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Characterization of Ceramic Matrix Composite Fasteners Exposed in a Combustor Liner Rig Test

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ABSTRACT
Combustion tests on SiC/SiC CMC components were performed in an aircraft combustion environment using the Rich-burn, Quick-quench, Lean-burn (RQL) sector rig. SiC/SiC fasteners were used to attach several of these components to the metallic rig structure. The effect of combustion exposure on the fastener material was characterized via microstructural examination. Fasteners were also destructively tested, after combustion exposure, and the failure loads of fasteners exposed in the sector rig were compared to those of as-manufactured fasteners. Combustion exposure reduced the fastener failure load by 50% relative to the as-manufactured fasteners for exposure times ranging from 50 to 260 hours. The fasteners exposed in the combustion environment demonstrated failure loads that varied with failure mode. Fasteners that had the highest average failure load, failed in the same manner as the unexposed fasteners.

INTRODUCTION
A major focus of NASA's Enabling Propulsion Materials (EPM) program was development of an advanced ceramic matrix composites (CMC's) for turbine engine combustor liners. CMC's offer great potential to improve turbine engine performance by reducing cooling requirements and NOx emissions by operating at higher temperatures than materials used for hot structures, such as Ni-base superalloys. A melt-infiltrated SiC fiber reinforced SiC matrix material (MI SiC/SiC) was the result of the collaborative efforts of NASA, General Electric, and Pratt & Whitney under the EPM program [1].

Concurrent with EPM material development activities, a combustion rig was designed to test MI SiC/SiC components. The Rich-burn, Quick-quench, Lean-burn (RQL) sector rig was designed and fabricated to demonstrate the structural durability of the SiC/SiC liners in a combustion environment where stresses, temperatures, and pressures would accurately reflect the operating conditions found in a turbine engine [2,3].

The design of the RQL sector rig includes several different MI SiC/SiC component geometries for the combustor liner set, employing three different configurations to attach the CMC's to the metallic back structure. Attachments and fasteners are critical design features, requiring detailed attention and understanding for the successful insertion of CMC components into gas turbine engines.

In this paper, characterization of one fastener concept used in the sector rig, the Miller fastener [4], is discussed. The effect of combustion exposure on the fastener material was characterized via microstructural examination. Properties of fasteners exposed to a combustion environment for up to 260 hours during operation of the RQL sector rig were obtained through destructive testing and are compared to those of as-manufactured fasteners.

MATERIAL
Fasteners were machined from eight-ply MI SiC/SiC composite panels, manufactured by Honeywell Advanced Composites. The panels consisted of a slurry-cast, melt-infiltrated SiC matrix, reinforced with Sylramic™ SiC fibers in a $[0/90]_s$ lay up. The fiber tows were woven into 5-harness satin weave cloth. Fiber tow spacings of 18 and 22 ends per inch were utilized to manufacture the panels, resulting in a nominal fiber volume fraction of 35 and 42%, respectively. More details on the material can be found in reference 1.

FASTENER CONFIGURATION
The Miller fastener was developed to attach nozzle and combustor structural CMC components in an aircraft gas turbine engine [4]. The configuration used

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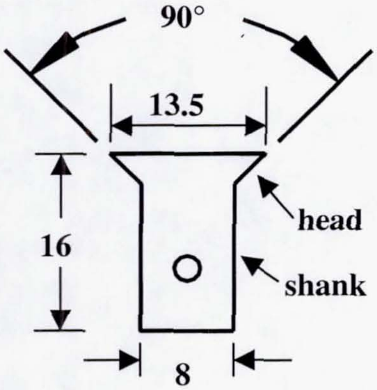


Figure 1 – Schematic of SiC/SiC fasteners. Dimensions are in mm.

for the MI SiC/SiC combustor liners is shown in Fig. 1. A schematic of the combustor liner attachment system is shown in Fig. 2. The combustor liners are reinforced with additional plies in the region of the fastener hole. The Miller fastener assembly consists of a metallic threaded clevis that supports a pin through the CMC shank. A Belleville washer provides

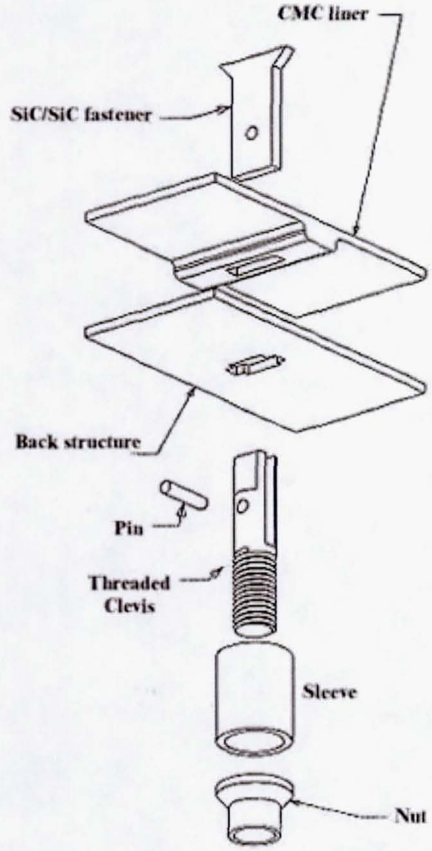


Figure 2 – Combustor liner fastener assembly.

compliance between the back structure and the threaded clevis. The assembly is completed with metallic nut to draw the CMC liner to the back structure. Three-dimensional finite element analyses were used to develop the fastener design [4]. Benchmark mechanical tests were conducted to minimize design angle, hole diameter and distance of the hole to the end of the fastener.

COMBUSTION EXPOSURE

The RQL sector rig was designed by Pratt & Whitney under the HSR program and was installed at NASA Glenn in 1998. The rig contains two rich zone liner cans transitioning to a 60° sector lean burn zone. Figure 3 is a schematic of the rig, along with images of the individual components. A full liner set consists of 28 liners of 6 different part geometries. Testing was conducted using a cycle designed to approximate the pressures, temperatures, and flow rates of an aircraft turbine engine combustor [5].

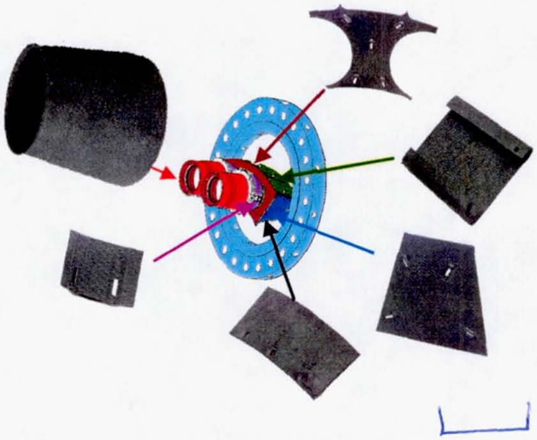


Figure 3 – Configuration of the Rich -burn, Quick-quench, Lean-burn (RQL) SiC/SiC sector rig.

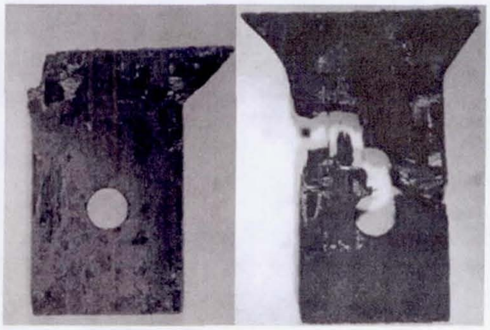
scale would be helpful to the reader!

Several liners were removed from the sector rig after 115 hours to conduct post-exposure analyses [3]. The rig was reassembled and 145 hours of additional testing was conducted. In addition, a few liners were removed during rig operation when periodic inspections revealed potential damage. After completion of 260 hours of operation, the rig was disassembled and all MI SiC/SiC combustor liners were removed.

The liner set included Miller fasteners that held 17 of the 28 components in the rig. As a result of the events described above, the liner set available for analyses included fasteners exposed for 53, 115, 145, 207, and 260 hours.

POST-EXPOSURE EXAMINATION

All fasteners were visually inspected to document their post-exposure condition. Damage in the head of the fastener was observed for about 60% of the fasteners removed intact. An extreme example of the observed damage mode is shown in Fig. 4a. This particular fastener could not be subjected to post-exposure destructive testing, but the majority of fasteners with cracks and chipping in the "ears" such as this had less severe damage and thus could be tested. Other fasteners failed in the shank region (Fig. 4b). Damage in the shank was most often observed when difficulties were encountered while removing the metallic nut from the threaded clevis (Fig. 2). About 25 % of the total fastener set was not suitable for destructive testing because of either severe "ear" damage such as in Fig. 4a or failure while attempting to remove them from the rig.



a. b.

Figure 4 – Damage of fasteners after removal from the sector rig.

Several fasteners were mounted for microscopic examination. The fasteners were held under vacuum to enable pores and cavities to out-gas. The metallurgical samples were then submerged in epoxy. The specimens were then placed in a pressure chamber and held at 10 MPa in a nitrogen environment to force epoxy into the pores and damage locations. After curing, the fasteners were then sectioned and lapped in preparation for final polishing, prior to examination.

A comparison of the microstructures of an as-manufactured fastener and one that was exposed in the combustion environment for 145 hours is shown in Fig. 5. The longitudinal, through-thickness cross sections reveal porosity in both fasteners. The large pore, in the as-manufactured fastener, exists in the head region. The most notable feature can be seen in the head of the exposed fastener in the form of fiber and composite damage. The dark regions indicate locations where fibers tows are missing due to preferential attack of the Sylramic fibers. This attack is due to the reaction of the boron nitride fiber interface with water vapor, present in the combustion gases [6]. Recession of SiC in a combustion environment can also occur due to SiO_2 scale volatility [7].

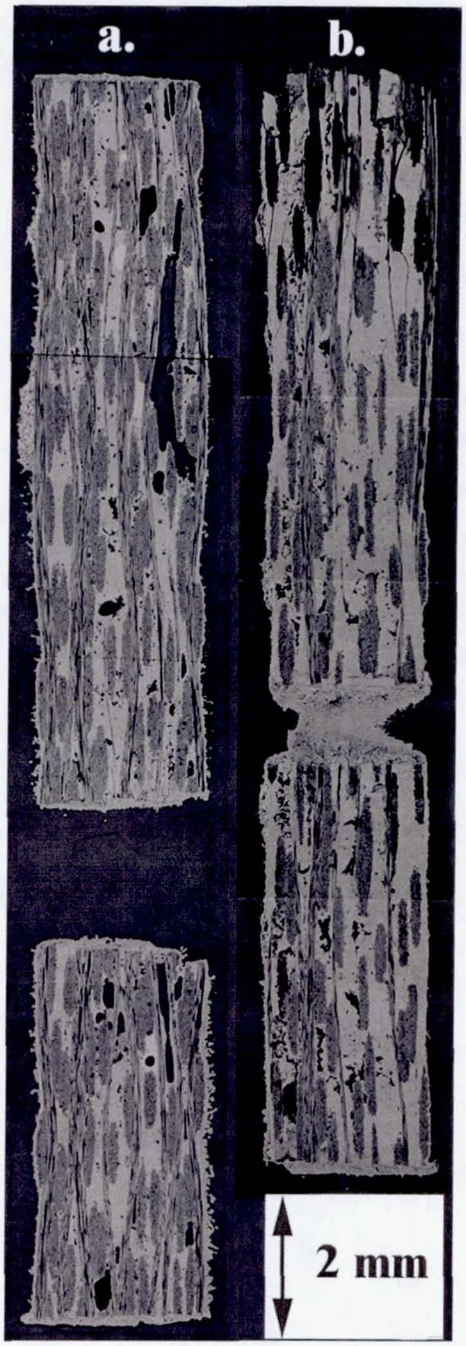


Figure 5 – Cross-sections of SiC/SiC fasteners, a) as-manufactured, b) exposed for 145 hours.

MECHANICAL TESTING OF FASTENERS

As-manufactured and exposed fasteners were destructively tested at room temperature to measure their failure loads using a servo-hydraulic test machine. A fixture was machined from a superalloy with the same fastener hole geometry of the CMC combustor liners (Fig. 6). A clevis and pin, machined for fastener attachment in sector rig, were used to connect the fasteners to a pull rod. Both ends of the fixture were gripped using the wedge grips of the test machine. Fasteners were tensile tested to failure under load control at a rate of 20 N/sec.

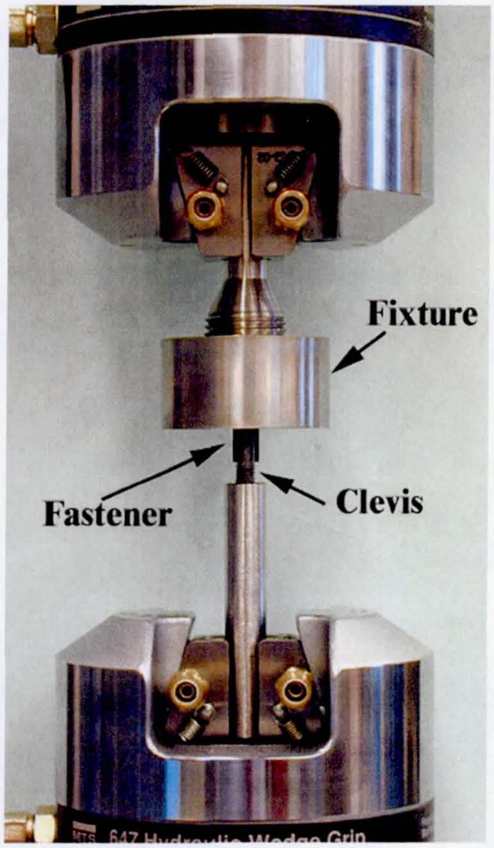


Figure 6 – Configuration for tensile testing of SiC/SiC fasteners.

DISCUSSION

The tensile failure mode observed for all the as-manufactured Miller fasteners is shown in Fig 7a. Approximately 17% of the combustion-exposed fasteners failed in the same manner, which is the desired failure mode [4]. Failure of the fastener through shear failure of the "ears" of the head occurred in 70% of the exposed fasteners (Fig. 7b) and was associated with observed "ear" damage documented prior to destructive testing. The failure mode of the rest of the exposed fasteners was associated with pre-existing cracks, such as seen in Fig. 7c.

The average failure load for the Miller fasteners as a function of failure mode is shown in Fig. 8. The as-manufactured fasteners failed at an average load of about 1900 N, while combustor-exposed fasteners that failed in the same mode had a 25% lower failure load. Failure of the fastener through "ear" shear failure yielded a failure load of 900 N. Those fasteners that failed due to pre-existing cracks had the lowest average failure load, 550 N.

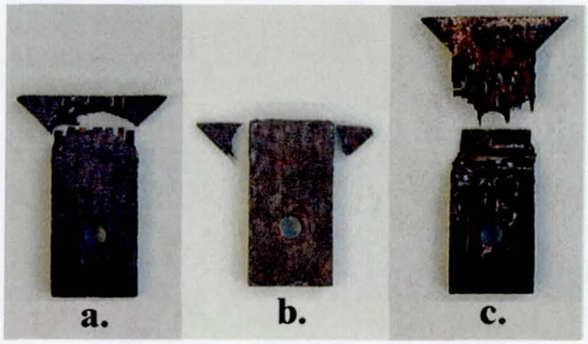


Figure 7 – Failure modes of tensile-tested SiC/SiC fasteners, a) as-manufactured material, b) "ear shear failure of exposed material, c) failure associated with pre-existing cracks.

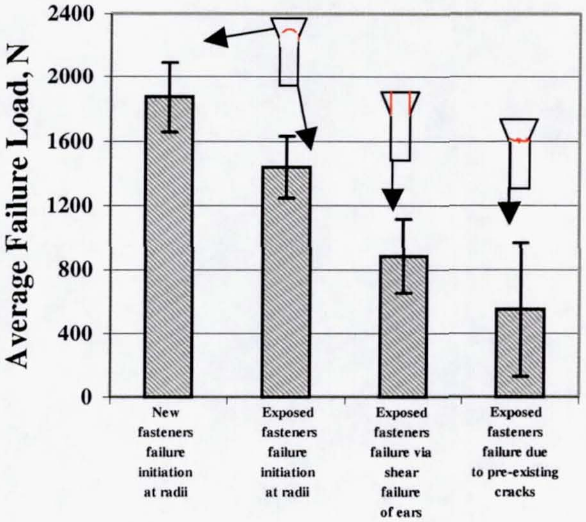
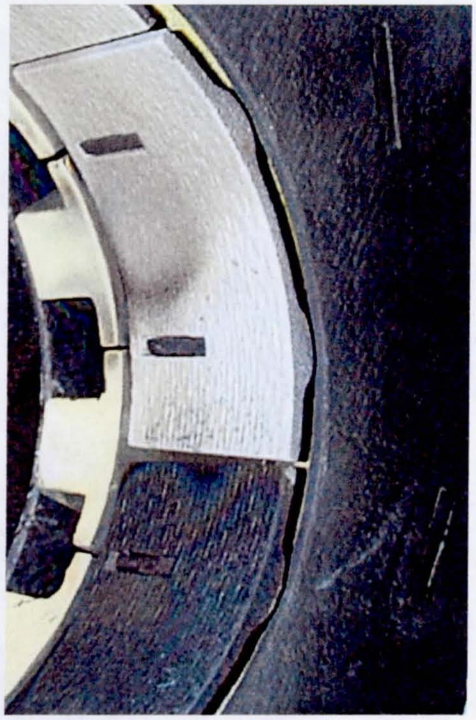


Figure 8 – Failure mode versus failure load for SiC/SiC fasteners tensile tested at 25 °C.

The effect of exposure time can be seen by examining data for fasteners that attached one combustor liner part, the lean transition liner (LTL). The RQL sector rig liner set consisted of twelve LTL's, each held in place with two Miller fasteners, Fig. 9. The exposure temperatures of the different liner parts in the sector rig varied. In addition, combustion gas chemistry and flow rate varied in different regions of the rig. Examination of fastener data for only one part can eliminate potential failure load differences due to varying exposure conditions. During the course of the 260 hours of rig operation, several of the LTL's and their fasteners were removed for reasons described earlier, resulting in the largest number of fasteners exposed for different times from a single part type. To eliminate the effect of failure mode on failure load, only data for LTL fasteners that failed via shear of the "ears" is shown as a function of exposure time in Fig. 10. Data for the as-manufactured fasteners is shown as well. Exposure of 50 hours reduced failure loads by

50% relative to the as-manufactured fasteners. The average fastener failure load of about 900 N was the same for all exposure times, up to the maximum of 260 hours. Note that during sector testing, LTL fasteners reached a maximum temperature of about 1200 °C at the head surface subjected to combustion flow.

a.



b.

Figure 9 – Lean Transition Liners, a) as-manufactured part, b) installed in the sector rig.

Comparing data for as-manufactured and for exposed fasteners that failed in the same manner as unexposed ones, an assessment of the material degradation due to combustion exposure can be made. A 25% reduction in failure load was measured for fasteners after 50 hours of exposure (Fig. 8). Additional damage as described above was likely responsible for the switch

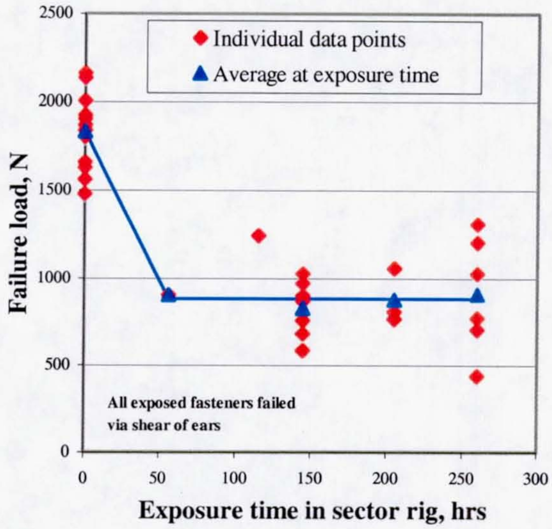


Figure 10 – Lean Transition Liner fastener failure loads after exposure in the sector rig.

of failure mode and further reduction of average strength for exposed fasteners.

SUMMARY AND CONCLUSIONS

Damage observed in fasteners removed from the sector rig was due to several factors. Loads imposed during fastener installation and/or removal likely caused some cracking. Rig mechanics had no prior experience with CMC hardware and may have accidentally induced damage during liner installation. Also as stated earlier, difficulties were sometimes encountered while removing the metallic nut from the threaded clevis, resulting in overloading of CMC fasteners. Material recession due to the combustion environment exposure also occurred (Fig. 5). A combination of installation damage and water vapor reaction may have resulted in damage that manifests itself as fasteners with low post-exposure failure loads. Reduction of the tensile loads imposed by the metallic clevis and nut during combustor testing likely resulted loosening of some of the Miller fasteners. Damage in the "ears" of the head due to relaxation of the nut torque was observed in fasteners after hot acoustic testing of CMC nozzle liners [8]. Despite the observed cracking and material recession, the Miller fasteners displayed the desired damage tolerance of a CMC component while operating in a harsh environment.

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