nu^2)}{(r_i^{tube})^2 t^2}} \quad (1)$$

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

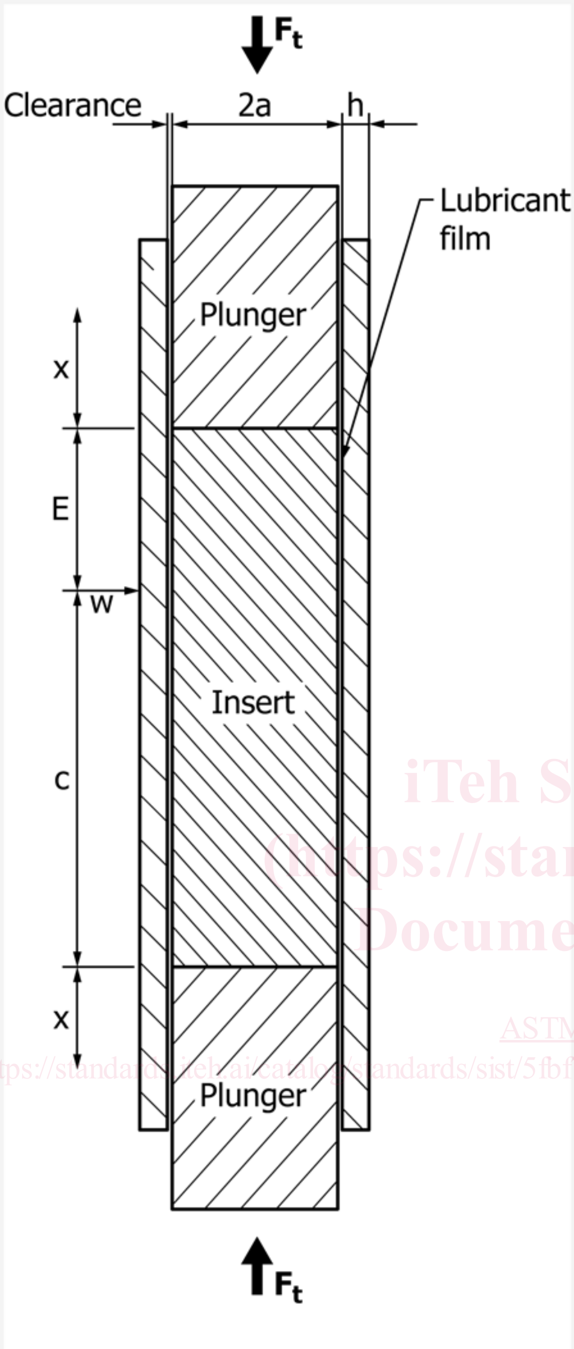

FIG. 2 Schematic of Uniaxially Loaded Insert [Ref 1]

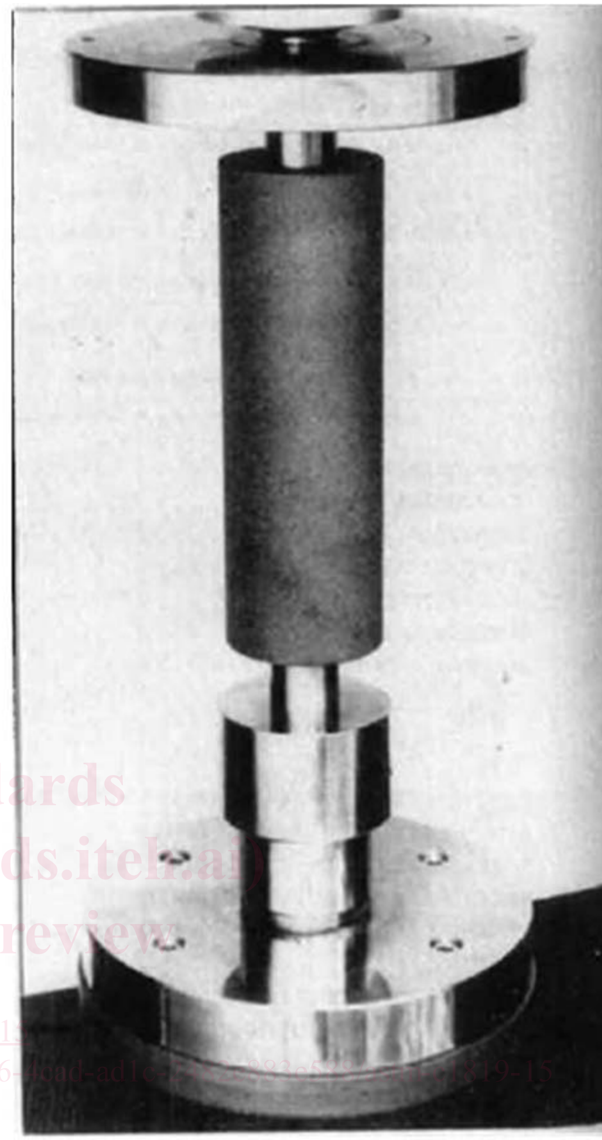

FIG. 3 Example of Test Setup for Uniaxially Loaded Tube [Ref 1]

TABLE 1 Maximum Recommended Insert Pressure

Shore Hardness (A)	Maximum recommended pressure (MPa=N/mm^2)
70	12
90	50
95	~130

where:

ν = Poisson's ratio of test material,
r_i^{tube} = inner radius of tubular test specimen in units of mm, and
t = wall thickness of tubular test specimen in units of mm.

NOTE 2—Example of a commercial CMC (ν = 0.15) tube with outer diameter of 100 mm and wall and tube wall thickness of 2 mm. In this case $\beta = \sqrt[4]{\frac{3(1-\nu^2)}{(r_i^{tube})^2 t^2}} = \sqrt[4]{\frac{3(1-0.15^2)}{([100-2(2)]/2)^2 2^2}} = 0.133$ 1/mm such that L = 9/β = 9/0.133 = 67.38 mm.

7.2.4 *Pushrods*—Pushrods are made from any material with sufficient compressive strength to prevent yielding of the pushrod and sufficient stiffness to prevent buckling. Final grinding of the pushrod diameters and pushrod ends is required to meet the requirements for wall clearance, face flatness, and perpendicularity/straightness as shown in Fig. 4.

7.2.4.1 Clearance between the pushrod and tube wall of the test specimen shall fall within the following limits:

$$0.04 \text{ mm} \leq c = (r_i^{tube} - r_o^{pushrod}) \leq \max\begin{cases} 0.04 \text{ mm} \\ 0.05*(2r_0^{pushrod}) \end{cases} \quad (2)$$