MECHANICAL, THERMAL, AND ELECTRICAL PROPERTIES OF NUCLEAR-GRADE SILICON CARBIDE COMPOSITES —R. Shinavski (Hyper-Therm HTC, Inc.), Y. Katoh and L. Snead (Oak Ridge National Laboratory)

OBJECTIVE

Objective of the present work was to acquire baseline properties data, including tensile properties, thermal conductivity, and electrical conductivity, of the reference nuclear grade material of silicon carbide fiber-reinforced, multilayered interphase, chemically vapor-infiltrated silicon carbide matrix (SiC/SiC) composite.

SUMMARY

Nuclear grade SiC/SiC composites combine the attributes of high temperature mechanical strength and toughness with a relative dimensional stability under high neutron fluences that address the primary requirement of survivability in application as a flow channel insert. Unirradiated, through-thickness thermal conductivity has been identified as one property that is not suitable for a flow channel insert. However calculations indicate that through architecturally creating a structure of the nuclear grade SiC/SiC that the targeted low thermal conductivity can be achieved. A database of properties is being developed on a number of nuclear grade SiC/SiC composite. This data accumulation has not yet measured all relevant properties, but has set out a methodology for generating these properties and statistically reducing the properties to a property that can be used for component design.

PROGRESS AND STATUS

Introduction

Nuclear grade silicon carbide fiber-reinforced silicon carbide matrix (SiC/SiC) composites have potential for use in components of fusion reactors subject to elevated temperatures and high neutron fluences. SiC/SiC composites are more suitable, than monolithic silicon carbide, for large structural components due to a significantly higher toughness, and resistance to catastrophic failure that is obtained by continuous fiber reinforcement. Such reinforcement results in nearly an order of magnitude improvement in failure strain. Thus due to Weibull effects, SiC/SiC composites are significantly more robust for producing larger components and structures.

Stoichiometric silicon carbide only has a small equilibrium dimensional change that occurs under neutron irradiation that makes these materials suitable for high neutron fluence environments. SiC/SiC composites composed of near stoichiometric SiC fibers (such as Hi-Nicalon Type S and Tyranno SA3) combined with a stoichiometric SiC matrix produced by chemical vapor infiltration have therefore been termed nuclear grade SiC/SiC. In particular, nuclear grade SiC/SiC is being considered as a candidate for the flow channel insert in fusion reactors.

Mechanical, thermal, and electrical property data for nuclear grade SiC/SiC are being accumulated to allow component design, and assess feasibility. Property databases for three configurations are being gathered. The nuclear grade SiC/SiC constructions considered use either a fabric-based architecture, a braided architecture, or a near unidirectional architecture. All of the composites were produced by Hyper-Therm HTC (Huntington Beach, CA) The first two of these constructions can be suitable for producing a flow channel insert; while the third is suitable for making small diameter pins that can be used for joining and locating components.

Mechanical Properties

Mechanical properties are highly dependent on the orientation and the volume fraction of fibers oriented in the loading direction. Figure 1 shows the range of tensile stress-strain response that can be obtained. In general, all architectures result in a failure strain of 0.5%, while the ultimate strength and proportional limit strengths increase in proportion to the fraction of fiber oriented in the loading direction. The ultimate strength, for instance can be increased by a factor of nearly 4X. However, composites such as with a 0+/-55 triaxial braid architecture have closer to in-plane isotropic mechanical properties than a highly anisotropic unidirectional composite. Although the ultimate strengths can be tremendously different with different composite architectures, the in situ fiber strength (i.e. the ultimate strength of the composite divided by the fiber volume fraction oriented in the load direction or close to the load direction (<~30º) with correction for mis-orientation) obtained is always 2.3 +/-0.1 GPa. This consistency allows reasonable prediction of the expected ultimate strength of a composite architecture that is selected to maximize design margins for a given load case.

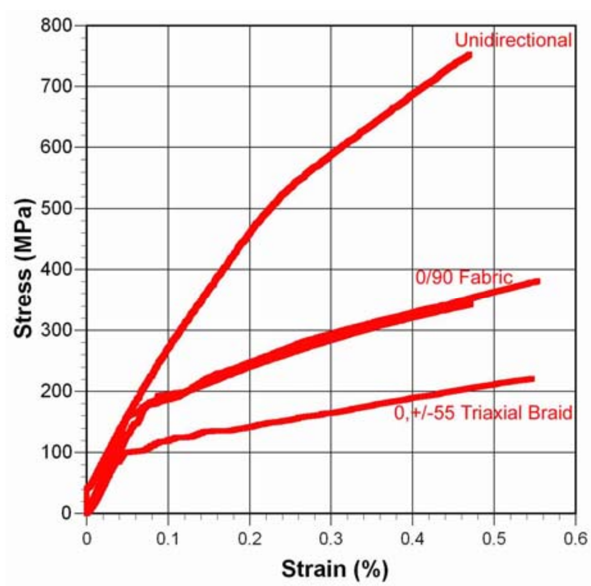

Fig. 1. Examples of the range of stress-strain response that can be obtained in nuclear grade SiC/SiC (Hi-Nicalon Type S/CVI SiC)

The mechanical test plan that is being performed consists of a significant number of room temperature and elevated temperature tensile tests such that a design allowable can be determined. Current status of the mechanical test effort is that a large fraction of the room temperature evaluations have been performed and a limited number of the elevated temperature tests have been performed. However the insensitivity of the nuclear grade SiC/SiC composites over the temperature range of interest (ambient to 800ºC) has been demonstrated to even higher temperatures (Figure 2). Table I presents a summary of the room temperature tensile testing that has been conducted for the respective architectures. Table II reduces these tensile properties to statistically acceptable B-basis allowable where there exists a 95% confidence that 90% of the material will be at or above this value. Further determination of a design allowable for a specific component must also be performed to take into consideration the size effect of the component on the mechanical properties. However in contrast to monolithic ceramics, fiber-reinforced composites have lower volume sensitivity. Additionally the desired factor of safety must also be considered. Similar testing will be completed at elevated temperatures in the upcoming year. Additionally further hoop direction tensile testing of the traixial braided geometry and the unidirectional architectures are required to improve the current statistical limitations in these orientations.

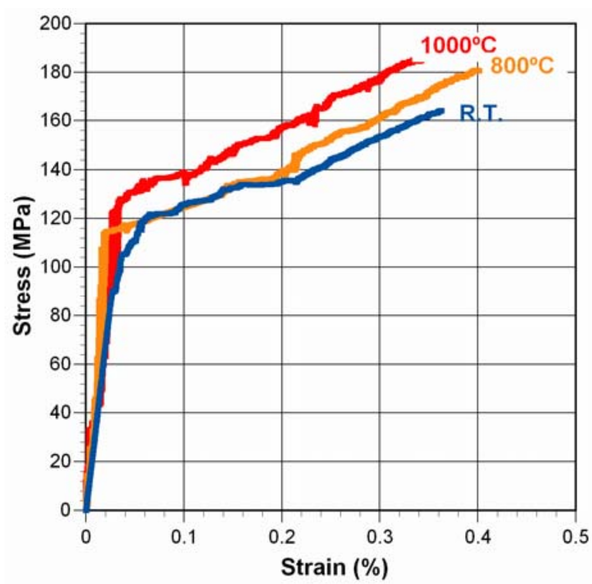

Fig. 2. Elevated temperature strength comparison of triaxially braided nuclear grade SiC/SiC tested in the axial direction as a function of temperature.

Table 1. Summary of the ambient tensile testing for nuclear grade SiC/SiC.

Material	Orientation	Elastic Modulus (GPa)	Ultimate Strength (MPa)	Failure Strain (%)	Prop. Limit Strength (MPa) 0.01% offset
Triaxial SiC/SiC	Axial	261+/-31 n=26	188+/-22 n=11	0.50+/-0.07 n=11	91+/-11 n=26
Triaxial SiC/SiC	Hoop	265+/-24 n=8	132+/-8 n=5	0.38+/-0.07 n=5	92+/-4 n=8
5 Harness Satin SiC/SiC	0/90	268+/-18 n=16	399+/-23 n=16	0.54+/-0.06 n=16	180+/-12 n=16
Unidirectional SiC/SiC	0	261+/-31 n=4	723+/-58 n=4	0.47+/-0.09 n=4	325+/-22 n=4

Table 2. B-basis statistical allowables for room temperature tension of nuclear grade SiC/SiC

Material	Orientation	Failure Stress (MPa)	Failure Strain (%)	Proportional Limit Stress 0.01% offset (MPa)
Triaxial SiC/SiC	Axial	138	0.23	72
Triaxial SiC/SiC	Hoop	94	0.10	79
5 Harness Satin SiC/SiC	0/90	344	0.39	157
Unidirectional SiC/SiC	0	481	0.08	232

Thermal Properties

Thermal conductivity and thermal expansion have been measured. These two properties are critical to application as a flow channel insert as a low thermal conductivity is required to adequately reduce the temperature of the ferritic steel blanket module, and differential thermal expansion combined with differential irradiation induced swelling dominate the induced stress in the flow channel insert. Table II shows the through-thickness thermal conductivity at three temperatures of interest. All values are the average of two measurements. In-plane thermal conductivities are ~2X the through-thickness values, which are more critical for application as a flow channel insert. The through-thickness thermal conductivity is higher than targeted for flow channel inserts by an order of magnitude in the unirradiated state. Achieving a 1-2 W/m/K thermal conductivity in the as-produced state presents the biggest challenge to using nuclear grade SiC/SiC composites for the flow channel insert. However recent calculations have indicated that by producing the SiC/SiC composite as a fluted core sandwich structure that the effective through-thickness conductivity can be reduced to as low as 1.2 W/m/K. Such a structure will also provide a compliant layer between the hot and cold surfaces to allow accommodation of both the differential thermal expansion strains and the differential irradiation induced swelling strains. The feasibility of producing a fluted core sandwich structure has been demonstrated in other CMC systems, but producibility in nuclear grade SiC/SiC has not yet been demonstrated. This area is a subject of ongoing development.

Table 3. Through-thickness thermal conductivity of nuclear grade SiC/SiC

Material	Orientation	Thermal Conductivity (W/m/K)		
		20ºC	500ºC	800ºC
Triaxial SiC/SiC	Through-Thickness	27.6	21.5	18.2
5 Harness Satin SiC/SiC	Through-Thickness	21.8	17.0	14.2

Thermal expansion has been measured to be nearly isotropic (within 0.1 ppm/ºC) regardless of orientation or architectural construction. The mean thermal expansion coefficient from RT-500ºC is 3.9 ppm/ºC, and 4.3 ppm/ºC from RT to 800ºC.

Electrical Properties

Both through-thickness and in-plane electrical properties have been measured on the 5 harness satin fabric-based nuclear grade SiC/SiC. The electrical conductivity measurement in-plane and through-thickness are summarized in Table IV. In-plane electrical conductivity is significantly higher than through-thickness conductivity presumably due to the continuity of the highly conductive, but albeit thin, multilayer SiC fiber coating that contains carbon interlayers. The through-thickness electrical conductivities are in a suitable range for the flow channel insert to minimize magnetohydrodynamic pressure drops.

Table 4. Electrical properties of nuclear grade SiC/SiC (5 harness satin fabric-based)

Orientation	Electrical Conductivity (S/m)					
	20ºC	100ºC	280ºC	360ºC	500ºC	760ºC
Through-Thickness	0.02	0.10	0.27	0.75	not measured	not measured
In-Plane (0/90)	310	310	330	350	380	460