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NASA Technical Memorandum 102540

Ultrasonic and Radiographic Evaluation of Advanced Aerospace Materials: Ceramic Composites

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Prepared for
Physics Department Seminars
sponsored by John Carroll University
University Heights, Ohio, April 11, 1990

NASA

ULTRASONIC AND RADIOGRAPHIC EVALUATION OF ADVANCED AEROSPACE MATERIALS: CERAMIC COMPOSITES

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ABSTRACT

Two conventional nondestructive evaluation techniques were used to evaluate advanced ceramic composite materials. It has been shown that neither ultrasonic C-scan nor radiographic imaging can individually provide sufficient data for an accurate nondestructive evaluation. Both ultrasonic C-scan and conventional radiographic imaging are required for preliminary evaluation of these complex systems. The material variations that have been identified by these two techniques are porosity, delaminations, bond quality between laminae, fiber alignment, fiber registration, fiber parallelism, and processing density flaws. The degree of bonding between fiber and matrix cannot be determined by either of these methods. An alternative ultrasonic technique, angular power spectrum scanning (APSS) is recommended for quantification of this interfacial bond.

INTRODUCTION

Advanced high-temperature, low-density composite materials are being developed for use in the next generation of aerospace systems. The High Speed Civil Transport (HSCT, fig. 1), an aircraft for transporting 250 passengers, at Mach 3.2 for 5000 n mi and the National Aerospace Plane (NASP, fig. 2) a transportation system that will take off, fly at Mach 25 directly into orbit and land like a conventional aircraft, will require advanced composite materials for both propulsion and structural components.

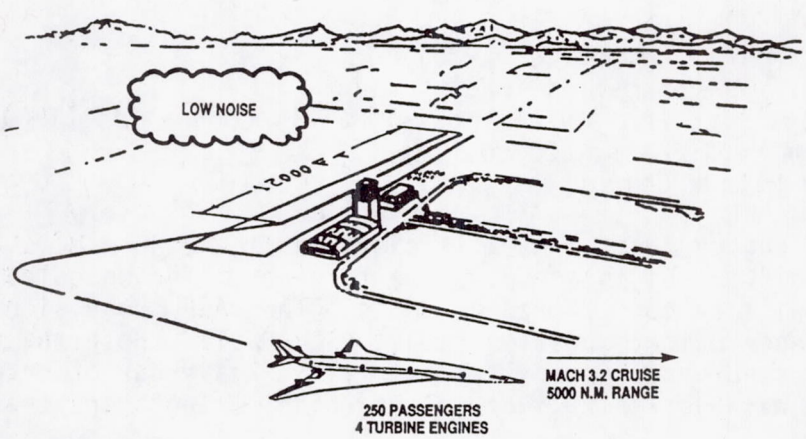


Figure 1. - High Speed Civil Transport (HSCT).

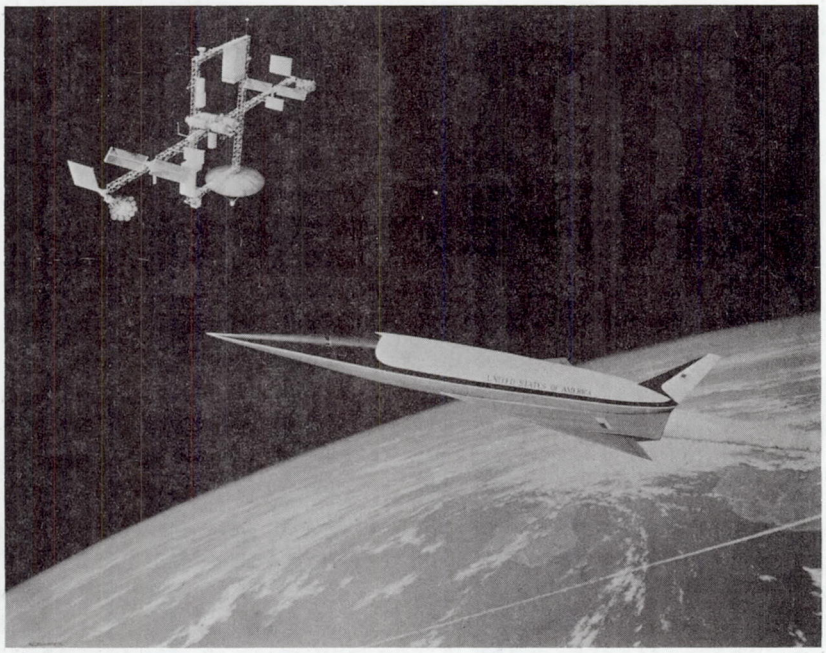


Figure 2. - National Aero-Space Plane (NASP).

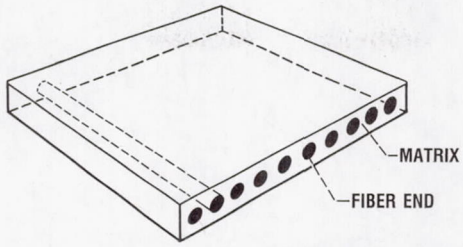
These composite materials consist of particles, whiskers, or fibers embedded in ceramic or metal matrices. The fibers may be parallel and lie in one plane (fig. 3(a)), layered to form crossplys (fig. 3(b)), woven into a three-dimensional pattern (fig. 3(c)), or wound to form cylinders. The composite matrix material may be polymeric, metallic, intermetallic, or ceramic. The wide range of composite materials under investigation for advanced aerospace systems is shown in table I. One advantage to using composites listed in table I is the increased ratio of ultimate strength-to-density (fig. 4) over conventional engine materials, e.g., superalloys like Inconel 100 (IN-100). The rapid progress in producing metal matrix composites has allowed actual test components to be manufactured. Here the NARloy-Z main combustion chamber (figs. 5 and 6) lining can be replaced by a metallic composite (fig. 7) that has a superior rupture strength.

TABLE I

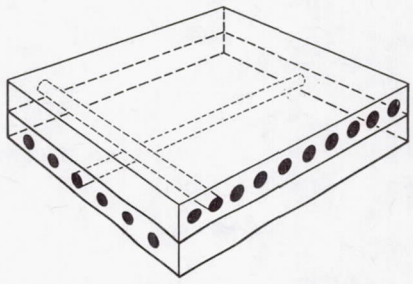
1. Polymer Matrix Composites (PMC)
2. Metal Matrix Composites (MMC)
3. Intermetallic (FeAl, NiAl, $MoSi_2$) Matrix Composites (IMC)
4. Titanium Metal Matrix Composites (TiMMC)
5. Ceramic Matrix Composites (CMC)

The propulsion engine for the HSCT is shown in figure 8. IMC's and TiMMC's will be used from the inlet up to the turbines. The uncooled turbines and ejector nozzle will be constructed of CMC's. The NASP propulsion system is a hydrogen-fueled supersonic combustion ramjet (SCRAMJET). Both the engine and airframe will require advanced composite materials. Heavy use of ceramic composites is expected because their light weight, high strength and thermal shielding properties.

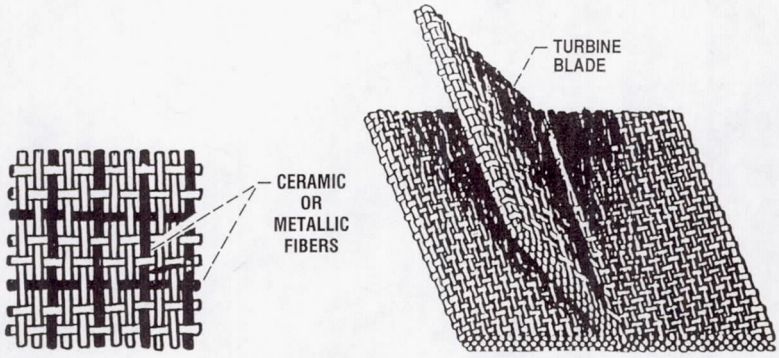
Research on monolithic ceramics (ref. 1) lead to the current developmental research on advanced high-temperature ceramic composites (ref. 2). A variety



(a) Monotape composite with fibers aligned along one direction.



(b) [0°/90°] cross-ply, laminated composite.



(c) 3-D woven fabric composite.

Figure 3. - Advanced composites.

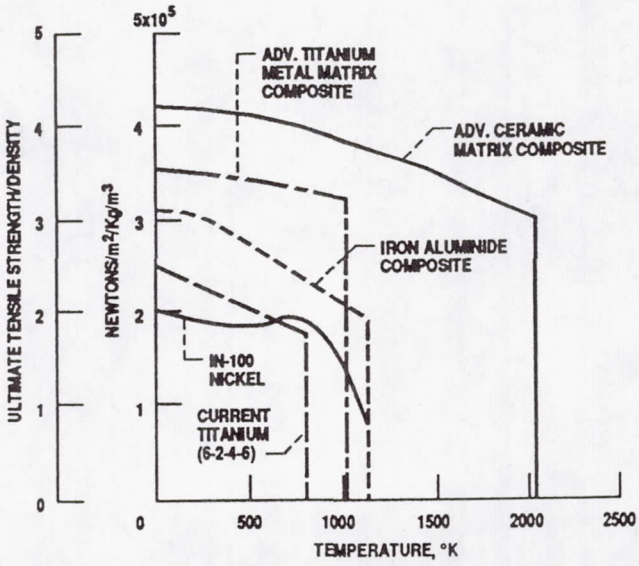


Figure 4. - Strength-to-density for advanced composites.

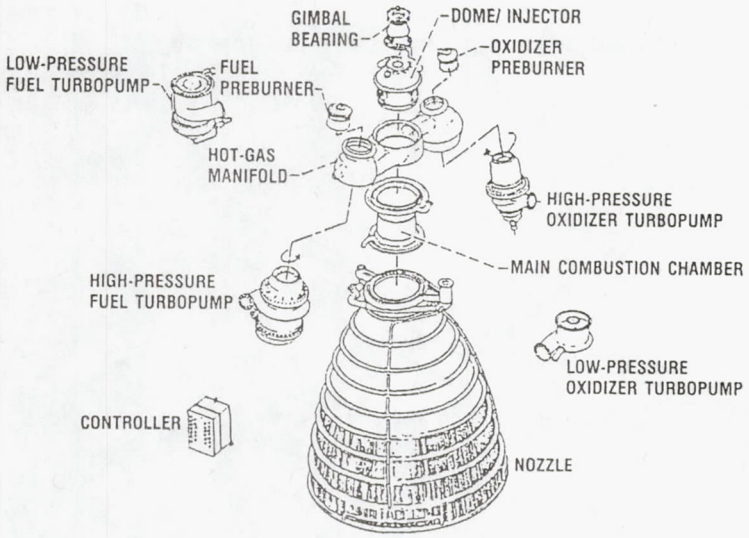


Figure 5. - Space Shuttle Main Engine (SSME).

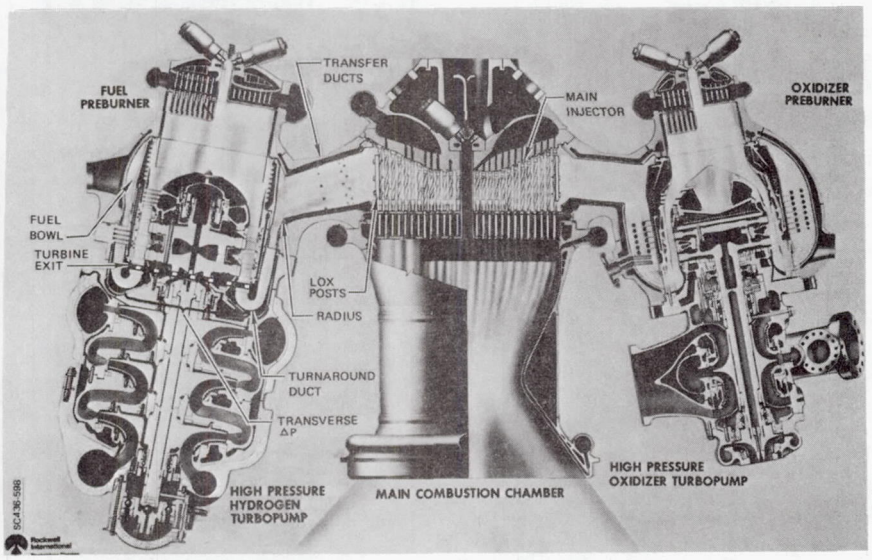


Figure 6. - SSME powerhead component arrangement.

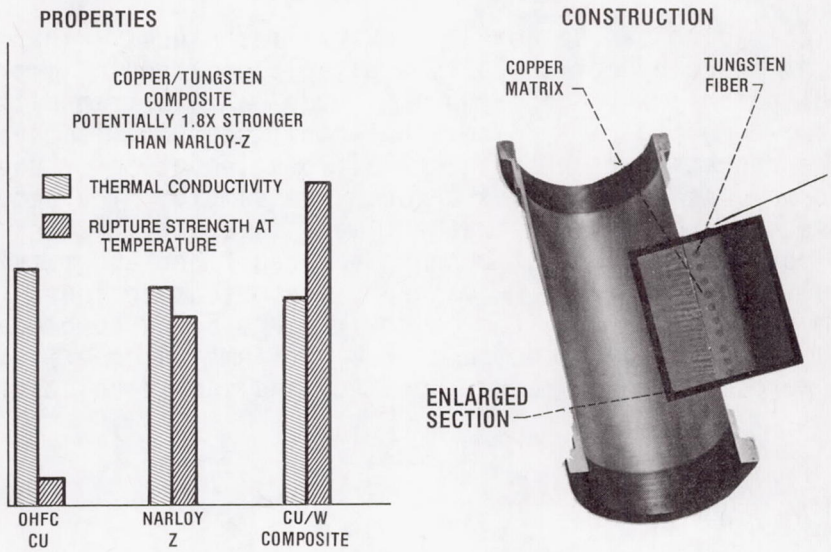


Figure 7. - Test MMC composite thrust (combustion) chamber.

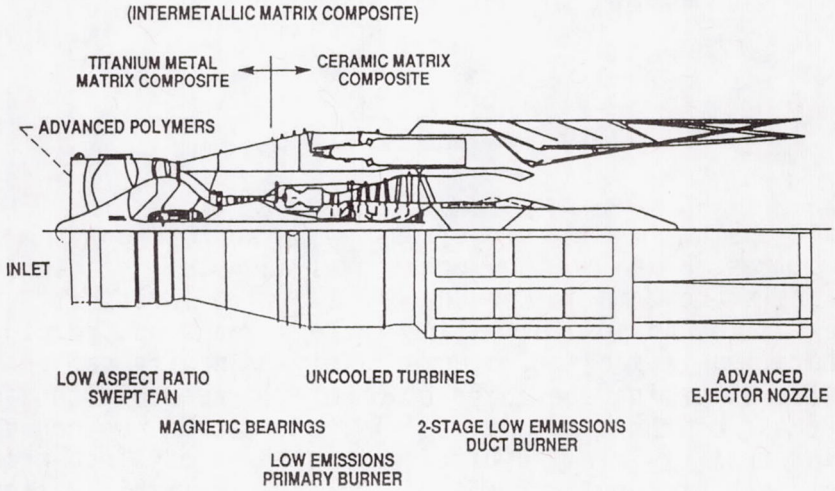


Figure 8. - HSCT engine materials.

of processing techniques are being investigated in an effort to produce high-temperature composites with optimized thermal and mechanical properties. Plasma spraying, reaction bonding, slurry pressing and sintering are typical techniques used to produce high temperature ceramic composites. These processes often result in a composite that has a wide variability in microstructure that usually affects thermal and mechanical properties.

Ultrasonic C-scans and x-ray radiography are two techniques used for non-destructive evaluation (NDE) of microstructural variations. These NDE methods reveal macroscopic internal features or flaws such as delaminations, porosity and cracks. These are important when considering the use of the tested material where strength and integrity must be assured. It is challenge to the NDE community to assist in the development of these advanced materials.

BACKGROUND

Ultrasonic imaging can be done by several techniques. The most common technique is that used by commercially available ultrasonic immersion C-scan systems. An ultrasonic wave of known amplitude A_o is transmitted through a sample as is shown in figure 9. The final amplitude A_f is used to form an image that is a representation of the relative attenuation or energy lost by the ultrasonic wave as it traverses through the sample. The amount of energy lost (high loss corresponds to decreased image intensity) is an indication of the amount of porosity, degree of bonding between fiber and matrix, and uniformity of the sample (ref. 3). Advanced ultrasonic techniques (e.g., angular power spectrum scanning (APSS)) for composites are being developed (ref. 3) that will make use of pattern recognition algorithms in order to characterize variations in porosity, fiber-matrix bonding, and sample uniformity.

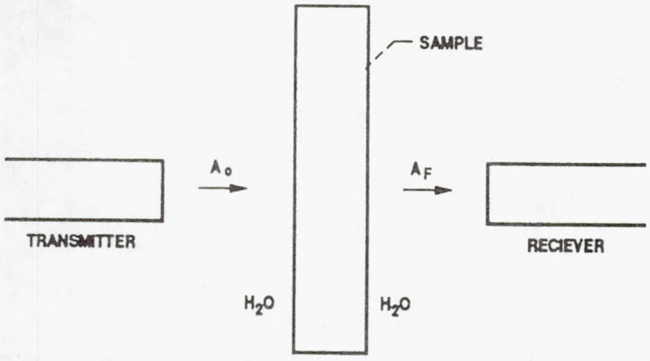


Figure 9. - Immersion ultrasonic C-scan arrangement.

Ultrasonic evaluation of composites may be approached from two directions. The complete composite can be interrogated as a whole system. The resultant ultrasonic signals are complicated and difficult to interpret. Since the actual scattering mechanisms that shape these signals has remained unknown their interpretation is subject to uncertainty. An alternative to this approach is to explicitly determine the interaction of ultrasound with each individual component or phase of the composite. This information is then used for formulating theories that explain the ultrasonic signals obtained from the full composite system. Recent results (ref. 3) indicate that this latter approach has been sucessful and can be used to determine microstructural uniformity, and mechanical and thermal integrity. The dominant ultrasonic scattering mechanisms for SiC and Si_3N_4 are listed in table II (ref. 3). The information in table II is used to help interpret ultrasonic C-scan images. As the ultrasonic wave travels through the composite, energy is scattered out of the main beam at each pore and fiber boundary. The amount of scattering is an indication of the number, presence, and character of each of these boundaries.

TABLE II*

1. Symmetric diffractive scattering at individual pores (Airy (ref. 4))
2. Symmetric diffractive scattering at fibers (Young (ref. 5))
3. Asymmetric refractive scattering at density gradients (Snell (ref. 6))

*Grain boundary scattering is negligible.

NONDESTRUCTIVE EVALUATION

Three composite systems were investigated using conventional ultrasonic C-scan (10 MHz, through transmission) and radiographic techniques. The three composite systems were SiC/Si_3N_4 with SCS-6 (140-μm diam SiC fiber), SiC (Nicalon)/Calcium Aluminosilicate (CAS), and SiC (Nicalon)/SiC.

The radiographic and ultrasonic C-scan of SiC/Si_3N_4 (SCS-6 fiber), [0°/90°], laminated composite NASP cooling panel is shown in figure 10. The x-ray image reveals misaligned or bowed fibers. The ultrasonic image indicates that there are regions (dark) between the laminae that did not bond (delaminations). The x-ray data indicates that the specimen is uniform in density, however, the ultrasonic data indicates that there are large variations in the amount of ultrasonic scattering throughout the sample area. It is believed that these variations are due to bond variations between the laminae.

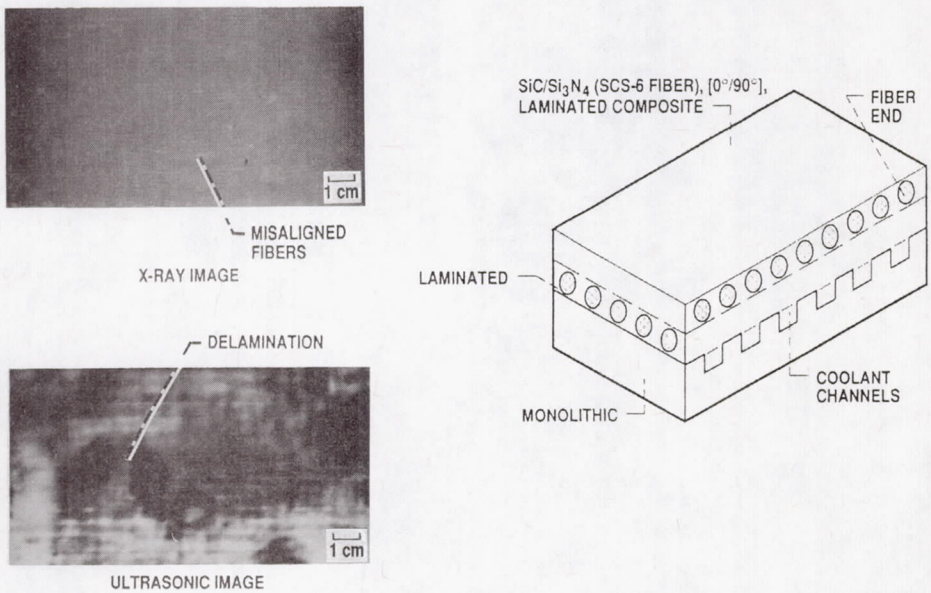


Figure 10. - X-ray and ultrasonic C-scan images of SiC/Si_3N_4 (SCS-6 fiber), [0°/90°], laminated composite NASP cooling panel.

Identically produced SiC/Si_3N_4 (SCS-6 fiber), [0°/90°], laminated composites can yield very different nondestructive evaluation results. Figure 11 shows the radiographic and ultrasonic data for two similarly produced samples. The x-ray data indicate that these two specimens have similar densities. In contrast, the low intensity of the ultrasonic image for specimen A indicates that there is relatively poor bonding between laminae. The highest intensity in the ultrasonic image for specimen B is a region having a good bond between laminae.

When comparing the radiographic and ultrasonic images for the SiC (Nicalon)/Calcium Aluminosilicate (CAS), [0°/90°], laminated composites (fig. 12), it is observed that low ultrasonic intensity (dark) corresponds to low density (light regions) in the x-ray image. Therefore, these dark ultrasonic regions are areas having low densities and not poor interlaminar bonds.

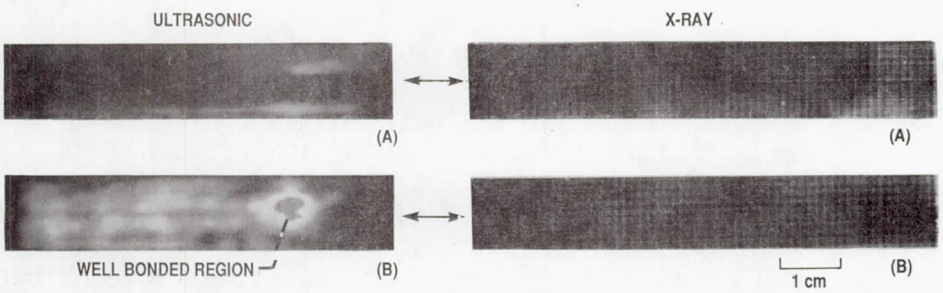


Figure 11. - X-ray and ultrasonic C-scan images of similarly produced SiC/Si_3N_4 (SCS-6 Fiber), {0°/90°], laminated composites.

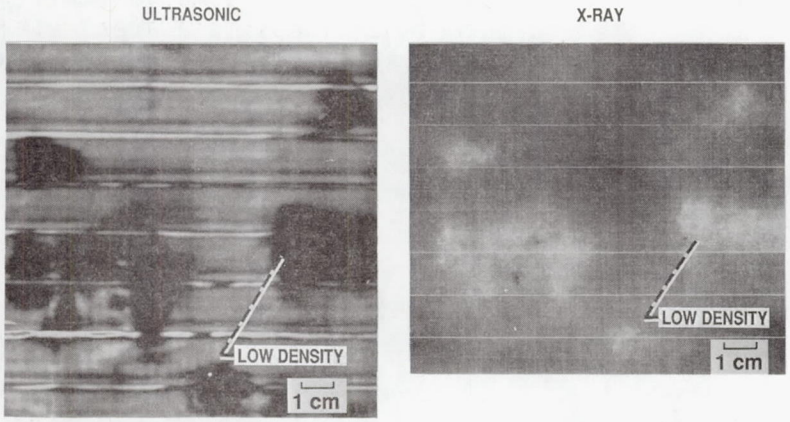


Figure 12. - X-ray and ultrasonic C-scan images of SiC(SCS-6)/Calcium Aluminosilicate (CAS), [0°/90°] composites.

The woven structure of SiC (Nicalon)/SiC, laminated composites yield very distorted ultrasonic images (fig. 13). For example, compare figures 12 and 13. Processing features, high-density circular regions, can be found in both the ultrasonic and x-ray data. The ultrasonic image intensity is low where the density is high (dark in the radiograph). The cross hatch pattern in the radiograph reveals the degree of registration between lamina. Registration effects can result in an erroneous determination of porosity variations. This occurs when nearly identical plies, with uniform fiber spacing, are laid up so that the fibers are slightly off axis. This slight misalignment of fibers produces a Moire (ref. 7) pattern (fig. 14) in the x-ray image that may be misinterpreted as porosity variations. The large number of fibers in ceramic composites results in an overlap, of Moire patterns. These overlapping patterns are not as clearly visable as that shown in figure 14. As of this writing Moire patterns have not been explicitly observed for ceramic composites. However, researchers should be aware of their effect on determination of density.

The NDE of these systems indicates that for laminated composite structures both radiography and ultrasonic C-scan evaluation are required. The x-ray evaluation can be used to determine porosity variations, fiber alignment and registration between layups. Ultrasonic evaluation can be used for determining delaminations, bond variations between laminae and porosity variations.

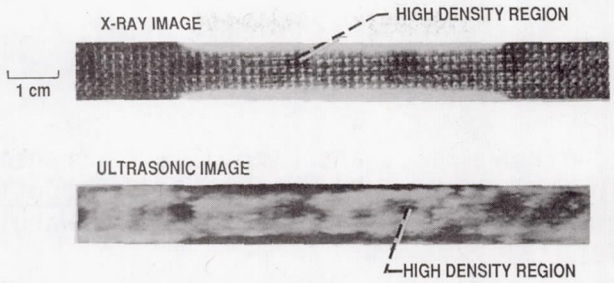


Figure 13. - X-ray and ultrasonic C-scan images of woven, SiC(Nicalon)/ SiC laminated composite.

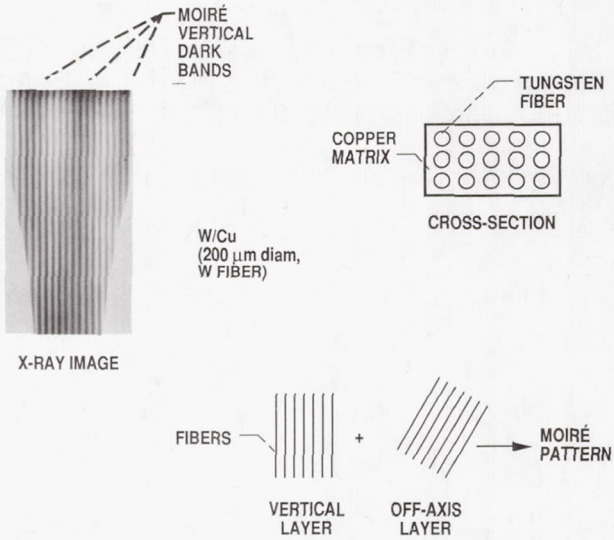


Figure 14. - X-ray image of W/Cu composite showing Moiré pattern.

In the above evaluations, the degree of bonding between the fiber and the matrix cannot be separated from effects due to porosity and variations in the number of fibers per unit volume. Further nondestructive analysis using the APSS technique will be required to obtain this information.

SUMMARY

Two conventional nondestructive evaluation techniques were used to evaluate advanced ceramic composite materials. It has been shown that neither ultrasonic C-scan nor radiographic imaging can individually provide sufficient data for an accurate nondestructive evaluation. Both ultrasonic C-scan and conventional radiographic imaging are required for preliminary evaluation of these complex systems. The material variations that have been identified by these two techniques are porosity, delaminations, bond quality between lamina, fiber alignment, fiber registration, fiber parallelism, and processing density flaws. The degree of bonding between fiber and matrix cannot be determined by either of these methods. An alternative ultrasonic technique, angular power spectrum scanning is recommended for quantification of this interfacial bond.

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Report Documentation Page

1. Report No. NASA TM-102540	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Ultrasonic and Radiographic Evaluation of Advanced Aerospace Materials: Ceramic Composites		5. Report Date
		6. Performing Organization Code
7. Author(s) Edward R. Generazio		8. Performing Organization Report No. E-5403
		10. Work Unit No. 510-01-1A
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546-0001		14. Sponsoring Agency Code

15. Supplementary Notes

Prepared for the Physics Department Seminars sponsored by John Carroll University, University Heights, Ohio, April 11, 1990.

16. Abstract

Two conventional nondestructive evaluation techniques were used to evaluate advanced ceramic composite materials. It has been shown that neither ultrasonic C-scan nor radiographic imaging can individually provide sufficient data for an accurate nondestructive evaluation. Both ultrasonic C-scan and conventional radiographic imaging are required for preliminary evaluation of these complex systems. The material variations that have been identified by these two techniques are porosity, delaminations, bond quality between laminae, fiber alignment, fiber registration, fiber parallelism, and processing density flaws. The degree of bonding between fiber and matrix cannot be determined by either of these methods. An alternative ultrasonic technique, angular power spectrum scanning (APSS) is recommended for quantification of this interfacial bond.

17. Key Words (Suggested by Author(s)) Composites; Nondestructive evaluation; Nondestructive testing; NDT; NDE; Radiography; Ultrasonics	18. Distribution Statement Unclassified – Unlimited Subject Category 38

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of pages 12	22. Price* A03

NASA FORM 1626 OCT 86

*For sale by the National Technical Information Service, Springfield, Virginia 22161