

# FOREIGN OBJECT DAMAGE RESISTANCE OF UNCOATED SiC/SiC COMPOSITES

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## ABSTRACT

2-D woven SiC/SiC composites fabricated by melt infiltration method were impact tested at room temperature and at 1316<sup>0</sup>C in air using 1.59 mm steel-ball projectiles at projectile velocities ranging from 110 m/s to 400 m/s. The extent of substrate damage with increasing projectile velocity was imaged and analyzed using optical microscopy and nondestructive evaluation (NDE) methods. The impacted specimens were flexure and tensile tested at room temperature to determine their residual mechanical properties. Results indicate that as the projectile velocity increases, internal damage in the target material also increases and the mechanical properties degrade. At velocities >300m/s, the projectile penetrates through the target material, but it still retains ~ 50% ultimate strength of the as-fabricated composites and exhibits non-brittle failure.

## INTRODUCTION

SiC/SiC composites fabricated by the melt infiltration method are candidate materials for turbine components such as combustor liners, nozzle vanes and blades because of their high temperature strength, and thermal conductivity [1]. In a combustion environment containing moisture, these materials suffer from rapid surface recession [2, 3] and to prevent this, an external environmental barrier coating (EBC) is required [4, 5]. Under thermal loading conditions alone, the EBC coated SiC/SiC components show microstructural and strength stability after ~14000 hr exposure to 1200<sup>0</sup>C in a combustion environment [6]. However, the stability of EBC coated SiC/SiC composites under impact conditions is not fully understood. The objectives of the study are several: first, to determine the impact resistance of both uncoated and EBC coated SiC/SiC composites; second, to assess influence of impact damage on the durability; third to develop novel methods of improving impact resistance of EBC coated SiC/SiC composites by controlling the fiber architecture and constituents. In this short paper, only the influence of impact at room temperature and at 1300<sup>0</sup>C in air on mechanical properties and the resulting impact damage mechanisms of the uncoated SiC/SiC composites are discussed.

## EXPERIMENTAL PROCEDURE

The Sylramic-iBN SiC fiber-reinforced SiC matrix composite panels used for impact study were fabricated at GE Power Systems Composites by a slurry-casting/melt infiltration method as reported in reference [7]. To describe the processing method briefly, the SiC fibers (Sylramic<sup>TM</sup>), produced in tow form by Dow Corning, were woven into 0/90, 5-harness satin fabric at Albany International Techniweave and then converted to Sylramic-iBN fibers at the NASA Glenn Research Center. The Sylramic-iBN fabric was cut into 230 x 150-mm pieces. Eight pieces of fabric were stacked, squeezed in a graphite fixture, and chemically vapor infiltrated with a thin layer of BN-based interphase coating followed by a layer SiC matrix over-coating to produce fiber preforms which contain open porosity ranging from 20 to 40 vol%. Subsequently, the remaining matrix porosity was filled with SiC particles at room temperature and then with molten silicon near 1400<sup>0</sup>C. For brevity, the Sylramic-iBN fiber-reinforced SiC/SiC composites

are henceforth referred to as SiC/SiC composites. The as fabricated SiC/SiC composites contained ~34 vol% SiC fibers, ~5 vol% BN coating, and ~58 vol% SiC coating, SiC particles, and silicon.

The nominal dimensions of as-fabricated composite panels were ~ 230-mm (L) x 150-mm (W) x 2.4-mm (T). The panels were machined into flexure specimens of dimensions 45-mm (L), 8-mm (W), and 2.2 to 2.4-mm (T) and tensile dog-boned specimens of dimensions 152-mm (L), 13-mm (W), and 2.2 to 2.4-mm (T) with a reduced gage section.

For impact testing of flexural specimens at room temperature and 1316<sup>0</sup>C in air an experimental apparatus as shown in Fig. 1 was used. Detailed descriptions of the apparatus and the testing procedure for impact testing can be found elsewhere [8, 9]. The specimens were partially supported at the specimen ends in the specimen holder. For impact testing of dog-bone shaped tensile specimens, an impact gun unit similar to that shown in Fig. 1 was used, but the specimens were held at their ends in a “C” shaped clamp and the gage section was heated by an atmospheric pressure burner rig mounted parallel to the specimen holder. In both test configurations, the specimens were impacted with hardened (HRC≥60) chrome steel-balls (~1.59-mm diameter) at velocity ranging from 110m/s to 400m/s.

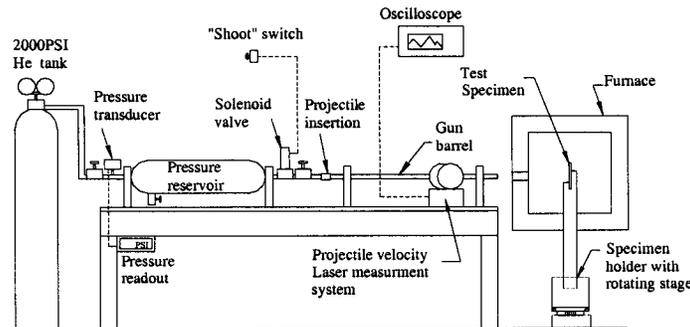


Figure 1. Impact testing apparatus with a specimen holder and a high-temperature furnace.

At each test condition only one specimen was tested. The extent of target specimen damage with increasing projectile velocity was imaged by optical microscope and microfocus x-ray radiography, computed tomography (CT), and thermal wave imaging

### Post-Impact Strength Testing

Strength testing of impacted target specimens was performed at ambient temperature in air to determine the severity of impact damage on flexural properties by using a four-point flexure fixture with 20-mm inner and 40-mm outer spans. Each impacted specimen was loaded in the flexure fixture such that its impact site was subjected to tension within the inner span. An LVDT was used to determine the center deflection of specimens during strength testing. An electromechanical test frame was used in displacement control with an actuator speed of 0.5 mm/min. For tensile testing, each impact tested dog-bone specimen was loaded in a servo-hydraulic test frame equipped with self-aligning grips, and a spring-loaded clip-on gauge was attached to the 25-mm long straight section of the dog-boned specimen to monitor the displacement. The specimens were tested at room temperature until failure at a crosshead speed of 1.3 mm/min. One specimen was tested for each exposure condition.

## RESULTS AND DISCUSSION

Figure 2 shows a SEM micrograph of the cross section of an as-fabricated SiC/SiC composite. The composite is essentially a layered structure consisting of woven fiber plies interspersed with SiC matrix which is composed of SiC particles and silicon. The gray region in the photograph is the SiC fiber tows coated with CVI BN and SiC coatings. The white region is the SiC matrix. Dark regions in the tow indicate closed porosity.



Figure 2. SEM photograph of a cross-section of an as-fabricated SiC/SiC composite showing distribution of SiC fiber tows in the SiC matrix

### Impact Morphology

In general, optical and thermal wave images of impact tested specimens taken from the impacted side showed indents, craters or deep holes with their size depending on impact velocity and temperature. In addition damage to the backside of the specimen was also noticed at impact velocities  $> 110\text{m/s}$ . In all tested specimens, the size of the damaged zone measured by thermal wave imaging was always greater than that measured by the optical method [10]. Also for a given impact velocity and temperature, the size of the damage zone measured by the thermal wave imaging on the impacted side was always smaller than that on the back side [10]. This suggests greater amount of internal damage. It appears that the shock waves created by the projectile upon impact to the frontal side travels to the back side and reflects back to the front. In this process tensile stresses are created in the backside. If these stresses are greater than the interlaminar tensile strength, delamination cracks are formed in the composites due to backside tensile stresses.

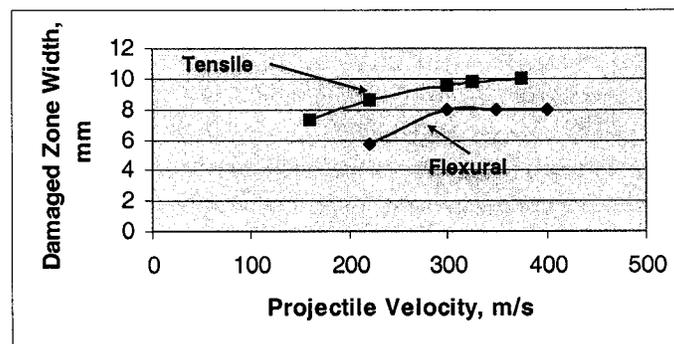


Figure 3. Variation of damaged zone width with projectile velocity for SiC/SiC composites tested at room temperature

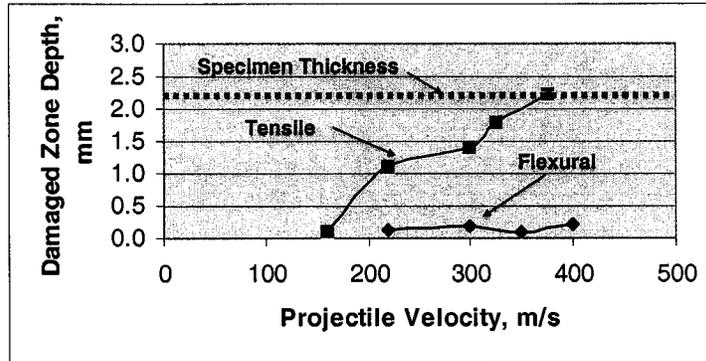


Figure 4. Variation of damaged zone depth with projectile velocity for SiC/SiC composites tested at room temperature.

Figure 3 shows the width of the impact damage zone as a function of projectile velocity for flexural and tensile specimens impact tested at room temperature. The width of damaged zone was measured by thermal wave imaging. The data indicated that as the projectile velocity increases, width of the damage zone increases initially and then reaches a plateau corresponding to the width of the specimen. This suggests that back side tensile stresses and edge effects cause delamination to start and propagate to the edge of the specimen beyond certain impact velocities. Delamination is probably caused by poor interlaminar tension between fiber plies and the SiC matrix.

Figure 4 shows the depth of the impact damage zone as a function of projectile velocity for SiC/SiC composite specimens impact tested at room temperature. The through-the-thickness damage was measured by CT. The dotted line in the figure indicates nominal thickness of the impacted specimens. For tensile specimens, as the projectile velocity increased, the depth of damage also increased. At projectile velocities  $> 300\text{m/s}$  the damage zone extends across the thickness of the specimen. In other words, the projectile perforated the specimen. On the other hand, flexural specimens showed considerably lower through-the-thickness damage with increasing projectile velocity. The reason for this behavior is not clearly understood. However CT images indicate increasing amount of delamination with increasing projectile velocity. Although not shown in this paper, the damaged zone depth was much greater for specimens tested at  $1316^{\circ}$  than at  $25^{\circ}\text{C}$ , possibly due to plasticity of the matrix at high temperature [10].

### Post-Impact Strength

Variation of room temperature ultimate flexural strength with increasing projectile velocity for the flexural specimens tested at room and  $1316^{\circ}\text{C}$  in air is shown in Fig. 5 Included in the figure for comparison are the ultimate flexural strength values for the as-received SiC/SiC composites. One specimen at each temperature impacted at the lowest velocity (i.e.,  $160\text{ m/s}$  at  $25^{\circ}\text{C}$  and  $115\text{ m/s}$  at  $1316^{\circ}\text{C}$ ) did not fracture at the impact site because of negligible impact damage, and its resulting strength was close to the as-received strength. As seen in the figure, post-impact strength decreased with increase in impact velocity at both temperatures which is attributed to increased impact damage. The impact damage resulted from both frontal contact and backside bending stresses, resulting in more significant strength degradation.

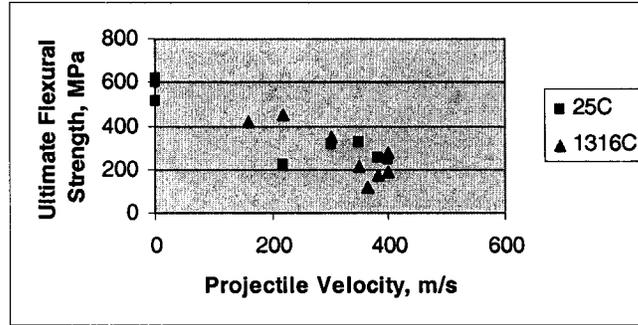


Figure 5. Variation of room temperature ultimate flexural strength with projectile velocity for SiC/SiC composites impact tested at room temperature and 1316<sup>0</sup>C in air.

Comparison of data indicates that loss in ultimate flexural strength for specimens tested at a given projectile velocity at 25 and 1316<sup>0</sup>C is nearly the same. However, the observed size of frontal damage zone at 1316<sup>0</sup>C was greater than that at 25<sup>0</sup>C [10]. This implies that the overall combined damage (fiber-matrix debonding, delamination, shearing of matrix, and matrix/fiber cracking etc.) that control strength would remain almost similar in severity at both temperatures.

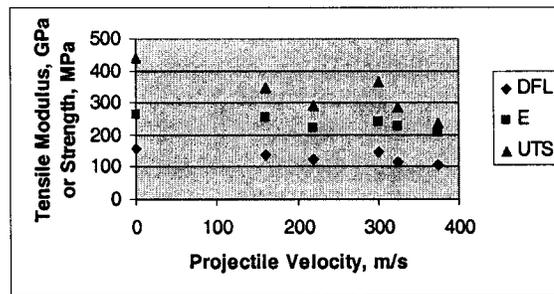


Figure 6. Variation of room temperature tensile properties with projectile velocity for SiC/SiC composites impact tested at room temperature in air.

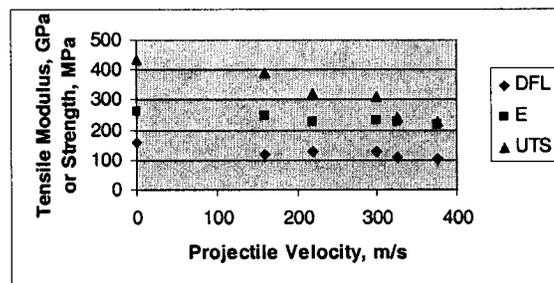


Figure 7. Variation of room temperature tensile properties with projectile velocity for SiC/SiC composites impact tested at 1316<sup>0</sup>C in air.

Figures 6 and 7 show room temperature tensile data for SiC/SiC composites impact tested at room temperature and 1316<sup>0</sup>C, respectively. In the figures, the symbols DFL, E, and UTS refer to stress corresponding to deviation from linearity, Young's modulus, and ultimate tensile strength, respectively. For comparison purposes included in both figures are DFL, E and UTS values for the as-produced SiC/SiC composites. It is clear from the figures that as the projectile

velocity increases, E and DFL decreases slowly compared to UTS. The fact that impacted specimens display UTS value greater than the DFL stress value suggests strain capability beyond matrix fracture.

## SUMMARY OF RESULTS

Uncoated 2-D woven SiC/SiC composites were impact tested at 25<sup>0</sup> and 1316<sup>0</sup>C in air at projectile velocities ranging from 110m/s to 400 m/s. Their residual strength properties were measured at room temperature. The extent of impact damage with projectile velocity was accessed by optical and NDE methods. Relevant findings are the following:

- (1) With increase in projectile velocity, the width and depth of the impact damaged zone increases.
- (2) Impact causes delamination, bucking, fiber fracture and shearing of matrix. Edge effects and poor interlaminar tensile strength are possible reasons for delamination.
- (3) Impact damage causes a decrease in DFL stress, Young's modulus, and ultimate strength of the composite. Even when the projectile pierced through the thickness, the composite displayed non-catastrophic failure, indicating strain tolerance beyond matrix fracture.

## REFERENCES

- <sup>1</sup>D. Brewer, *Mat. Sci. and Eng.*, **A261**, 284-291, (1999).
- <sup>2</sup>R.C. Robinson and J.L. Smialek, *J. Am. Ceram. Soc.*, 82 (7): 1817-1825, 1999.
- <sup>3</sup>E.J. Opila, J.A. Smilaek, R.C. Robinson, D.S. Fox, and N.S. Jacobson, *J. Am. Ceram. Soc.*, 82 (7): 1826-1834, 1999.
- <sup>4</sup>K.N. Lee, *Surface Coating Technology*, 133-134, 1-7, 2000.
- <sup>5</sup>K.N. Lee, D.S. Fox, J.I. Eldridge, D. Zhu, R.C. Robinson, N.P. Bansal, and R.A. Miller, *J. Am. Ceram. Soc.*, 86 (8): 1299-1306, 2003.
- <sup>6</sup>N. Miriyala, J. Kimmel, J. Price, K. More, P. Tortorelli, H. Eaton, G. Linsey, and E. Sun, "The Evaluation of CFCC Liners after Field Testing in a Gas Turbine-III," ASME paper # GT2002-30585, (2002).
- <sup>7</sup>S. K. Lau, S. J. Calandra, and R. W. Ohnsorg, US Pat. #5,840, 221, (1998).
- <sup>8</sup>S. R. Choi, J. M. Pereira, L. A. Janosik, and R. T. Bhatt, *Ceram. Eng. Sci. Proc.*, **23**[3] 193-202 (2002).
- <sup>9</sup>S. R. Choi, J. M. Pereira, L. A. Janosik, and R. T. Bhatt, "Foreign Object Damage Behavior of Two Gas-Turbine Grade Silicon Nitrides by Steel Ball Projectiles at Ambient Temperature," NASA/TM-2002-211821, National Aeronautics & Space Administration, Glenn Research Center, Cleveland, OH (2002).
- <sup>10</sup>R.T. Bhatt, S. R. Choi, L.M. Cosgriff, D. Fox, and K.N. Lee, "Damage Mechanism in Uncoated and EBC Coated SiC/SiC Composites Impact Tested at 25 and 1316<sup>0</sup>C in air" to be published.