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FRACTURE AND CREEP RUPTURE BEHAVIOR OF NOTCHED OXIDE/OXIDE AND SiC/SiC CMC

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ABSTRACT

Woven Oxide/Oxide and SiC/SiC ceramic matrix composites (CMC) are targeted for high-temperature aerospace applications such as combustors, combustor liners, exhaust washed structures, exhaust nozzle flaps and seals, and blade outer air seals. Some of these components contain stress concentration sites such as holes and attachment points. During service, these locations will be subjected to long-term exposures. Hence, the knowledge of the effect of sustained (creep) loading on the deformation and rupture of notched Oxide/Oxide and SiC/SiC composites is required for durability assessment. The results from creep tests of unnotched and notched Nextel™720/Alumina-Silica (Nextel™720/AS-0) and Melt Infiltrated (MI) HI-NICALON-Type-S/SiC (MI HI-NICALON-S/SiC) are discussed in this paper. Nextel™720/AS-0 was evaluated at 1100°C and MI HI-NICALON-S/SiC at 1200°C in laboratory air. In the case of large notches, i.e., notch length greater than the average tow size, the notch-sensitivity increased significantly under sustained loading for both composites. Nextel™720/AS-0 specimens with straight-through effusion holes (hole diameter = 0.5 mm) were also subjected to sustained loading at 100MPa/1100°C. In this case, the presence of effusion holes did not affect the overall creep response.

KEYWORDS

ceramic matrix composite, creep, effusion holes, fracture, notch-sensitivity, oxide/oxide, sic/sic, woven cmc

INTRODUCTION

Woven Oxide/Oxide and SiC/SiC ceramic matrix composites are being demonstrated for high-temperature aerospace applications with temperature requirements in the range of 1000-1300°C [1-4]. Current targeted aerospace turbine engine components, such as combustors, combustor liners, divergent flaps and seals, contain bolted attachment points and cooling holes. Local stresses in these regions often exceed the proportional limit of the composite, resulting in damage and crack initiation. Hence, component design using CMC will require knowledge of the notched fracture behavior and damage progression under service thermomechanical loading conditions. Most of the results on the notched behavior of Oxide/Oxide and MI SiC/SiC CMC correspond to monotonic tensile loading [5-14]. Recently, John et al. [8,9] and McNulty et al. [12] studied the effects of long-term loading on notched Oxide/Oxide at 1100°C and MI SiC/SiC at 815°C, respectively. Based on specimens with large notches (i.e., notch length greater than tow size), these studies [8,9,12] reported an increase in notch-sensitivity when exposed to temperature for 100+ hours.

Components such as combustors are designed to contain effusion holes, which are used to lay down a film of cooling air on the hot wall to create a boundary layer effect and to cool the component by providing more internal surface area. The effusion holes are typically of the order of 0.50 mm diameter, which is approximately half the average fiber tow size. This paper summarizes the results of a recent study [10] on the creep behavior of Oxide/Oxide at 1100°C. The results are compared to the creep behavior of specimens with large notches. In addition, the creep behavior of notched MI SiC/SiC at 1200°C is also discussed.

MATERIAL AND EXPERIMENTAL PROCEDURE

The Oxide/Oxide CMC used in this study was Nextel™720/AS-0, which was manufactured by COI Ceramics, Inc., San Diego, CA. Figure 1(a) shows the microstructure of Nextel™720/AS-0. The matrix consists of a porous alumina-silica (AS) that is weakly bonded to the fibers without an engineered interphase. Approximately 400 Nextel™720 fibers were bundled together in tows and woven into a balanced eight-harness-satin weave (8HSW) cloth. The fiber mat had a (0/90) layup with final CMC volume fraction ≈ 0.46.

The SiC/SiC CMC used in this study was HI-NICALON-S/SiC, which was manufactured by Honeywell Advanced Composites, Inc, Newark, DE. Figure 1(b) shows the microstructure of MI HI-NICALON-S/SiC. The matrix is described as Melt-Infiltrated (MI) SiC. The HI-NICALON-Type-S (HI-NICALON-S) fibers were bundled together in tows and woven into a balanced five-harness-satin weave (5HSW) cloth. The fiber mat had a (0/90) layup with final CMC volume fraction ≈ 0.33.

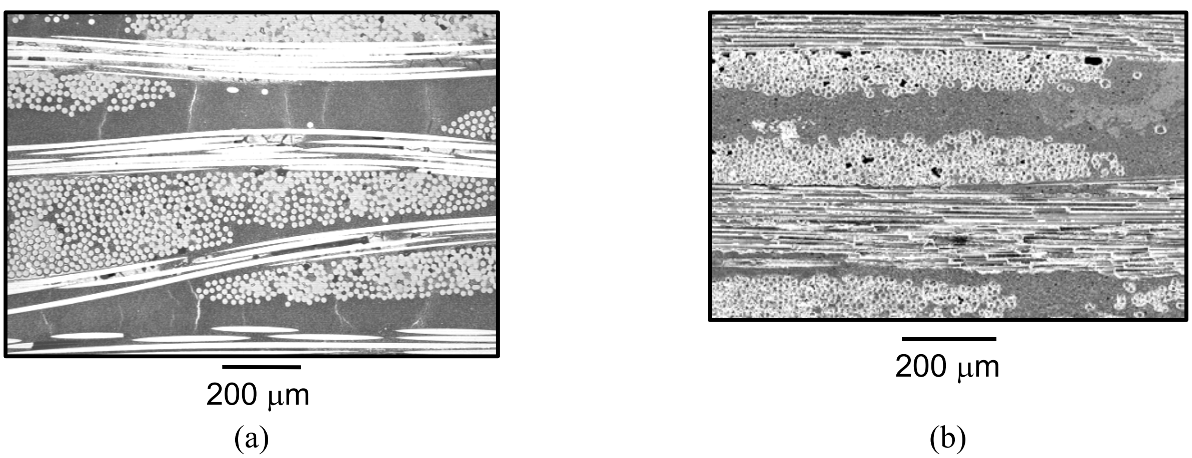
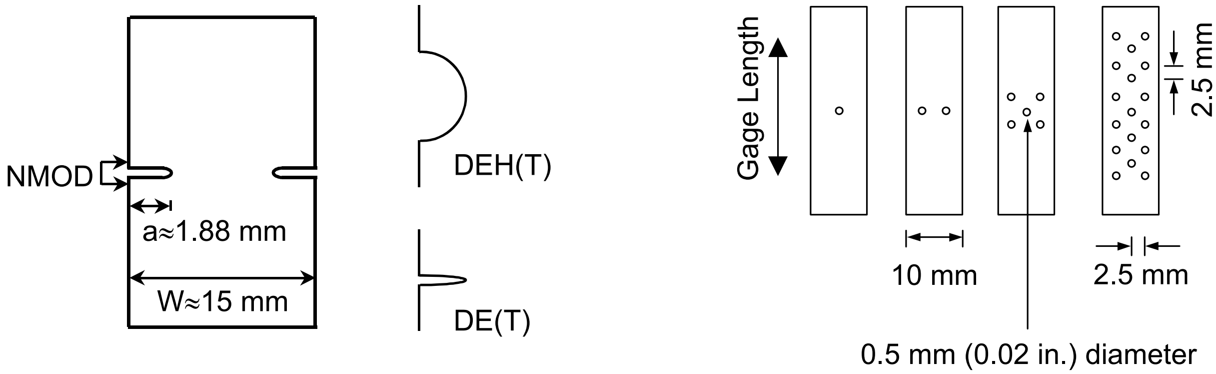


Figure 1: Microstructure of (a) Nextel720/AS-0 and (b) Melt Infiltrated HI-NICALON-S/SiC.

During this study, baseline tensile tests were conducted using dogbone specimens. For the conventional notch sensitivity tests, straight-sided specimens with large notches (notch length greater than the average tow size) were used. Semi-circular notches, DEH(T) and sharp notches, DE(T) were used during this study, Figure 2(a). The semi-circular and sharp notches were machined using a drill and a thin diamond saw (≈ 0.1 mm thick), respectively. In all these tests, the notch mouth opening displacement (NMOD) was measured. Figure 2(b) shows the effusion hole patterns used for this study. The nominal dimensions of the specimens were, width (W) = 10.0 mm in gage section, thickness (B) ≈ 2.5 mm and gage length ≈ 12.5 mm. All effusion holes were 0.5 mm in diameter with the hole axis perpendicular to the loading axis. The hole density studied in this investigation was ≈ 8 holes/cm^2 (≈ 50 holes/in^2).

The specimens were measured and photographed to document the condition of the holes prior to testing. The specimen ends were tabbed with fiberglass tabs to provide a flat uniform surface for the smooth grip surfaces and to minimize the possibility of grip failure. The specimens were mounted in a precisely aligned, rigid grip system that minimized specimen bending and rotation. A clamshell furnace with SiC heating elements and four-zone control were used for the elevated temperature creep tests. Thermal profile maps on the specimen showed that the specimen was uniformly heated, ± 0.6%, over the entire gage section of the specimen. All creep tests were loaded to the maximum stress at a loading rate of 20 MPa/s.



(a) CMC: Nextel™720/AS-0 & MI HI-NICALON-S/SiC (b) CMC: Nextel™720/AS-0

Figure 2: Schematic of (a) double edge notched, and (b) effusion hole specimens.

RESULTS AND DISCUSSION

The unnotched tensile behaviors of Nextel™720/AS-0 and MI HI-NICALON-S/SiC are shown in Figures 3(a) and 3(b), respectively. Nextel™720/AS-0 exhibits nearly linear behavior until failure at 23 and 1100°C with insignificant temperature dependence. The proportional limit (PL), defined as deviation from initial linear response, for Nextel™720/AS-0 was ≈ 75 and 80 MPa at 23°C and 1100°C, respectively. In contrast, MI HI-NICALON-S/SiC exhibits bi-linear response at 23°C and 1200°C with significantly higher ultimate tensile strength (UTS) than that of Nextel™720/AS-0. The PL for MI HI-NICALON-S/SiC was ≈ 145 and 150 MPa at 23°C and 1200°C, respectively.

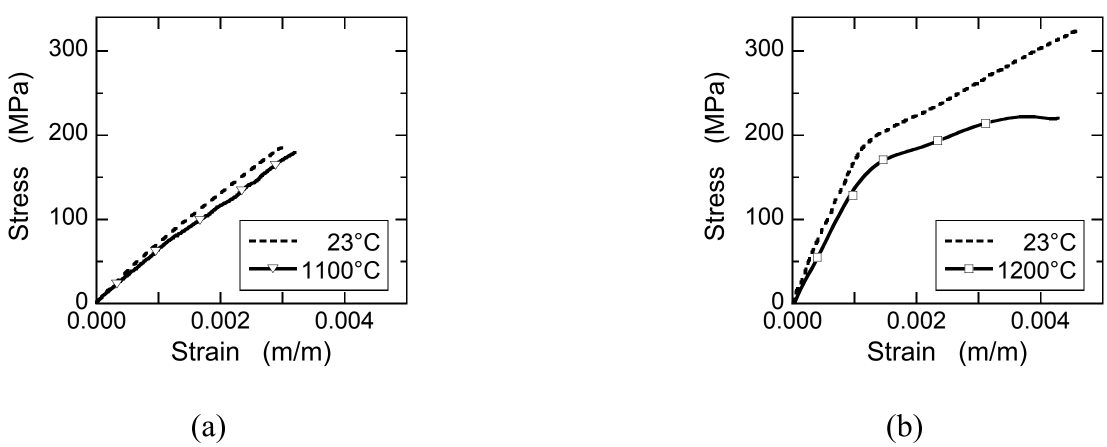


Figure 3: Tensile behavior of (a) Nextel™720/AS-0 and (b) Melt Infiltrated HI-NICALON-S/SiC.

The net-section strength normalized with respect to the corresponding unnotched UTS versus notch length is plotted in Figures 4(a) and 4(b) for Oxide/Oxide and MI SiC/SiC systems, respectively. At room temperature, Nextel™720/AS-0 [This study, 11] is notch-insensitive while Nextel™610/MA [5] is notchsensitive. At 1100°C, Nextel™720/AS-0 exhibits mild notch-sensitivity (≈15%) at notch length (2a) ≈ 4.5 mm. At room temperature, MI HI-NICALON-S/SiC from this study exhibits slight notch-sensitivity, similar to that reported by McNulty et al. [12,13] and Morscher et al. [14] for other SiC/SiC composites. At 815°C, MI Sylramic/SiC exhibited notch-sensitivity similar to that at room temperature [12]. In contrast, MI HI-NICALON-S/SiC was notch-insensitive at 1200°C.

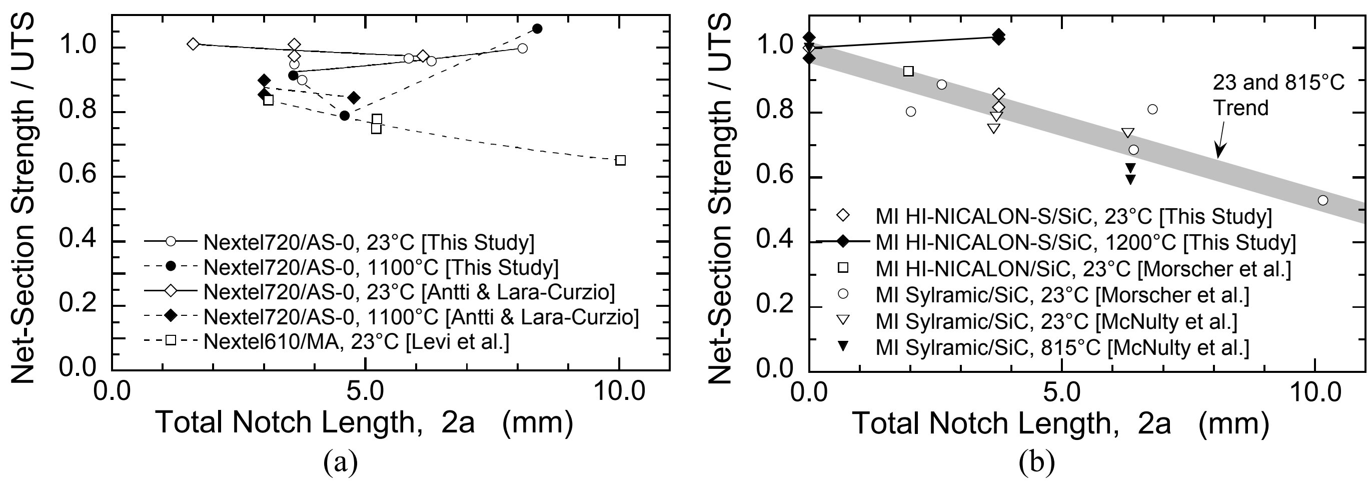


Figure 4: Notch sensitivity of (a) Nextel™720/AS-0 and (b) MI HI-NICALON-S/SiC under tensile loading.

The notched strength data shown in Figure 4 for Oxide/Oxide and MI SiC/SiC systems correspond to short-duration tensile tests. During service, the CMC components will be subjected to long-term thermomechanical loading. Hence, durability assessment of such long-life components require knowledge of the notched behavior under long-duration test conditions. Sustained loading (creep) tests were conducted on unnotched and notched Nextel™720/AS-0 and MI HI-NICALON-S/SiC specimens at 1100°C and 1200°C, respectively, Figure 5.

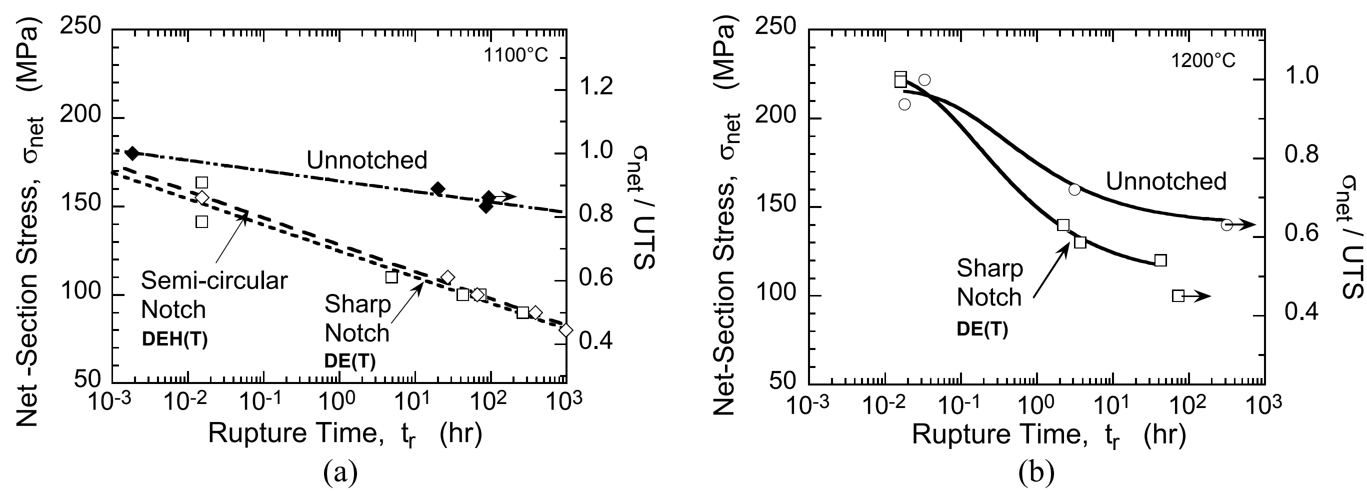


Figure 5: Notch effects on creep rupture behavior of (a) Nextel™720/AS-0 and (b) MI HI-NICALON-S/SiC.

The unnotched Nextel™720/AS-0 shows excellent creep strength of ≈ 150 MPa which is ≈80% of UTS and well above the PL≈80 MPa. Unnotched MI HI-NICALON-S/SiC also shows similar creep strength (≈150 MPa) which is close to the PL. Hence, the maximum design stress for long-life components (with no notches) is similar for both Nextel™720/AS-0 and MI HI-NICALON-S/SiC. When large notches (notch length ≈ 2 mm) are introduced, the net-section stress that can be sustained by the composite at 100+ hours decreases significantly. For Nextel™720/AS-0, the notch strength decreased to ≈ 85 MPa, which is close to the unnotched proportional limit. This decrease is independent of the type of notch. For MI HI-NICALON-S/SiC, the notch strength decreased to 110 MPa, which is ≈ 73% of PL. These results are summarized in Table 1. Also shown in Table 1 are the 815°C results from McNulty et al. [12] based on low-cycle fatigue tests with a 2 hour dwell time. At 815°C, the reduction in notch strength is greater than that observed at 1200°C. These results show that design of long-life components with stress concentration sites should be based on careful detailed durability assessment studies with sub-elements simulating the actual features.

TABLE 1
CREEP STRENGTH OF NEXTEL™720/AS-0 AND MI HI-NICALON-S/SiC

Creep Strength at rupture time = 100+ hr [This study]			LCF Threshold [McNulty et al.]
Geometry	Nextel™720/AS-0 at 1100°C	MI HI-NICALON-S/SiC at 1200°C	MI Sylramic/SiC at 815°C
Unnotched	≈ 150 MPa	≈ 150 MPa	165 MPa
Notched	≈ 85 MPa	≈ 110 MPa	60-85 MPa

Since the large notch specimens exhibited significantly increased notch-sensitivity under sustained loading in contrast to the short-duration tensile loading, a program was initiated to evaluate the performance of specimens with effusion holes under creep loading. The creep behavior of Nextel™720/AS-0 with effusion holes (8 holes/cm^2) is shown in Figure 6. The overall creep deformation is similar to that of the unnotched specimen. Following the creep tests, retained strength tests were conducted at room temperature and compared with the unnotched tensile behavior in Figure 7. The stress-strain response of specimens with effusion holes is identical to that of unnotched material. The decrease in UTS is similar to that observed for unnotched specimens. Hence, under creep loading conditions, Nextel™720/AS-0 with effusion holes @ 8 holes/cm^2 could be expected to respond similar to the unnotched composite. Additional tests are in progress to understand the effect of higher stress levels on the creep behavior of specimens with effusion holes and the relationship between hole size and notch-sensitivity.

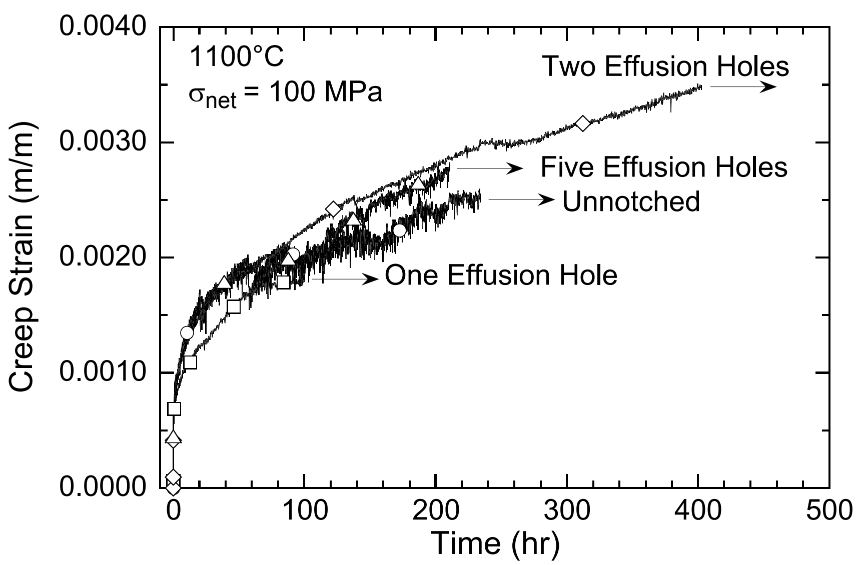
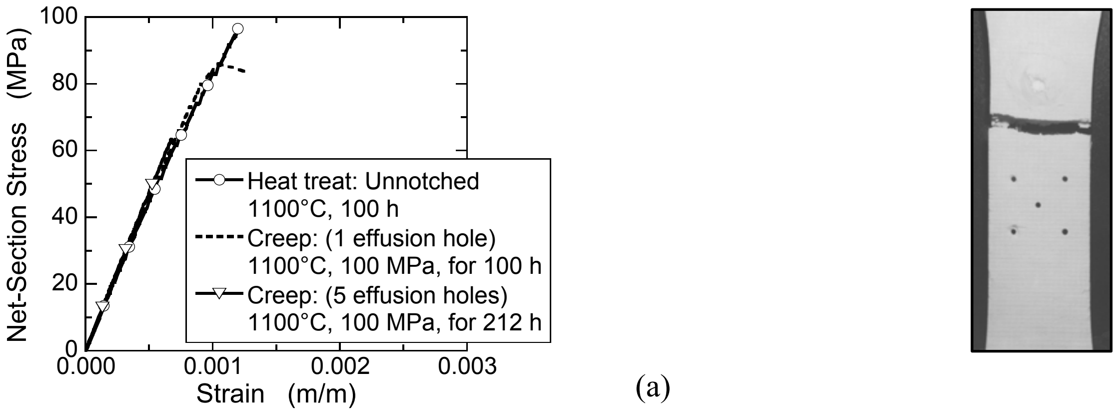


Figure 6: Creep deformation of Nextel™720/AS-0 specimens with effusion holes.



(a) (b)

Figure 7: (a) Retained strength (@23°C) of creep-tested Nextel™720/AS-0 specimens with effusion holes. (b) Fracture profile of effusion hole specimen after retained strength test.

CONCLUSIONS

Notch-sensitivity of woven Nextel™720/AS-0 and MI HI-NICALON-S/SiC with (0/90) layup increases significantly under sustained (creep) loading conditions. The creep strength (in terms of net-section stress) decreases ≈ 40% and 27% for Nextel™720/AS-0 and MI HI-NICALON-S/SiC, respectively. The creep behavior of Nextel™720/AS-0 with effusion holes (8 holes/cm^2) was similar to that of the unnotched composite.

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REFERENCES

[1] IHPTET Brochure, Turbine Engine Division, Propulsion Directorate (AFRL/PRT), Air Force Research Laboratory, Wright-Patterson Air Force Base, OH, USA.
[2] Brewer D. (1999) *Materials Science and Engineering A* 261, 284.
[3] Ohnabe, H., Masaki, S., Onozuka, M., Miyahara, K., and Sasa, T. (1999) *Composites: Part A* 30, 489.
[4] Zawada, L.P. and Lee, S.S. (1995) *Ceramic Engineering and Science Proceedings* 16, 337.
[5] Levi, C.G., Yang, J.Y., Dalgleish, B.J., Zok, F.W. and Evans, A.G. (1998) *Journal of the American Ceramic Society*, 81, 2077.
[6] Heathcote, J.A., Gong, X.-Y, Yang, J., Ramamurty, U., and Zok, F.W. (1999) *Journal of the American Ceramic Society*, 82, 2721.
[7] Kramb, V.A., John, R., and Zawada, L.P. (1999) *Journal of the American Ceramic Society* 82, 3087.
[8] John, R., Buchanan, D.J., and Zawada, L.P. (2000) *Ceramic Eng. and Science Proceedings* 21, 567.
[9] John, R., Buchanan, D.J. and Zawada, L.P. (2000) *STP 1392 ASTM* 172.
[10] Buchanan, D.J., Kramb, V.A., John, R., and Zawada, L.P. (2001) *Ceramic Engineering and Science Proceedings* Accepted.
[11] Antti, M-L. and Lara-Curzio, E. (2001) *Ceramic Engineering and Science Proceedings* Accepted.
[12] McNulty, J.C., He, M.Y., Zok, F.W. (2001) *Composites Science and Technology* Accepted.
[13] McNulty, J.C., Zok, F.W., Genin, G.M., and Evans, A.G., (1999) *J. of the Am. Cer. Soc.* 82, 1217.
[14] Morscher, G., Gyekenyesi, J.Z., and Gyekenyesi, A.L., (2001) *Proceedings of 46th ASME IGTI.*