Ceramics and Composites for Sustainable Nuclear and Fusion Energy

HOOP TENSILE STRENGTH OF CMC TUBES FOR LWRS APPLCATIONS USING INTERNAL PRESSURIZATION VIA ELASTOMERIC INSERT: NEW ASTM TEST METHOD

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ABSTRACT

The US DOE plans to replace conventional zirconium-alloy fuel rod tubes in light water reactors (LWR) with those consisting of SiC/SiC CMCs to enhance fuel performance and accident tolerance. SiC/SiC CMCs show tolerance to the irradiation and chemical environments of LWRs. Failure modes in LWR fuel cladding include loss of gas tightness and mechanical integrity due to the build-up of internal gas pressure and the swelling of fuel pellets. Therefore, determination of the hoop tensile strength is critically important for evaluation of SiC/SiC CMC fuel claddings. A new ASTM standard test method (C1819) has been developed and is in the final publication stages. The standard uses internal pressurization developed by longitudinal compression of an elastomeric insert to produce radial pressure that results in tensile hoop stresses in CMC tubular test specimens. This test method is based on sound, theoretical analysis of the stresses developed in tubes subjected to internal pressure over a finite length inside a semi-infinitely long tube. The new ASTM test method contains information on test specimen dimensions, testing geometries, test conditions and results interpretation based on this theory and subsequent empirical tests applied to various materials and geometries. This test method is intended for for material development, material characterization, material screening, and quality assurance.

INTRODUCTION

US Department of Energy (US DOE) has proposed replacing conventional zirconium-alloy fuel rod tubes in light water reactors (LWRs) with fuel rods fabricated in whole or in part from ceramic matrix composite (CMC) materials in order to enhance fuel performance and accident tolerance.[1,2,3,4] Because of their demonstrated tolerance to the irradiation and chemical environments of LWRs, silicon carbide continuous fiber-reinforced silicon carbide-matrix (SiC/SiC) CMCs have been targeted for this application. It is noteworthy that SiC/SiC materials exhibit high strength at elevated temperatures and low chemical activity (e.g., no exothermic reaction with water that produces hydrogen gas as zirconium demonstrates at elevated temperatures). In addition, the high-temperature properties of SiC/SiC CMCs indicate that the fuel system using this CMC can retain its geometry and fuel protective functionality even during an accident. Elimination of the exothermic zirconium and water reaction (and the attendant generation of free hydrogen) also increases the temperature at which the fuel can operate, thereby lowering the type of risks created during an accident scenario [1,2].

Anticipated failure modes for the LWR fuel cladding include loss of gas tightness and mechanical integrity due to the build-up of internal gas pressure and the swelling of fuel pellets. Thus, it is critically important to rigorously determine the hoop tensile or equivalent strength properties when evaluating SiC/SiC CMC fuel claddings.

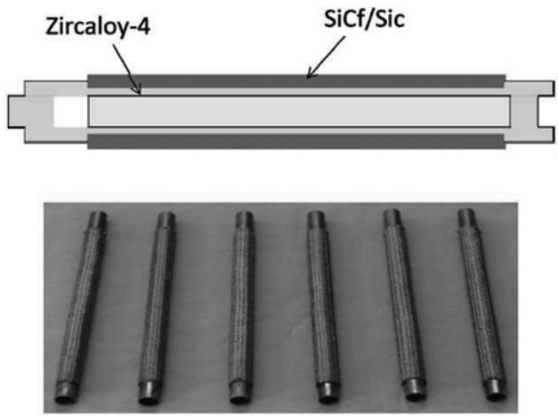

Figure 1 SiC/SiC CMC cladding for LWR fuel rods (from Ref 1)

SiC/SiC CMCs consist of high-strength silicon carbide fiber secondary (or reinforcement) phase in a high-temperature silicon carbide primary (or matrix) phase. In addition to high strength and high fracture resistance at elevated temperatures, this type of composite structure combined with the silicon carbide material results in potentially greater resistance to neutron radiation[5] compared to conventional materials. The ceramic reinforcement in the form of fibre tows have high filament counts (500-2000) and are woven with large units cells, several millimeters in size. In tubular configurations the composites may be constructed as a 1-D filament wound, 2-D laminate, or 3-D (weave or braid) configuration depending on what tensile, shear, and hoop stresses are considered. The fiber architecture in the tubes can be geometrically tailored for highly anisotropic or uniform isotropic mechanical and thermal properties.[2, 3]

Tubular geometries for nuclear applications present challenges for both the material fabricators and the material evaluators of SiC/SiC CMCs. For fabricators, challenges include the following: how to make seamless tubes with multiple direction architectures?; how to ensure integrity in the radial direction?; and how to create uniform wall thickness and uniform/nonporous matrices? For evaluators, challenges include: how to build on decades of experience with consensus standards and data bases for "flat" material forms?; how to interpret information from tests of test specimen in component form?; and how to adapt expertise at room temperature in ambient environments to conditions at high temperature in specific extreme-use environments?

It is important to note that until recently, there were no commonly-accepted design methodologies for tubular components comprised of advanced composite, and in particular, there few mechanical test standards for any of these properties of tubular geometry ceramic composite components. Fortunately, in 2013, a new standard[6] for axial tensile strength of CMC tubes approved and published by ASTM as C1773 "Standard Test Method for Monotonic Tensile Behavior of Continuous Fiber-Reinforced Advanced Ceramic Tubular Test Specimens at Ambient Temperature"[6] after several years of development.

It in important to note that use of CMCs in LWR applications requires mechanical test standards to support not only material development and property databases, but also design codes and component specification documents, as well as Nuclear Regulatory Commission (NRC) regulations on nuclear design approval, certification, and licensing.[3, 4, 5] In particular, mechanical test standards for nuclear-grade CMCs are necessary to provide accurate, reliable, and statistically-significant data as determined from technically-rigorous, well-defined test methods, detailed test specimen preparation, comprehensive reporting requirements, and commonly-accepted terminology. Development and design of LWR components composed of CMCs could be hampered and delayed if appropriate standards of mechanical test methods are not available in a timely manner.

It is noteworthy that the timing of nuclear applications of SiC/SiC CMCs in LWR components is such that they can advance an existing mature specialized technology of CMCs. In particular, the large strides in development of SiC/SiC CMC materials and structure technology were made possible by funding from the aerospace and defense industries/agencies. Additionally, current evaluation and application of SiC/SiC CMCs in fusion reactors (first wall) and tristructural-isotropic (TRISO) fuel forms provide established properties under extended neutron irradiation and at high temperatures as well as very hot steam environment. Expanding, statistically-significant data bases for SiC/SiC CMCs now exist because of the evolution of consensus test methods and design codes. Finally, maturation of volume-scale manufacturing capability for all types of CMCs including SiC/SiC CMCs adds to the availability and understanding of these materials.

Professional organizations such as American Society of Mechanical Engineers (ASME) and ASTM International are leading the way in developing the codes, specifications, and test standards for CMCs in nuclear applications. ASTM International Committee C28 on Advanced Ceramics has a particular focus on mechanical test standards for CMCs.[7, 8] Specifically, ASTM Subcommittee C28.07 on Ceramic Composites has published fourteen standards for CMCs (e.g., tensile, flexure, shear, compression, creep, fatigue, etc.) [7, 8]

Mechanical testing of composite tube geometries is distinctly different from testing flat plates because of the differences in fiber architecture (weaves, braids, filament wound), stress conditions (hoop, torsion, and flexure stresses), gripping, bending stresses, gage section definition, and scaling issues.[5] Because there are no commonly-accepted design methodologies for advanced composite tubular components, there are almost no mechanical test standards for any properties of tubular ceramic composite components.

Therefore, in this paper, some aspects are presented for a new ASTM standard test method for hoop tensile strength of CMC tubes that has been approved in 2015 via consensus balloting (C1819)[11]. This new standard uses axial compression of elastomeric inserts to produce radial internal pressure and resulting hoop stresses in composite tubular test specimens. This new standard is based on sound, theoretical analysis of the stresses developed in tubes subjected to internal pressure over a finite length inside a semi-infinitely long tube [9, 10] The new standard uses theory as well as subsequent empirical tests applied to various materials and geometries. This test method (a.k.a., overhung tube method) is for material development, material comparison, material screening, material down selecting and quality assurance.

ASTM STANDARD TEST METHOD

A working group within ASTM Subcommittee C28.07 on CMC tube testing developed the new standard[11]: C1819 "Standard Test Method for Hoop Tensile Strength of Continuous Fiber-Reinforced Advanced Ceramic Composite Tubular Test Specimens at Ambient Temperature Using Elastomeric Inserts" over a two year period with final approval by balloting received in 2015. This new standard is discussed in the following sections. The working group is also preparing a second draft, "Standard Test Method for Hoop Tensile Behavior of Continuous Fiber-Reinforced Advanced Ceramic Composite Tubular Test Specimens at Ambient Temperature Using Internal Pressurization" that will be the subject of a future publication.

- Material Variability, including Anisotropy, Porosity, and Surface Condition
- Test Specimen Size, Fiber Architecture, and Gage Section Geometry Effects
- Out-Of-Gage Failures and Extraneous Stresses
- Slow Crack Growth, Strain Rate Effects, and Test Environment
- Accurate Strain/Elongation Measurement

Figure 2 Range of “interferences” in test CMC materials

SCOPE AND APPLICATION

This new standard 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.

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.

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).

EXPERIMENTAL FACTORS

CMCs generally exhibit “graceful” failure from a cumulative damage process, unlike monolithic advanced ceramics that fracture catastrophically from a single dominant flaw. The testing of CMC (both flats and tubes) has a range of different material and experimental factors that interact and must be controlled and managed (See Fig. 2). These factors must be managed and understood to produce consistent, representative failures in the gage section of test specimens. Tubular test specimens with cylindrical geometries provide particular challenges in the areas of gage section geometry, loading failures, extraneous “parasitic” stresses (including biaxial and triaxial stresses), and out-of-gage failures.

TEST SPECIMEN GEOMETRIES

Test Specimen Size -- CMC tubes are fabricated in a wide range of geometries and sizes, across a spectrum of fiber-matrix-architecture combinations. It is not practical to define a single test specimen geometry that is universally applicable. The selection and definition of a test specimen geometry depends on the purpose of the testing effort. With that consideration, the test method is generally applicable to tubes with outer diameters (D_o) of 10 to 150 mm and wall thicknesses (t) of 1 to 25 mm, where the ratio of the outer diameter to wall thickness is commonly $D_o/t = 5$ to 30. Tube sections used for test specimens may vary depending on the type of test (e.g., 25 mm to 1000 mm). In many cases, the wall thickness is defined by the number of plies and fiber-reinforcement architecture of the available tube geometry, particularly for woven and braided configurations.

Experience has shown that successful tests can be maximized by using consistent ranges of relative gage section dimensions. Previous studies[9,10] have shown that pressurized length of the tube, L, and hence initial length of the insert should be:

$$L \geq 9 / \beta$$

and (1)

$$\beta = \sqrt[4]{\frac{3(1-v^2)}{\left(r_i^{tube}\right)^2 t^2}}$$

where r_i^{tube} is the inner radius of tubular test specimen, t is the wall thickness in the gage section of the tube and v is Poisson's ratio of test material. Deviations from the recommended geometries may be necessary depending upon the particular composite tube geometry being evaluated.

TEST EQUIPMENT AND PROCEDURES

Test setup, Force and Strain Measurement, Data Acquisition -- The test method can use a standard load frame with a hydraulic or screw drive loading mechanism and standard force transducers for controlled axial loading for the elastomer insert test method. Guidance is given regarding type, composition and properties of the elastomeric insert material. Primary hoop strain measurement can be measured by strain gages and/or string extensometers in the "gage section." If required, an environmental test chamber may be used to control humidity and ambient temperature. Data collection should be done with a minimum of 50-Hz response and an accuracy of ±0.1 % for all data.

Test Procedure -- Generally, a displacement-based, test mode is used to avoid "run-away" tests that sometimes occur in force-control tests. Test mode rates are chosen so as to produce test specimen failures in 5-50 s. Failure within one minute or less should be sufficient to minimize slow-crack growth (SCG) effects. If slow crack growth is observed (e.g. under slow test mode rates), subsequent tests can be accelerated to reduce or eliminate slow crack growth. The test specimen is tested in hoop tension to fracture. The test specimen is retrieved for failure analysis and post-test dimensional measurement. A minimum of five valid tests is required for the purposes of estimating a mean. A greater number of tests may be necessary, if estimates regarding the form of the strength distribution are required. Fractography is suggested if the failure mode and fracture location are of interest.

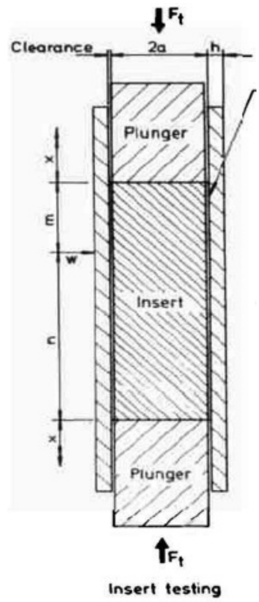

Figure 3 Illustration of test setup for insert testing (Ref. 10)

CALCULATION, REPORTING, PRECISION AND BIAS

Calculations -- Using the measured force data along with the measured strain and/or deformation data as well as the test specimen dimensions, the resulting hoop stress-strain curve for each test specimen is determined. Calculation of the hoop tensile stress is shown in Fig. 4 under the assumption of linear, elastic, homogeneous, isotropic material behavior. Note that calculations for the elastomeric insert method may need to account for friction effects between the insert and the walls of the tubular test specimen[10]. From the stress-stain curve, the following hoop tensile properties are determined: i) ultimate hoop tensile strength and corresponding strain, ii) fracture hoop tensile strength and corresponding strain, iii) proportional limit hoop tensile stress and corresponding strain, iv) elastic modulus in the circumferential direction, v) modulus of toughness.

$$\sigma_\theta = P\left[\frac{2r_i^2}{r_o^2 - r_i^2}\right] and\ \varepsilon_\theta = measured\ directly$$

[at outer radius for internal pressure]

where: $P = f(F_{axial}, A_{insert}, Elastic\ Constants, stiffnesses))$

Figure 4 Calculation of hoop stress for elastomeric insert

Reporting -- The test method provides detailed lists of reporting requirements for test identification, material and test specimen description, equipment and test parameters, and test results (statistical summary and individual test data).

Precision -- CMCs have probabilistic strength distributions, based on the inherent variability in the composite: fibers, matrix, porosity, fiber interface coatings, fiber architecture and alignment, anisotropy, and inherent surface and volume flaws. This variability occurs spatially within and between test specimens. Data variation also develops from experimental variability in test specimen dimensions, volume/size effects, extraneous bending stresses, temperature and humidity effects and the accuracy and precision of transducers and sensors.

CURRENT STATUS AND FUTURE WORK

Now that ASTM Test Method C1819 has been approved, ASTM Committee C28 is planning interlaboratory testing programs per ASTM Practice E691[12] to determine the precision (repeatability and reproducibility) for a range of ceramic composites, considering different compositions, fiber architectures, and specimen geometries. A round-robin interlaboratory testing program for hoop tensile strength will be organized and executed, given available material, funding, and participating laboratories.

CONCLUSIONS

There is a real need for a comprehensive and detailed consensus test standard for hoop tensile strength testing of CMC tubes. This need is based on the certification and qualification requirements for CMC tubes in nuclear fission reactors. Test standards for tubes are needed because tests on flat composite panels are not representative of the architecture and geometry of composite tubes, with their 2-D and 3-D fiber architectures. The new ASTM standard test method C1819 for hoop tensile testing of CMC tubes is comprehensive and detailed, providing strong procedural documents using the conventional ASTM format. This new standard test method is applicable to 1-D, 2-D, and 3-D CMC tubes with diameters up to 150 mm and wall thicknesses up to 25 mm. The test method addresses the following experimental issues -- test specimen geometries and preparation, different loading methods, test equipment, interferences (material, specimen, parasitic stresses, test conditions, etc), testing modes and procedures, data collection, calculations, reporting requirements, and precision/bias.

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