Silicon–Carbide Composite Materials for the ARIES–I Reactor Study

S. Sharafat, N. M. Ghoniem, S. P. Grotz, L. Y. Lee, and The ARIES Team
University of California, Los Angeles, CA USA

ABSTRACT

High-performance ceramics offer new possibilities for future power reactors. The higher allowable operating temperatures of ceramics relative to that of metals results in improved efficiencies. Ceramic structures are also advantageous from a safety and waste disposal stand point, since they promise low dose, low radioactivity, and very low afterheat. Until recently, the brittle failure behavior of monolithic ceramic materials has posed a problem for using ceramics as structural materials. Recent developments in manufacturing and processing of silicon fiber reinforced ceramics, make these materials strong candidates for the structural material of future reactor power plants. The thermomechanical properties of silicon carbide reinforced ceramics are reviewed. Micromechanical equations are used to approximate properties of the proposed reinforced silicon carbide materials for the first wall and blanket structure of the ARIES-I tokamak reactor. The ANSYS finite element structural analysis code is used to estimate normal operating thermal and pressure stresses in the silicon carbide first wall. It is concluded that with minor extrapolations from todays manufacturing experience, SiC-composites offer a viable structural material choice for future fusion reactor components.

1. INTRODUCTION

The ARIES project is a multi-institutional effort exploring the potential of tokamaks as an attractive and competitive commercial power reactor (Conn, et al., 1987). Several different versions of the tokamak are being considered with varying degrees of extrapolation in plasma physics and technology. A summary of the preliminary design of the ARIES-I fusion power core (FPC) is reported by Grotz, et al. (Grotz, et al., 1989). The ARIES-I design features a low activation ceramic composite as the structural material for the FPC.

Ceramics have many desirable characteristics when compared to metals. One of the most attractive characteristics of ceramics is their high-strength at high temperatures. Typical operating temperatures of non-refractory metals do not exceed 600°C, while ceramics can potentially be operated between 1000 and 1500°C. Because of the very low level of radioactivity induced in ceramics exposed to fusion neutrons they have been considered for structural materials in the past (Hopkins, et al., 1985) for fusion reactors.

Despite advantages of ceramics over metals, the brittle fracture response of bulk ceramic materials causes the fracture tensile strength of monolithic ceramics to have wide statistical distributions making the failure points unpredictable. Furthermore, failure of monolithic ceramic materials is generally catastrophic, i.e., cracks propagate rapidly through the entire stressed region. To alleviate these two concerns, worldwide R & D programs (Cassidy, et al., 1987) have been intensified using two different approaches: (1) development of high-performance monolithic ceramics; (2) development of reinforced ceramic composites.

High-performance ceramics are produced by improving ceramic manufacturing processes aimed at reducing fabrication induced flaws, developing near-net shape processing techniques, improving sintering aids, and developing transformation-toughened and particle-toughened ceramics. In recent years, a number of high-performance ceramics have successfully been developed (Kamo, 1987) for use in high-temperature advanced gas-turbine engines, adiabatic diesel engines, rotary Wankel, and Stirling engines.

The second approach to develop ceramic materials with predictable performance characteristics, high strength, improved strain-tolerances, and higher toughness is through the use of fibers dispersed in the ceramic matrix. High strength can be achieved by transferring the load from the matrix to the fibers, taking advantage of the superior tensile strength of the fibers. Fracture-toughness values for ceramic matrix composites (CMCs) are very high because energy is absorbed as fibers are pulled out of the matrix causing crack deflection, crack arrest, or crack blunting. Figure 1 compares the typical stress-strain curves for monolithic silicon carbide (SiC) and unidirectionally-reinforced SiC-composite materials. The SiC-composite material referred to in this work consists of SiC-matrix material reinforced with SiC-fibers. The fracture toughness of a material is directly proportional to the area under the stress-strain curve (see Fig. 1) and it represents the energy required to fracture a material. Figure 1 clearly shows the large improvement in the fracture toughness of SiC-composites over monolithic SiC. The strain tolerances of SiC-composite materials greatly exceed those of monolithic ceramics. Strains values above 2.5% are routinely measured for such composites (Hopkins, 1986), whereas monolithic SiC exhibits strain values of less than 0.1% at initiation of fracture (see Fig. 1).

A significant improvement of SiC-composite materials is the avoidance of catastrophic failure modes. As depicted in Fig. 1, the SiC-composite material continues to carry a significant amount of the load after ultimate stress is reached, while monolithic ceramics fail catastrophically at their ultimate stress loads. The SiC-composite sample of Figure 1 carries up to ~55% of the ultimate stress load at a 2.8% strain level; ceramic composite materials are currently being developed with stress-strain curves characteristic of metals. With further efforts, CMCs will hopefully behave as predictable as metallic alloys but with greatly improved performance capabilities. Based on the significant advances in CMC materials achieved during the infancy phase of the industry, it is not premature to extrapolate from todays laboratory-scale materials to large-scale commercial CMC components to be build in the future.

The next section will summarize some SiC-composite material characteristics. Micromechanical design equations for composite materials are used to predict SiC-composite properties. These properties are then used to estimate pressure and thermal stresses induced in the ARIES-I first wall structure using the ANSYS (DeSalvo, et al., 1977) finite element code. It is concluded that SiC composites offer potential significant advantages as structural material for future fusion reactors.

2. SiC COMPOSITE PROPERTIES

The properties of SiC materials depends, to a large extent, on the manufacturing process; often the name of the material bears the process name, such as hot pressed SiC (HP-SiC). Silicon carbide materials with flexural strengths up to 750 MPa have been manufactured. These high-strength SiC materials can only be manufactured into small samples of simple geometry. The main method used to improve the strength is through fiber reinforcement. Mechanical and physical properties of two commercially available SiC fibers are listed in Table 2. Among the many SiC-composite fabrication methods, chemical-vapor infiltration (CVI) is most widely used, where a fibrous SiC preform is infiltrated with silane gases in a furnace. Silicon carbide is deposited from the decomposition of methyltrichlorosilane (CH_3SiCl_3) gas at temperatures less than 1200°C. Typical infiltration times of the order of weeks were necessary to produce millimeter thick SiC-composite materials, however, recently new processes have been developed by the Oak Ridge National Laboratory that reduce infiltration times from weeks to about 24 hours (Stinton, et al., 1986). Chemical-vapor infiltrated SiC-composites typically have between 10 to 15 % porosity. Efforts are underway aimed at reducing the porosity in order to improve mechanical properties.

Table 1
PROPERTIES OF SiC FIBERS (Fitzer, 1986)

Property	PCS-SiC*	CVD-SiC†
Diameter (μm)	9 -15	100 - 140
Length	Endless	Endless
Tensile Strength (GPa)	1.9 - 3.0	2.5 - 3.7
Young's Modulus (GPa)	180 - 200	380 - 420
Density (g/cm^3)	2.55 - 2.58	3.4 - 3.5
Thermal Exp. Coefficient (10^{-6}K^{-1})	3.1	4.2 - 4.5

* PCS=polycarbosilane-derived fibers; † CVD=chemical vapor deposited fibers

Lack of data on the thermo-mechanical properties of SiC still necessitates the use of the micromechanical design equations (Chamis, 1987). Such design equations are used to estimate the longitudinal and transverse properties. Special care is taken to incorporate neutron irradiation effects on SiC fiber and SiC matrix properties. For the SiC matrix material, the truncated and irradiated Weibull distribution function for the tensile strength of CVD SiC with a near-zero probability of failure was used (Price, et al., 1982). Samples of CVD SiC were first proof-tested and consequently irradiated up to 10^{26} n/m^2 with fast neutrons (E_n >0.1 MeV). Some samples showed close to 700 MPa flexural strength with a high failure probability, however, an average flexural strength of about 435 MPa was shown to have a near 100% survival probability. Assuming that the tensile strength of ceramics is about 0.75 of the flexural strength, 350 MPa was taken as the tensile strength of the CVD matrix material. The effect of temperature on the strength of SiC bulk material depends on the manufacturing process and environment. Up to 1300°C, silicon-based carbides and nitrides show insignificant levels of loss of strength (Davidge, 1984). Thus, 350 MPa can be taken as a conservative estimate for the high temperature (1000°C) tensile strength of CVD SiC matrix materials that has been irradiated.

To use conservative values for the SiC fibers, one has to incorporate the degradation of the strength of the SiC fibers during weaving or braiding processes and the effects of length. This degradation is caused by an increase in surface flaws on the fibers and also by fiber breakage during preform fabrication. To account for this effect, the Weibull distribution of the tensile strength of SiC yarns is used. Yarns or tows contain between 500 to 1000 monofilament fibers. The strength of SiC yarns is about 2 to 4 times less than that of individual fibers. The average tensile strength of SiC yarn made from PCS-SiC was measured to be 1388 MPa and 1063 MPa for 5 and 25 cm gage lengths, while individual SiC fibers have average strengths of above 2400 MPa (Fang, et al., 1986). Using yarn properties instead of the superior fiber properties, a tensile strength of 750 MPa is chosen. This value was taken for a near-zero probability of failure data accumulated by Fang after testing over 2000 samples (Fang, et al., 1986).

The effects of the length of the fibers were investigated by Fukada (Fukada, et al., 1981). A conservative correction coefficient has been formulated to account for a fraction of fibers to break during manufacturing of the composite material. Assuming 1 out of about every 7 fibers (17 %) to break during fabrication, a numerical value of 0.5 is estimated for the correction factor of the tensile strength of SiC fibers. This factor reduces the effective strength of the SiC fibers to a highly conservative value of 375 MPa.

The superior, high-temperature strength of SiC fibers is well documented. In particular, the effects of various environments were studied (Fukunaga, et al., 1986). SiC fibers in vacuum retain their full strength to about 1200°C. Strength degradation is measured when the fibers are heated in air due to surface-oxidation processes. Therefore, care must be taken during the manufacturing of SiC-composites to minimize the amount of trapped oxygen before the CVI process begins.

The effects of neutron irradiation on PCS-SiC fibers was investigated in Japan as part of a new national R&D program aimed at developing SiC-composite materials (Hayashi, 1985). Both, 14 MeV neutrons form the RTNS-II facility in the U.S. and fission reactor neutrons were used (Okamura, et al., 1987). Samples were irradiated to fluences of 5×10^{20}

n/m^2 (14 MeV) and 1×10^{25} n/m^2 (fisson spectrum). No significant change in the average tensile strength (2.7 MPa) and the average flexural strength (1.3 GPa) was measured for irradiation up to about 1×10^{24} of fast neutrons. At 1×10^{25} n/m^2, the tensile strength rises to about 3.2 GPa and the flexural strength increases to about 1.5 GPa. However, the average Young's Modulus rises steadily from an unirradiated-fiber value of 160 GPa to about 215 GPa at 1×10^{25} n/m^2 with a corresponding drop in elongation from 1.8 % to 1.6 %. These preliminary results show that SiC fibers have excellent stability under neutron irradiation. Therefore, in estimating SiC fiber properties neutron irradiation effects are neglected until a more extensive data base has been developed.

In summary, the conservatively estimated SiC fiber strength value of 375 MPa reflects the degradation effects of weaving a fibrous SiC preform, fiber breakage during manufacturing, and the high-temperature (1000°C) operation capability in an intense neutron-irradiation environment.

3. COMPOSITE DESIGN STRESS LIMITS

To estimate the tensile strength of the SiC-composite, the rule of mixtures is used to formulate micromechanical design equations. For example, the CMC tensile strength in the direction parallel to the fiber orientation (longitudinal) is estimated as:

$$\sigma_c = V_f \sigma_{uf} f(b) + V_m \sigma_{um} f(v)$$

where: σ_c is the failure strength of the composite, σ_{uf} is the tensile strength of fibers, σ_{um} is the tensile strength of matrix, V_f is the volume fraction of fibers, V_m is the volume fraction of matrix, $f(b)$ is the coefficient that accounts for fiber breakage (0.5), and $f(v)$ is the matrix void fraction

Figure 2 shows the estimated longitudinal strengths of the SiC-composite as a function of fiber volume fraction with various matrix void fractions. By defining 2/3 of the composite tensile strength as the maximum design stress limit, SiC composite would have an allowable design stress limit of about 180 MPa at 1000°C with a 10% porosity and a fiber volume fraction of 0.6. It should be noted here that the safety factor of 2/3 is an extrapolation of the design limit usually applicable to metallic alloys. At present time similar guidelines for ceramic materials of CMCs do not exist. Future experience with CMCs and better understanding of the failure modes of CMCs will eventually dictate firm guidelines for determining allowable design stresses.

To estimate other longitudinal and transverse properties such as Young's Modulus, compressive strengths, shear strength, Poisson's ratio, and thermal conductivity the CLASS code (Kibler, 1987) is used. Properties are calculated based on the rule of mixtures. For a SiC-composite material with a 0.5 fiber volume fraction and a fiber orientation pattern of 0°/45°/90°/-45° the following properties are determined (x-longitudinal, y-transverse):

Elastic Modulus:	$E_{xx} = 364$ GPa
	$E_{yy} = 357$ GPa
Shear Modulus:	$G_{xy} = 160$ GPa
Poisson's Ratio:	$\nu_x = 0.17$
	$\nu_y = 0.157$
Thermal Conductivity:	$k_{xx} = 22.5$ W/mK
	$k_{yy} = 19.6$ W/mK
Expansion Coefficient:	$\alpha_x = 3.751 \times 10^{-6}/°C$
	$\alpha_y = 3.779 \times 10^{-6}/°C$

Preliminary normal operating thermal and pressure stress analysis using the ANSYS code show that the maximum stress in the ARIES-I first wall SiC structure are less than 40 MPa (tensile), with a maximum wall temperature of 780°C.

4. SUMMARY

Recent advances in SiC-composite manufacturing processes have greatly improved the failure mode behavior, strain tolerances, and fracture toughness of these ceramics. Micromechanic design equations were used to estimate material properties for typical SiC-composite materials. These calculations reflect the degradation of fiber and matrix material properties due to imperfect manufacturing techniques and neutron irradiation effects at high temperatures. The maximum allowable design stress of the SiC-composite was estimated to be 180 MPa at 1000°C . Preliminary first wall stress analysis shows that the thermal and pressure stresses are below the estimated design limit. In conclusion, recent improvements in ceramic-composite material properties has made SiC-composites an attractive material choice for fusion reactors.

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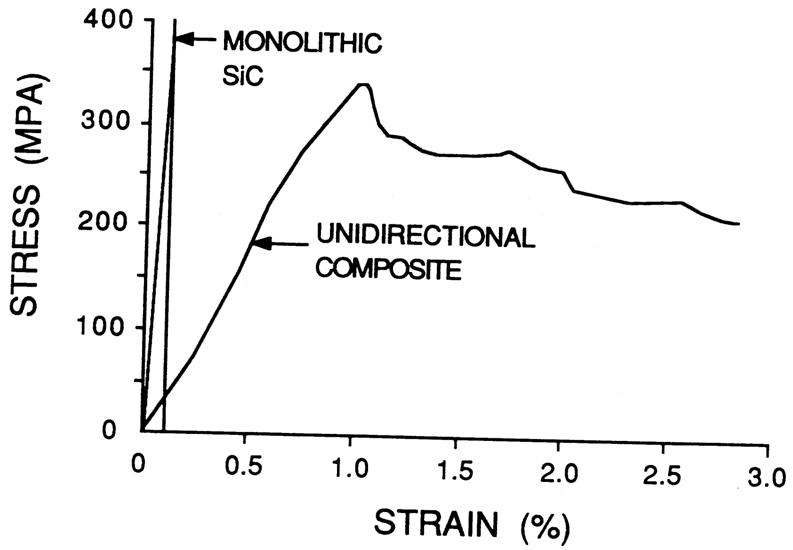

Figure 1. Stress-strain curve of unidirectional SiC-fiber-reinforced SiC-composite (Stinton, et al., 1986).

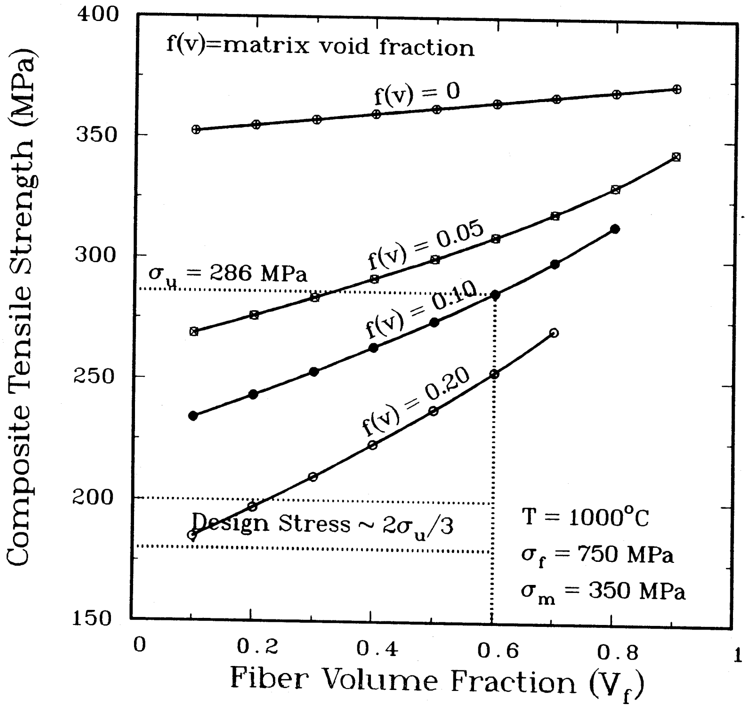

Figure 2. Longitudinal SiC-composite tensile strength estimated from micromechanical design equations (σ_f is the SiC fiber tensile strength; σ_m is the SiC matrix tensile strength).