Strength and Fatigue Analysis of Fibrous Silicon Carbide for ICF Reactor Applications

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STRENGTH AND FATIGUE ANALYSIS OF FIBROUS SILICON CARBIDE FOR ICF REACTOR APPLICATIONS*

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Since silicon carbide fiber has been proposed as a first wall material for inertial confinement fusion reactors, a program has been initiated to identify static and dynamic mechanical strength characteristics. Static failure stress was found to be very high but considerably less than values reported for single filaments. Low cycle fatigue curves have been developed for a range of alternating and mean stresses. Fractured fibers generally show brittle characteristics for both static and fatigue failures.

1. INTRODUCTION

The mechanical design of first walls of inertial confinement fusion reactors is unusually difficult because of the very severe loads which develop from target ignition: x-rays, neutrons, target debris, reflected driver energy, mechanical shock, etc. Energy deposition is generally intense, occurs over extremely short time spans and is repetitious. Such conditions limit the choice of materials. Among candidate high temperature materials, silicon carbide has excellent potential for these applications. It has been proposed as the first wall material in two conceptual designs, HIBALL[1] and LIBRA. LIBRA is currently being developed by Fusion Power Associates in the US and Kernforschungszentrum Karlsruhe in the Federal Republic of Germany. The first wall in each design uses SiC in a fibrous form. Thus characterization of the static and cyclic strength of SiC fiber has been initiated to support these design efforts.

2. LIBRA CAVITY

The LIBRA design can be classified as a demonstration reactor based upon a light ion driver system. A schematic diagram of the reaction chamber is shown in Fig. 1. The cavity is encircled by an annular bank of vertical tubes, identified as INPORT units.[2] The diameters of INPORTs in the first two rows are 3 cm; behind these are 5 and 10 cm units. Figure 2 represents the basic INPORT concept. Individual tubes are fabricated from continuous SiC fiber, braided to produce a pliable porous component. Liquid $Li_{17}Pb_{83}$, used as a coolant and breeding material, flows axially within the INPORT and also through the tube wall to develop a thin protective outer film. The preliminary design of Fig. 3 would permit relatively convenient assembly and tensile preloading by means of compression spring systems. Flanged ends of INPORTs can be rigidized and strengthened for support by chemical vapor deposition of additional SiC.

3. FIBER CHARACTERISTICS AND INPORT DEVELOPMENTS

The fiber used is "NICALON®," manufactured by a polymer pyrolysis process by Nippon Carbon Co., Japan. It is composed of ultrafine β-SiC crystals with excess carbon. The number of filaments per yarn is 500, with an

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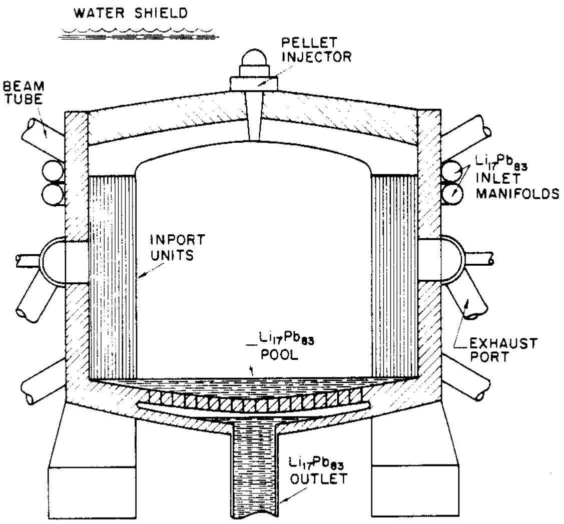

FIGURE 1
Schematic of LIBRA reaction chamber.

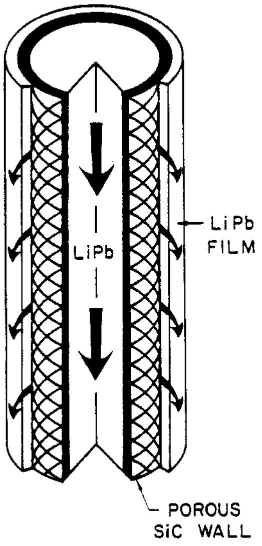

FIGURE 2
Sectioned INPORT unit.

individual average diameter of 12.6 μm.

In earlier work, McDonnell-Douglas Corp., St. Louis, used this type of SiC to braid

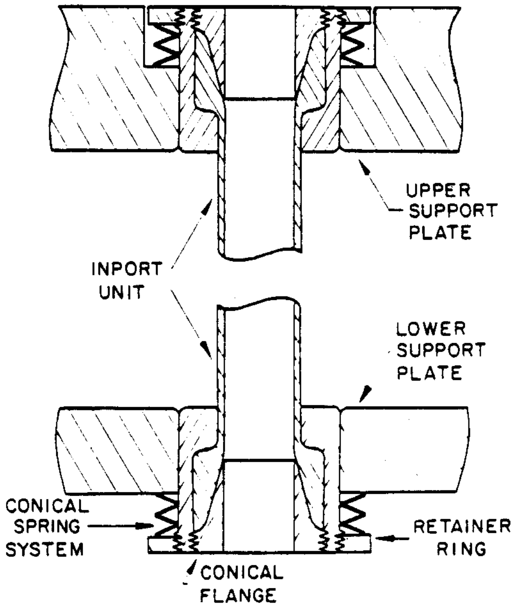

FIGURE 3
Support mechanisms for INPORT.

INPORTs and performed tension tests as well.[3] Tubes were made with and without axial tows. In addition, some INPORTs received a SiC chemical vapor deposition (CVD) treatment; tests were carried out at two temperatures: 350 and 550°C. It was found that the CVD process substantially increased the tensile strength. This improved load sharing of fibers but resulted in a brittle tube. Axial cords in untreated tubes failed prematurely since they were carrying essentially the total axial load. Without axial members, the elongation is substantial for untreated INPORTs. No change in strength was observed as a result of testing at the two temperatures. From this experience, improved designs will be developed and additional strength testing will be done.

4. FIBER BUNDLE TENSION TESTS

Tensile tests were carried out on fiber bundles to determine strength and elastic modulus and to qualitatively identify failure characteristics. A MTS T5002 universal testing machine was used with load grips designed for fibrous materials as shown in Fig. 4. Overall failure was characterized by "brooming" which could imply a sequential fiber failure and a definite knee on the stress-strain diagram. Figure 5 indicates that the dominant failure mode is simultaneous failure of a majority of the fibers. This diagram is representative of the tests performed. In general the consistency was very good with an average maximum load, tensile strength and modulus of 84.4 N, 1.346 GPa and 90.04 GPa, respectively. Because of nonuniform load sharing, these numerical results for fiber bundle tests can be expected to be lower than for individual fibers. Fracture surfaces are clean breaks on planes normal to the fiber axis as shown in Figs. 6 and 7. The dark central circular area in Fig. 7 may be the result of a penny crack which originated and subsequently propagated across the fiber.

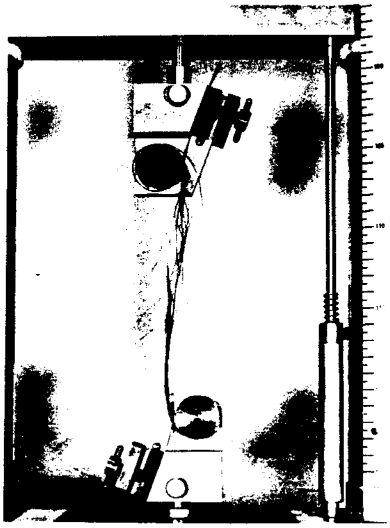

FIGURE 4
Tensile failure of SiC fiber bundle.

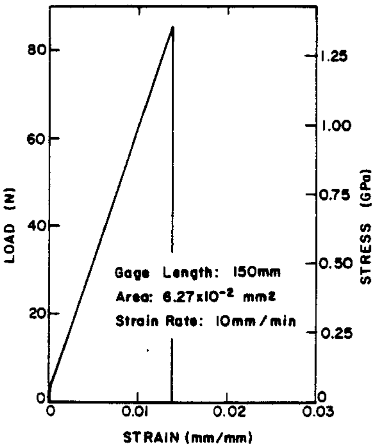

FIGURE 5
Tensile test of SiC fiber bundle.

5. FATIGUE TESTS OF FIBER BUNDLES

The same apparatus was used for static and dynamic testing. The gauge length for all samples was 15 cm and the maximum load frequency was 0.25 Hz. The load state consisted of a tensile mean stress (σ_m) and a cyclic alternating stress (σ_a). The various combinations were such as to produce a maximum value less than the fracture stress (σ_f) and a minimum greater than zero. In Fig. 8, alternating stress as a fraction of fracture stress is plotted as a function of the number of cycles to failure. Note that the curve for σ_m/σ_f equal to 40% terminates at a value of σ_a/σ_f equal to 40%. Curves for mean stresses of 50% and 60% have been extended to the simple tension data corresponding to $N_F = 0.5$. Similarly maximum tensile stress can be plotted as a function of the number of cycles to failure as shown in Fig. 9. The results indicate the possibility of an endurance limit but additional high cycle tests are needed. The development of graphs such as Fig. 10 can be useful for design purposes. Rays are shown for different ratios fo σ_a/σ_m, the largest acceptable value being 1.0. In using such curves, for example, a point stressed to state

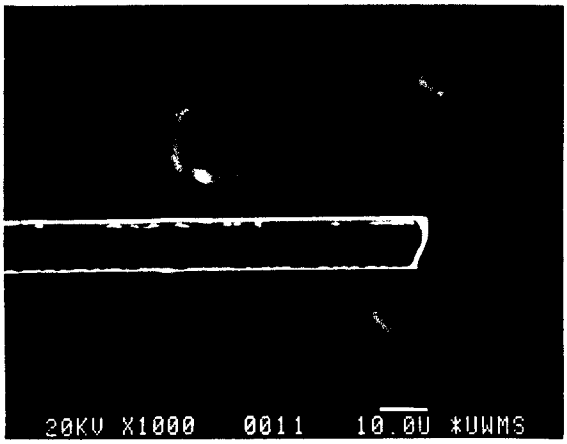

FIGURE 6
SEM micrograph of filament tensile failure.

FIGURE 7
SEM micrograph of filament tensile failure.

"A" could sustain 10^2 cycles but not 10^3. SEM micrographs were also taken of fatigued fibers. Figures 11 and 12 are typical, characterized by a more complex or rougher fracture surface than static tension. A small percentage of fibers failed on inclined surfaces in more complex patterns. Figure 13 shows a scalloped curved surface usually associated with progressive cyclic failure.

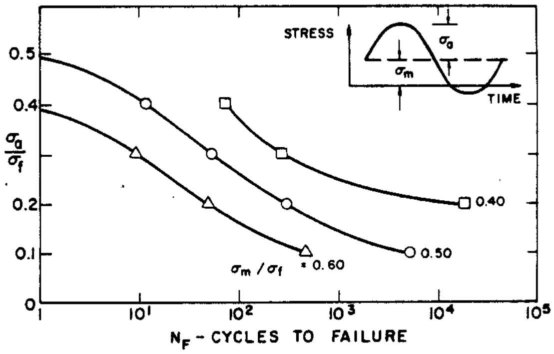

FIGURE 8
Alternating stress amplitude vs. number of cycles to failure.

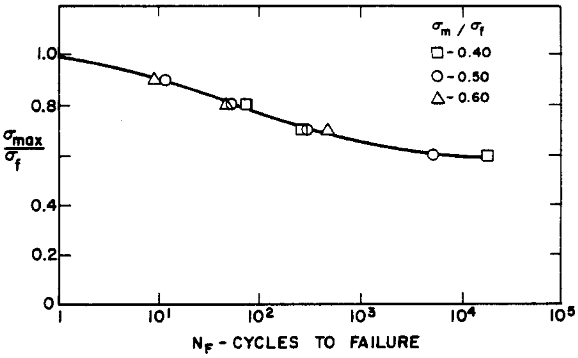

FIGURE 9
Maximum tensile stress vs. number of cycles to failure.

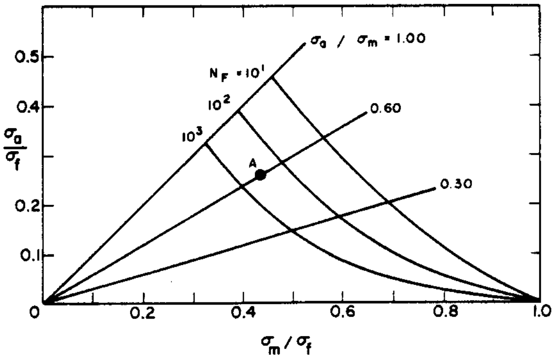

FIGURE 10
Alternating stress vs. mean stress for various cycles to failure.

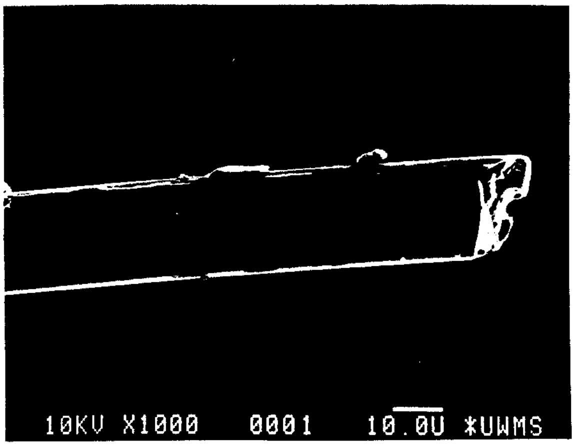

FIGURE 11
Fatigue fiber fracture at 18,600 cycles for $\sigma_m/\sigma_f = 40\%$; $\sigma_a/\sigma_f = 20\%$.

FIGURE 12
Fatigue fiber fracture at 18,600 cycles for $\sigma_m/\sigma_f = 40\%$; $\sigma_a/\sigma_f = 20\%$.

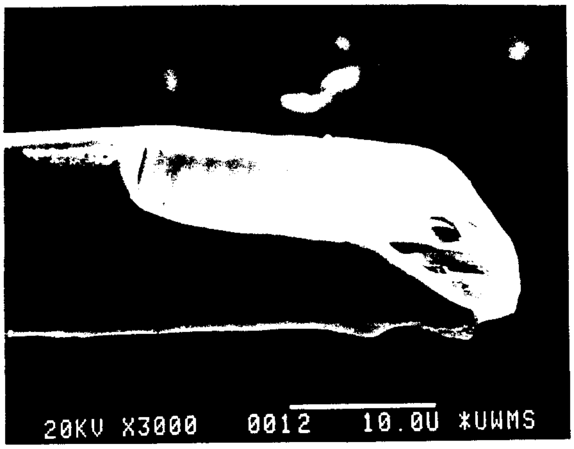

FIGURE 13
Fatigue fiber fracture at 13,700 cycles for $\sigma_m/\sigma_f = 40\%$; $\sigma_a/\sigma_f = 20\%$.

6. CONCLUSIONS

Preliminary static and fatigue strength tests of silicon carbide fiber bundles support expectations for potential use in ICF first wall applications. The INPORT concept is a component which can take advantage of the high strength and flexibility of the material. However, refinements in the design will be eventually needed to improve load sharing among the fiber elements. Also, additional testing is needed over a wider range of stress and proposed operating conditions.

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3. J. Sapp, "An Investigation into the Use of Graphite and Silicon Carbide in Heavy Ion Beam Reactors," McDonnell-Douglas Tech. Rep. #7F-05-E016-5507 (1982).