STP1309-EB/Mar. 1997

Summary

Since its establishment in 1991, ASTM Subcommittee C28.07 on Ceramic Matrix Composites has actively promoted the development of test methods for continuous-fiber ceramic composites (CFCCs) and the transfer of research results related to these materials. Indeed, a workshop organized by David C. Cranmer at the National Institute of Standards and Technology, Gaithersburg, Maryland, in February 1990, helped set the stage for the establishment of ASTM Subcommittee C28.07 and resulted in the publication, ''Workshop on Assessment of Testing Methodology for Glass, Glass-Ceramic, and Ceramic Matrix Composites,'' by D. C. Cranmer, *Journal of Research of the National Institute of Standards and Technology,* Vol. 96, No. 4, 1991, pp. 493–501. Following the establishment of ASTM Subcommittee C28.07, a more informal workshop was organized by George D. Quinn in January 1992 at the ASTM Committee C28 meetings in Cocoa Beach, Florida. Finally, a formal workshop entitled ''Thermal and Mechanical Test Methods and Behavior of Continuous Fiber Ceramic Composites (CFCCs)'' organized by Michael G. Jenkins, Stephen T. Gonczy, and Edgar Lara-Curzio was held in June 1994 at the ASTM Committee C28 meetings in Montreal, Quebec.

The impetus for these workshops was that anticipated engineering applications of CFCCs in industrial, aerospace, and propulsion systems require materials to be exposed to service cycles in various aggressive environments which may include simultaneous temperature and load cycling or thermal or mechanical shock. Materials testing and characterization elucidate aspects of the unique damage-tolerant behavior (''toughness'') of this class of advanced ceramics. This information can enable proper formulation of models used for component lifetime prediction and design and guide material development. It was hoped that these workshops would assist in continuing the premarket penetration standardization process required to ensure timely and rapid introduction of these emerging materials into international markets. Researchers from industry, academia, and government who participated in this workshop discussed topics in the following areas:

- development and application of novel test methods and equipment;
- application of standardized test methods;
- environmental and thermal effects;
- tensile, compressive, or shear strength behavior;
- creep/creep rupture behavior;
- cyclic fatigue including frequency, waveform, and amplitude effects;
- thermomechanical fatigue:
- deformation behavior;
- multiaxial loading as applied to test specimen coupons or components (for example, tubes);
- effects of fiber architecture including laminate, fabric, or braided reinforcements;
- specimen design, including volume and geometrical effects; and
- interfacial property measurement and effects of composite performance.

By 1996, ASTM Subcommittee C28.07 had succeeded in introducing four test methods for CFCCs. While CFCCs are said to be an enabling technology for U.S. industry, test methods are viewed as being an enabling supporting technology. Thus, without the common language and procedures of standardized test methods, CFCCs cannot be refined and improved to fill their premier role on the advanced technology. The symposium "Thermal and Mechanical Test Methods and Behavior of Continuous Fiber Ceramic Composites" was held in Cocoa Beach, Florida, 8–9 Jan. 1996, with the intent of formally introducing novel test methods for CFCCs, presenting some of the unique aspects of the thermal and mechanical behavior of CFCCs, and addressing the application of existing standarized test methods to CFCCs. The presentations and the collection of papers in this special technical publication, ASTM STP 1309, are the results of recent research and development programs for CFCCs.

The papers in this STP are a significant contribution to the development and understanding of the behavior of continuous-fiber ceramic matrix composites. Each of the papers in the five sections is briefly summarized in the following paragraphs with some perspective on the significance of the work.

Room-Temperature Test Results/Methods

"Influence of Test Mode, Test Rate, Specimen Geometry, and Bending on Tensile Mechanical Behavior of a Continuous Fiber Ceramic Composite" by Piccola, Jenkins, and Lara-Curzio—the ASTM Test Method for Monotonic Tensile Strength Testing of Continuous Fiber-Reinforced Advanced Ceramics with Solid Rectangular Cross-Section Specimens at Ambient Temperatures (C 1275) was used to investigate the effects of test mode, test rate, specimen geometry, and bending on the mechanical behavior of a CFCC. Analysis of variance showed no effect of test mode and test rate on proportional limit stress and ultimate strength but an effect of specimen geometry for ultimate strength but not proportional limit stress.

"Effect of High Strain Rate on the Tensile Behavior of Nicalon™/CAS Continuous-Fiber Ceramic Composites" by Sánchez, Puente, Elizalde, Martín, Martínez, Daniel, Fuentes, and Beesley—Tensile properties of a CFCC were measured as a function of strain rate. Novel test methods included the use of piezoelectric load cells and strain gages and showed that fracture strength and strain energy density increased with increasing strain rate. These trends were related to fracture mode and damage in the material.

"Shear Strength of Continuous Fiber Ceramic Composites" by Lara Curzio and Ferber—Two test methods for shear strength testing of CFCCs are presented: double-notched compression for interlaminar shear strength and Iosipescu shear test to determine in-plane shear strength. Experimental results are presented for two CFCCs and are related to the thickness of fiber coating.

"Unloading-Reloading Sequences and the Analysis of Mechanical Test Results for Continuous Fiber Ceramic Composites" by Steen and Vallés—Intermittent unloading-reloading cycles are shown to be a powerful tool to assist the interpretation of the mechanical response of a CFCC. A correlation between fiber-matrix interfacial phenomena and the unloading-reloading response is drawn. Implications of the technique for modeling the mechanical behavior of CFCCs are discussed.

High-Temperature Test Results/Methods

"The Effect of Hold Times on the Fatigue Behavior of an Oxide/Oxide Ceramic Matrix Composite" by Zawada and Lee—An oxide fiber-reinforced oxide matrix ceramic composite was tested under monotonic, cyclic, and constant loading. The effect of temperature, maximum stress, frequency, and hold time were examined. Increased strain accumulation occurred with decreasing frequency and increasing hold times.

''Subcritical Crack Growth in Ceramic Composites at High Temperature Measured Using Digital Image Correlation'' by Mumm, Morris, Dadkhah, and Cox—An in-situ experimental technique allowed high-resolution, high-sensitivity determination of full-field strains during high-temperature testing. Creep crack growth was investigated in a CFCC at 1150°C. Crack opening displacements werr monitored for advancing bridged cracks and related to models for crack growth.

''Tensile and Fatigue Behavior of a Silicon Carbide/Silicon Carbide Composite at 1300°C'' by Ünal—Monotonically and cyclically loaded response of a CFCC was studied in nitrogen at 1300°C. Fiber architecture and the interphase material contributed to failure occurring in stages. In monotonically loaded tests, failure occurred by creep of bridging fibers. In cyclically loaded tests, failure occurred by brittle fracture.

''Stress-Temperature-Lifetime Response of Nicalon Fiber-Reinforced Silicon Carbide (SiC) Composites in Air'' by Lin and Becher—Time-to-failure tests were conducted in four-point flexure in ambient air at elevated temperatures to study the effects of stress level and temperature on the performance of a CFCC. A threshold stress was identified, although the thickness of the graphitic interface did not have as great an effect as oxidation inhibitors.

''Fatigue Crack Growth Behavior of a Woven HPZ/Silicon Carbide Ceramic Matrix Composite'' by Kramb and John—Fatigue crack growth behavior in a CFCC was monitored using optical and scanning electron microscopy in addition to compliance techniques. Comparison of crack growth in the CFCC and the monolithic matrix was used to deduce the fiber/matrix interfacial shear stress during crack propagation. This stress was correlated to the fiber-bridging stress and the crack opening displacements.

''Creep-Rupture Behavior of a Nicalon/SiC Composite'' by Verrilli, Calomino, and Brewer—High-temperature creep tests were performed on a CFCC at constant maximum stresses equal to or less than the proportional limit stress. Intermediate temperature tests in ambient air caused decreased creep lives, whereas higher temperature tests in a vacuum produced run-out lives. An oxidation-embrittlement damage mechanism was identified.

''Retained Tensile Properties and Performance of an Oxide-Matrix Continuous-Fiber Ceramic Composite After Elevated-Temperature Exposure in Ambient Air'' by Munson and Jenkins—Oxide matrix CFCC specimens were exposed for 1, 24, and 100 h at 800 and 1000°C in ambient air. Retained tensile properties at room temperature showed small decreases in elastic modulus and proportional limit stress, but large decreases in ultimate tensile strength and modulus of toughness as a result of the degradation of the interphase and fibers.

Nondestructive Characterization

''Characterization of Damage Progression in Ceramic Matrix Composites Using an Integrated NDE/Mechanical Testing System'' by John, Buchanan, Stubbs, and Herzog—A unique integrated nondestructive evaluation/mechanical test system was developed to characterize damage progression in CFCCs. Conventional extensometry plus ultrasonic surface and longitudinal wave transducers were used to track damage. A correlation between experimental results and the NDE method are shown.

''Infrared-Based NDE Methods for Determining Thermal Properties and Defects in Ceramic Composites'' by Ahuja, Ellingson, Steckenrider, and Koch—Flashed infrared light is used to heat instantaneously CFCC components. Digital images of the temperature distribution are used to detect internal defects (for example, delamination or porosity) and are also used to determine thermal diffusivity. Correlations are shown between the nondestructive characterization technique and actual defects.

"Measurement of Orthotropic Elastic Constants of Ceramic Matrix Composites from Impact Sound" by Sakata and Ohnabe—The elastic constants of CFCCs were measured from a combination of the impact sound, natural frequencies, and finite element analysis of small specimens and a jet engine component. Damage of the component after operation of the jet engine is correlated to the reduction of the elastic modulus of the material.

Modeling and Processing

"On the Optimal Design of Fiber-Reinforced Laminates" by Kalamkarov—An optimal design algorithm is proposed for fiber-reinforced laminate CFCCs with a prescribed stiffness. The design problem is generalized to account for the minimization of the volume content of fibers. Examples are used to illustrate the effectiveness and advantages of the developed method.

"A Model for the Creep Response of Oxide-Oxide Ceramic Matrix Composites" by Zuiker—A numerical model was developed to predict the creep response of CFCCs. In the model, Mori-Tanaka estimates of overall elastic response in conjunction with transformation-filed analysis are used to predict the inelastic deformation. Good correlation is shown between the model and experimental results over a wide range of temperatures and stresses.

"Fatigue Life Modeling of Hybrid Ceramic Matrix Composites" by Newaz and Bonora—Cyclic fatigue of a hybrid glass matrix was characterized. Damage evolution was monitored as a function of fatigue cycles and stress levels via stiffness loss. The magnitude of damage was dependent on strain level. A stiffness reduction model was proposed as a function of fatigue life and was successful in predicting damage evolution/fatigue life in the hybrid CFCC.

"Secondary Processing Effects and Damage Mechanisms in Continuous-Fiber Ceramic Composites" by Ramulu, Prasad, Malakondaiah, and Guo—Comparisons are made of CFCC surfaces machined by conventional diamond-grit grinding and nonconventional abrasive water jet (AWJ) cutting. AWJ cut surfaces show a through-thickness variation of roughness and associated cutting/damage mechanisms. The increased damage of AWJ is of concern in applying this machining technique to CFCCs.

Testing of Tubes

"Design, Fabrication, and Burner Rig Testing of Three-Dimensional Woven Ceramic Matrix Composite Flanged Hoop Subelements" by Wildman and Khandelwal—Design considerations for a CFCC flow path duct for high-performance turbine engines are detailed. Test considerations and results for high-temperature testing in a burner rig to simulate the engine operating conditions are reported. Retained strengths are obtained for CFCC subelements that survived the burner rig tests.

Michael G. Jenkins
Department of Mechanical Engineering
University of Washington, Seattle, WA;
Symposium cochair and coeditor.

Edgar Lara-Curzio
Metals and Ceramics Division
Oak Ridge National Laboratory,
Oak Ridge, TN;
Symposium cochair and coeditor.

Stephen T. Gonczy
Gateway Materials Technology,
Mt. Prospect, IL;
Symposium cochair and coeditor.

Noel E. Ashbaugh
University of Dayton Research Institute
University of Dayton, Dayton OH;
Symposium cochair and coeditor.

Larry P. Zawada
Materials Directorate
Wright Laboratory,
Wright-Patterson AFB, OH;
Symposium cochair and coeditor.