

Nondestructive Evaluation of Ceramic Matrix Composite Combustor Components

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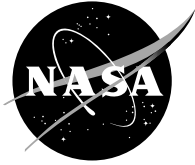
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Prepared for the
29th Annual Review of Progress in Quantitative Nondestructive Evaluation (QNDE)
sponsored by the Quantitative Nondestructive Evaluation Programs
Bellingham, Washington, July 14–19, 2002

National Aeronautics and
Space Administration

Glenn Research Center

Acknowledgments

This work was supported by the NASA Ultra-Efficient Technology Program and NASA contract NAS3-26385.

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Summary

Combustor liners fabricated from a SiC/SiC composite (silicon carbide fibers in a silicon carbide matrix) were nondestructively interrogated before and after combustion rig testing by x-ray, ultrasonic, and thermographic techniques. In addition, mechanical test results were obtained from witness coupons, representing the as-manufactured liners, and from coupons machined from the components after combustion exposure. Thermography indications correlated with reduced material properties obtained after rig testing. The thermography indications in the SiC/SiC liners were delaminations and damaged fiber tows, as determined through microstructural examinations.

Introduction

The pursuit of lower emissions and higher performance from gas turbine engines requires the development of innovative concepts, such as the use of advanced materials for key engine components. One such engine component is the combustor, where liners fabricated from a ceramic matrix composite, silicon carbide fibers in a silicon carbide matrix (SiC/SiC), are under evaluation. SiC/SiC composite technology has progressed from the fabrication of simple coupons to subelements and presently to actual components (refs. 1 to 4). This last area posed a significant challenge to nondestructive evaluation (NDE) techniques because of the complex geometries involved.

To evaluate SiC/SiC components in a combustion environment, the rich-burn, quick-quench, lean-burn (RQL) sector rig was designed and fabricated. The purpose of the sector rig testing was to demonstrate the structural durability of the SiC/SiC liners in a combustion environment where stresses,

temperatures, and pressures would as accurately as possible reflect the operating conditions found in a turbine engine.

X-ray, ultrasonic, and thermographic techniques were used to inspect the as-manufactured SiC/SiC components and the liners after combustion testing. The purpose of this study was to characterize the postexposure condition of one SiC/SiC combustor liner part through NDE evaluation via thermography and mechanical property measurement.

Experimental

Material and Component

Combustor liners were manufactured by Honeywell Advanced Composites from a SiC/SiC composite developed under the NASA Enabling Propulsion Materials program. A chemical-vapor-infiltrated, slurry-cast, and melt-infiltrated SiC matrix was reinforced with Sylramic SiC fibers. The fiber tows were woven into 5-harness satin weave cloth. More details on the SiC/SiC material can be found in reference 5.

The sector rig liner set consisted of 6 component geometries and a total of 28 liners (fig. 1). For this study, one of the six components, the lean-zone inside-diameter liner (LZID) was examined. The LZIDs are curved plates, each covering about a 30° arc of the total 60° sector, as shown in figure 1. A twelve-ply-thick leading edge reinforces the attachment hole region. The rest of the LZID is six plies thick. LZIDs containing 34- and 40-percent fiber volume were tested.

Flexure coupons were machined from the as-manufactured and exposed sector parts to obtain mechanical properties. The as-manufactured parts were supplied with extra material that was machined into test coupons. The exposed parts were machined to obtain test coupons of the same geometry as that used for the witness testing. Three-point flexure testing was conducted at 815 °C. Reference 6 gives more details on the mechanical test procedures.

Combustion Testing

The Preheated Combustor and Materials Test Facility (PCMTF) at NASA Glenn Research Center was used to conduct the RQL sector rig testing. Air temperature (T3), pressure (P3), and flow rate (W3) were varied to approximate the anticipated service cycle of the High Speed Civil Transport (HSCT) engine combustor (ref. 7). All aspects of an HSCT flight operation, such as takeoff, climb, cruise, and decent, are included in the 230-min test cycle.

The combustion testing was periodically interrupted to remove some of the SiC/SiC liners for postexposure analysis. After 260 hr of operation, the rig was disassembled and all SiC/SiC combustor liners were removed.

NDE Techniques

As-manufactured and combustion-exposed SiC/SiC components were inspected using x-ray film radiographic, ultrasonic, and thermographic techniques. Radiography is sensitive to volumetric features, such as large voids and gross porosity or thickness variations, but cannot detect planar (laminar) features, such as delaminations in ceramic matrix composites. Ultrasonic techniques have a high sensitivity for the detection of delaminations, but a quantitative interpretation of the data is difficult as they are affected by many experimental setup parameters. Thermography techniques are also very sensitive to delaminations and when used in a through-transmission setup to determine thermal diffusivity, which is a material

property, the data can be quantitatively analyzed to relate with the detailed structures of defects (ref. 8). In this study, only the thermography results will be discussed.

A transient through-transmission (through-thickness) thermography method was used on the tested liners. Two high-energy flash lamps generate a heat pulse that travels through the thickness of the parts (fig. 2). The raw data consist of multiple-layered images acquired at 120 Hz. A total of 40 frames was typically suitable to capture the temperature rise. The analysis technique was based on that given by Parker (ref. 9). The front surface temperature rise is given by

$$T(L, t) = \frac{Q}{\rho CL} \left[1 + 2 \sum_{n=1}^{\infty} (-1)^n \exp \left(-\frac{n^2 \pi^2}{L^2} \alpha t \right) \right] \quad (1)$$

where T is the temperature, L is the liner thickness, t is the time elapsed, Q is the amount of heat absorbed by the liner from the flash lamps, α is the thermal diffusivity, ρ is the material density, and C is the specific heat of the material. Using the time to reach half the maximum detected temperature ($t_{1/2}$), the thermal diffusivity at each pixel can be calculated by

$$\alpha = \frac{1.37 L^2}{\pi^2 t_{1/2}} \quad (2)$$

At regions of planar defects, such as delaminations, the material surface temperature is lower than that of the undamaged composite and will take a longer $t_{1/2}$ to reach the equilibrium part temperature (note that the part will eventually reach an equilibrium constant temperature if sufficient time is given). Therefore, from equation (2), the regions with damaged material will have lower thermal diffusivities.

The thermal diffusivity calculated from equation (2) is proportional to the thickness squared. Because it is impossible to provide thickness values for all pixels of an imaged part, it is common to use a representative thickness (typically the averaged thickness) for the calculation of the diffusivity image for the entire part. This method has some shortcomings when thickness variation is large. For example, in the case of a uniform material of constant diffusivity, equation (2) dictates that for a pixel with a thickness twice that of a second pixel, the half-rise time $t_{1/2}$ at the first pixel will be four times longer than that of the second. However, if we choose to use the thickness of the second pixel for calculating diffusivities at all pixels, the calculated diffusivity at the first pixel would appear to be four times lower than its real diffusivity. Similarly, the diffusivity calculated from equation (2) appears to be higher for a thinner pixel. Therefore, care should be taken when interpreting measured diffusivity images. Note that this equation is exact when a test part has a uniform thickness.

Results

An example of thermography results obtained for three LZIDs after 115 hr of sector rig testing is shown in figure 3. Part 216–1 contains 34-percent fiber volume fraction, and the other two contain 40 percent. The thickness of the middle sections of the liners was used to calculate the diffusivity values in the image. The apparent diffusivities are lower at the strips with fastener holes where the material is thicker and are higher at the left edges where the material is thinner. In addition to these diffusivity variations due to a thickness change, regions with considerably lower diffusivities can be observed in all liners, especially for 216–1.

To investigate the origin of local lower diffusivity values, a LZID was sectioned and polished. Figure 4 shows the microstructure of a cross section taken from 216–1. The line on the thermography image in figure 3 shows the location of the cross section. Damaged SiC fiber tows and delamination

cracks can be seen. The diffusivity reduction shown in figure 3 is related to the damage (i.e., delamination) of the ceramic matrix composite material due to the sector testing. For a single delamination, Sun (ref. 8) showed that the diffusivity reduction could be used to determine the (air gap) thickness of the delamination.

Thermal diffusivity data for another LZID with 34-percent fiber volume, which was exposed in the combustion environment for 145 hr, is shown in figure 5. Thermal diffusivity values are plotted in figure 5(a) along seven horizontal lines passing through several interesting regions in the thermal diffusivity image of 216–2. Although there is a thickness variation near both vertical edges of the liner, the thickness is uniform in the middle section and this value is used in the diffusivity calculation. In this middle section, the measured diffusivity is uniform in undamaged regions (e.g., line 7). Reduced diffusivity representing damage of varying severity is shown in other regions (lines 1 to 6). Figure 5(b) plots the width-averaged diffusivity along the length for the regions where four coupons were machined from the part to obtain flexure strength. It is apparent that coupons 2 to 4 contained large damaged areas with significant thermal diffusivity reductions and that coupon 1 had only slight damage near the region of thickness transition at the right. It is interesting to note that fracture occurred near the locations where the lowest diffusivities were observed for coupons 2 to 4.

Flexure strengths obtained from these coupons are compared with the thermal diffusivity in table I. The postexposure strength obtained from these coupons decreased with the decreasing ratio of the coupon-averaged thermal diffusivity to the mean thermal diffusivity (α/α_m), revealing the correlation between the thermal diffusivity data and strength.

The normalized flexure strength versus combustion exposure time for coupons machined from all LZIDs tested in the sector rig is shown in figure 6. The normalized flexure strength was calculated as the ratio of the strength of a coupon machined from a tested LZID to the average as-fabricated strength obtained from the LZID witness coupons for the same part. The strength decreases with increasing exposure time for the parts with 34-percent fiber volume, whereas the strength of the 40-percent fiber volume decreased after 115 hr of exposure. Also, coupons machined from component regions with thermography indications had lower strengths than coupons from regions with no NDE indications. As a function of exposure time, the strength data sets for coupons with and without NDE indications follow the same trends.

Summary

1. Combustor liners fabricated from SiC/SiC were tested in an aircraft engine environment using the rich-burn, quick-quench, lean-burn (RQL) sector rig for up to 260 hr. SiC/SiC liners were periodically removed during the rig operation to conduct postexposure analyses.

2. Degradation of the SiC/SiC material occurred and was in the form of delaminations and damaged fiber tows for the combustor liner parts examined, namely, the lean-zone inside-diameter liners (LZIDs).

3. Thermography was effective in imaging this damage in the SiC/SiC liners, whereas radiography and ultrasonic inspections were less sensitive.

4. Strength was measured by testing coupons machined from combustion-exposed parts and compared with witness (as-manufactured) data. For parts with 40-percent fiber volume, the strength decreased after 115 hr. However, exposure of only 10 hr decreased the strength of parts with 34-percent fiber volume.

5. For the exposed parts, coupons machined from regions that had thermography indications had lower strengths than coupons machined from regions that had no indications.

6. Local thermal diffusivity correlated with measured coupon strength for exposed SiC/SiC combustor liners.

References

1. Brewer, D.; Ojard, G.; and Gibler, M.: Ceramic Matrix Composite Combustor Liner Rig Test. ASME Paper TE00CER03-03, 2000.
2. Miriyala, Narendernath; Fahme, Anthony; and van Roode, Mark: Ceramic Stationary Gas Turbine Program—Combustor Liner Development Summary. ASME 2001-GT-0512, 2001.
3. Corman, Gregory, et al.: Rig and Gas Turbine Engine Testing of MI-CMC Combustor and Shroud Components. ASME 2001-GT-0593, 2001.
4. Igashira, Ken-Ichiroh, et al.: Development of the Advanced Combustor Liner Composed of CMC/GMC Hybrid Composite Material. ASME 2001-GT-0511, 2001.
5. Brewer, David: HSR/EPM Combustor Materials Development Program. Mater. Sci. Eng., vol. A261, 1999, pp. 284–291.
6. Verrilli, Michael J., et al.: Evaluation of Post-Exposure Properties of SiC/SiC Combustor Liners Tested in the RQL Sector Rig. NASA TM—2002-211380, 2002.
<http://gltrs.grc.nasa.gov/cgi-bin/GLTRS/browse.pl?2002/TM-2002-211380.html>
Accessed Jan. 6, 2003.
7. Shaw, Robert J.; Koops, Leigh; and Hines, Richard: Progress Toward Meeting the Propulsion Technology Challenges for a 21st Century High-Speed Civil Transport. NASA TM-113161 (ISABE-97-7045), 1997. <http://gltrs.grc.nasa.gov/cgi-bin/GLTRS/browse.pl?1997/TM-113161.html>
Accessed Jan. 7, 2003.
8. Sun, J.G.: Analysis of Quantitative Measurement of Defect by Pulsed Thermal Imaging. Paper presented at the Review of Progress in Quantitative NDE, Brunswick, ME, 2001.
9. Parker, W.J., et al.: Flash Method of Determining Thermal Diffusivity, Heat Capacity, and Thermal Conductivity. J. Appl. Phys., vol. 32, no. 9, 1961, pp. 1679–1684.

TABLE I.—COMPARISON OF THERMAL DIFFUSIVITY AND COUPON STRENGTH
FOR LEAN-ZONE INSIDE-DIAMETER LINER (LZID) 216-2 AFTER
145 HR OF TESTING IN COMBUSTION ENVIRONMENT

Coupon	Ratio of coupon-averaged thermal diffusivity to mean thermal diffusivity, α/α_m	Posttest 815 °C flexure strength, MPa
1	1.0	262
2	.6	229
3	.56	207
4	.47	131

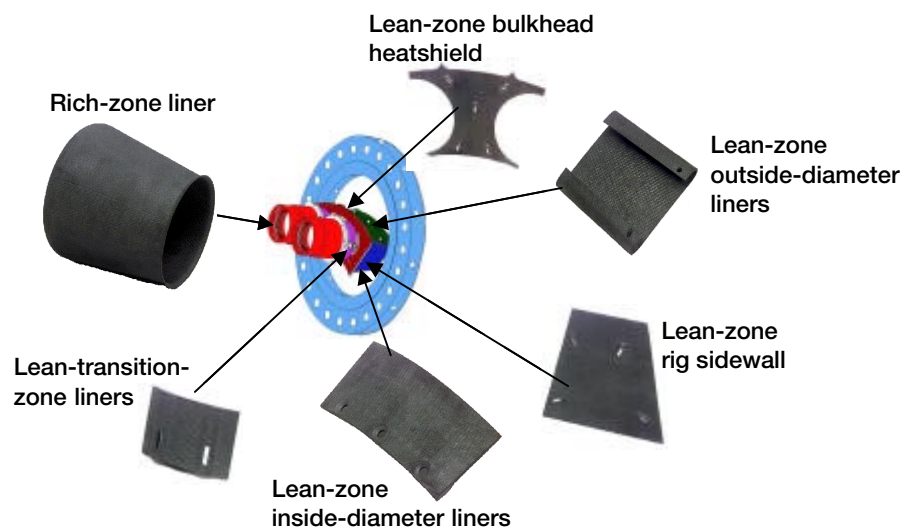


Figure 1.—Rich-burn, quick-quench, lean-burn (RQL) sector rig and images of all SiC/SiC parts.

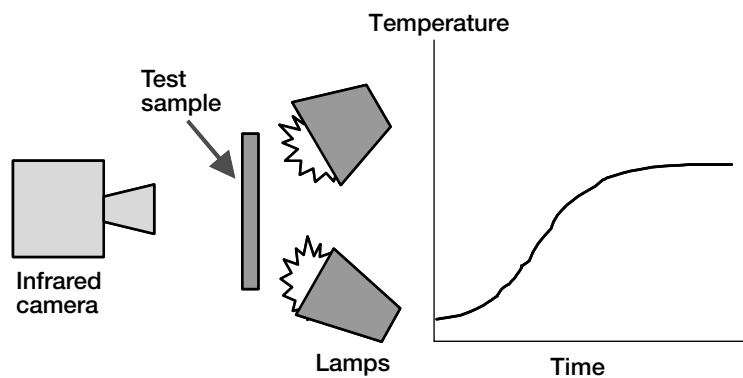


Figure 2.—Through-transmission (through-thickness) thermography test configuration.

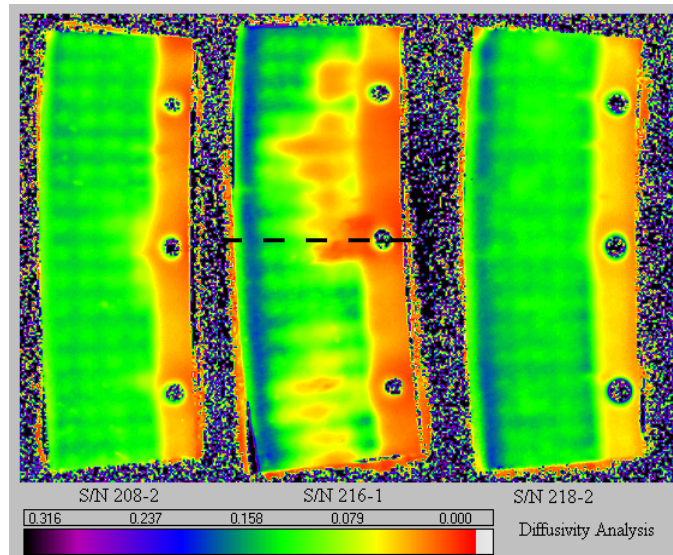


Figure 3.—Thermography of three SiC/SiC liners after 115 hr of sector rig testing. Part 216-1 contains 34-percent fiber volume fraction; parts 208-2 and 218-2 contain 40-percent fiber volume fraction.

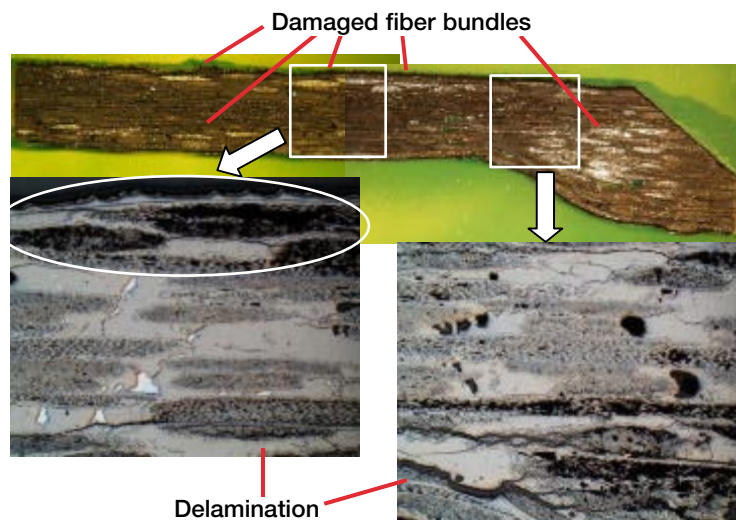


Figure 4.—Microstructure of LZID 216-1 after 115 hr of combustion exposure (black line in fig. 3 shows location of this section). Note the arrows that indicate damaged tows.

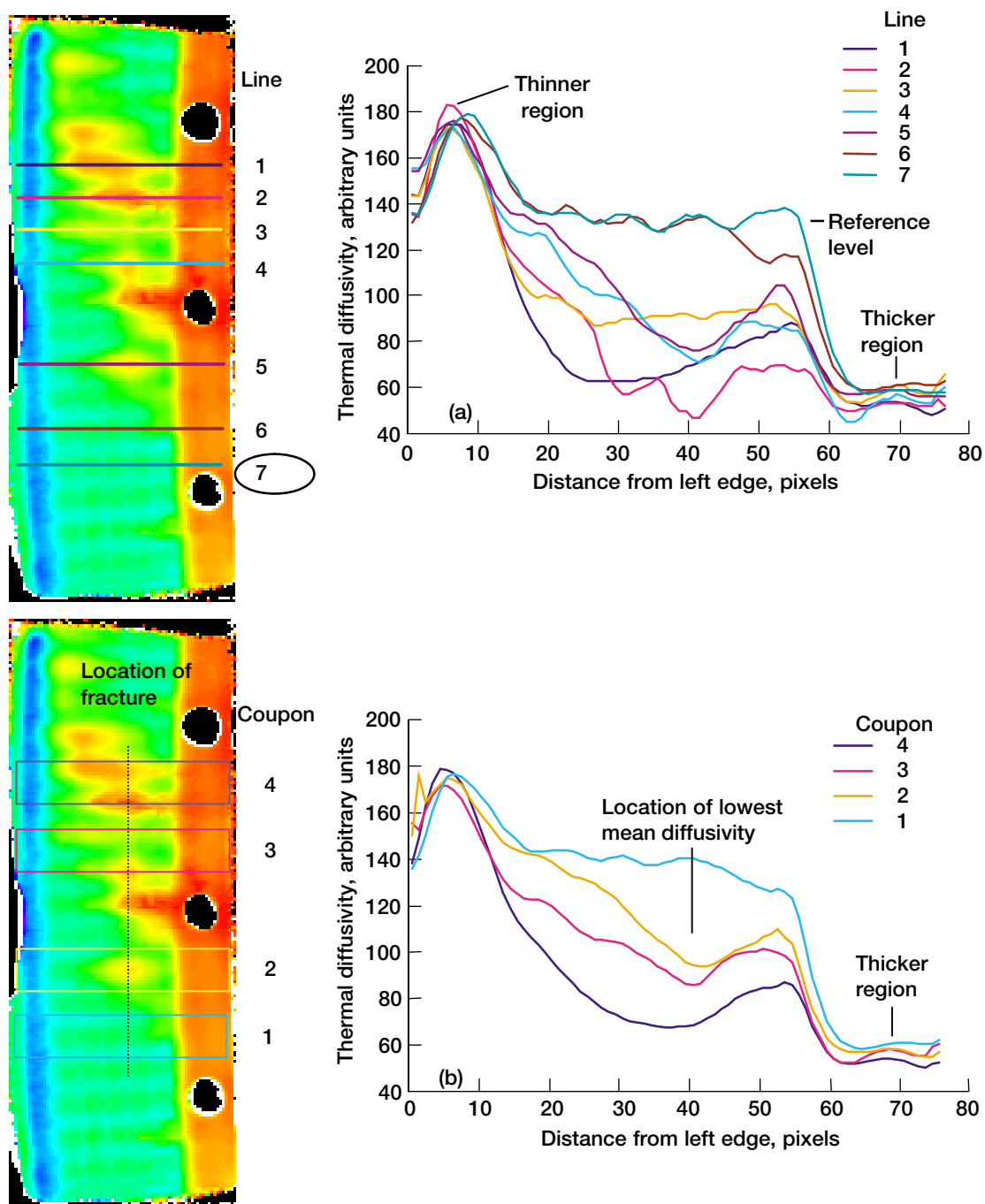


Figure 5.—Thermal diffusivity data for LZID 216–2 after 145 hr of combustion exposure. (a) Line plots at seven part locations. Note: line 7 is reference level. (b) Average values for regions of coupons machined for strength measurement.

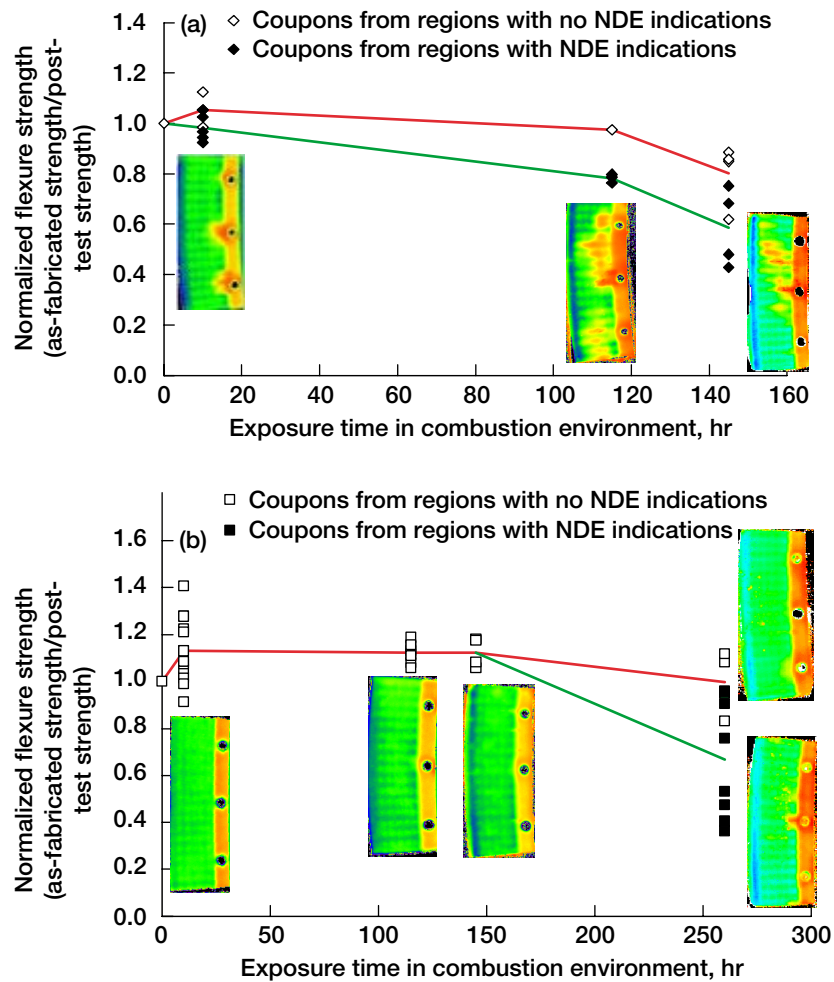


Figure 6.—Normalized flexure strength data obtained at 815 °C as function of exposure time for coupons machined from LZIDs. (a) Data for coupons from 34-percent fiber volume parts. (b) Data for coupons from 40-percent fiber volume parts.

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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE April 2003	3. REPORT TYPE AND DATES COVERED Technical Memorandum	
4. TITLE AND SUBTITLE Nondestructive Evaluation of Ceramic Matrix Composite Combustor Components			5. FUNDING NUMBERS WBS-22-714-04-15	
6. AUTHOR(S) Jiangang G. Sun, Michael J. Verrilli, Robert R. Stephan, Terry R. Barnett, and Greg C. Ojard				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191			8. PERFORMING ORGANIZATION REPORT NUMBER E-13702	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA TM-2003-212014	
11. SUPPLEMENTARY NOTES Prepared for the 29th Annual Review of Progress in Quantitative Nondestructive Evaluation (QNDE) sponsored by the Quantitative Nondestructive Evaluation Programs, Bellingham, Washington, July 14-19, 2002. Jiangang G. Sun, Argonne National Laboratory, Argonne, Illinois 60439; Michael J. Verrilli, NASA Glenn Research Center; Robert R. Stephan, Pratt & Whitney, East Hartford, Connecticut 06108; Terry R. Barnett, Southern Research Institute, Birmingham, Alabama 35211; Greg C. Ojard, United Technologies Research Center, East Hartford, Connecticut 06108. Responsible person, Michael J. Verrilli, organization code 5160, 216-433-3337.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Categories: 24 and 35 Available electronically at http://gltrs.grc.nasa.gov This publication is available from the NASA Center for AeroSpace Information, 301-621-0390.			12b. DISTRIBUTION CODE	
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14. SUBJECT TERMS Nondestructive tests; Ceramic matrix composites; Combustion; Silicon carbide; Composite structures; Mechanical properties			15. NUMBER OF PAGES 15	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	