

HIGH FREQUENCY LONGITUDINAL AND SHEAR WAVE  
INSPECTION OF GAS TURBINE CERAMICS

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ABSTRACT

To assure reliable performance of ceramic materials in gas turbine engines, where performance at 1400°C for up to 10,000 hours is required, it is necessary to screen out material with defects in the size range 10 to 100  $\mu\text{m}$  (0.0004 to 0.004 inches). Investigation of high frequency ultrasonic techniques has led to development of longitudinal and shear wave methods capable of detecting defects at least down to 25  $\mu\text{m}$  in size. The approach is to use a high frequency (45 MHz) ultrasonic pulse-echo immersion mode technique, making C-scan recordings of the results. Inspections have been performed on hot pressed and reaction bonded silicon nitride and hot pressed and sintered silicon carbide. Natural defects, seeded inclusions, and artificial surface cracks have been examined. Reference standards of hot pressed silicon nitride containing seeded defects and laser drilled holes have been developed. Four-point-bend testing and scanning electron microscopy have been employed to establish correlation with ultrasonic results.

This poster describes our NAVAIR sponsored development of high frequency ultrasonic inspection techniques for gas turbine ceramics and also, application of these techniques to the inspection requirements of the AiResearch/NAVSEA program for development of a ceramic gas turbine demonstration engine. The basic goal of the NAVAIR sponsored program was to demonstrate the feasibility of detecting defects in the 10 to 100  $\mu\text{m}$  (0.0004 to 0.004 inch) size range. Selection of high frequency ultrasonics was based on the principle that, for a wave to interact with a defect the wavelength must be of the same order of magnitude as the defect size, or smaller. This dictated the need for a higher frequency than is normally used in ultrasonic inspection to detect the small defects of interest. On the other hand, it was also recognized that if the wavelength approaches the grain size of the material, it will interact causing high background noise and high attenuation. It is the fine grain structure generally found in ceramics such as silicon nitride and silicon carbide which makes it possible to employ high frequency ultrasonics to detect small defects.

The basic technique developed employs an ultrasonic system operating in the pulse-echo mode at 25 to 45 MHz with a focused ultrasonic transducer. Figure 1 shows the arrangement for longitudinal wave inspection. The specimen and transducer are immersed in water with the transducer normal to the specimen surface. The transducer is scanned across the specimen and a C-scan recording is made of the results. We have found that for a 6.4 mm (0.25 inch) thick billet, scans are required at three focal planes to provide complete coverage. Because of the beam orientation, the strongest response is from a defect oriented parallel to the specimen surfaces. This, of course, is not usually the defect orientation of greatest interest. Figure 2 shows the arrangement for shear wave inspection. The same equipment is used, but the transducer is tilted at an angle (11° for hot pressed silicon nitride) in the direction of the scan. This results in a shorter ultrasonic wavelength for a given frequency and pro-

vides a beam in the specimen at about a 45 degree angle to the surface. This technique is more sensitive than the longitudinal wave technique and is better applicable to detecting defects which are oriented perpendicular to the specimen surfaces.

The following figures illustrate some of the capabilities of these techniques. The first group of six illustrate some of the work done on the NAVAIR sponsored program. Figure 3 shows a typical C-scan recording of a billet of Ceralloy 147A, hot pressed silicon nitride. This billet contained four seeded defects forming a 25 mm (1 inch) square near corner No. 3. Two of these defects, located on one diagonal, were 125  $\mu\text{m}$  (0.005 inch) diameter simulated voids (SV) consisting of aluminum oxide inclusions. The other two were 125  $\mu\text{m}$  (0.005 inch) diameter tungsten carbide inclusions (SWC). In addition to these seeded defects, a number of natural defects were detected in the billet. Figure 4 is a composite sketch showing each defect detected in the billet as a dot. The layout of four-point bend specimens is shown with specimen numbers on the outside of each specimen and the height of the ultrasonic pulse from the defect in cm on the inside. The pulse heights were obtained with the beam focused on the defect and are referenced to 4.0 cm for the reference simulated void. Figure 5 shows how each specimen was cut from the billet in order to place the defect near the tensile surface during testing. The 6.4 x 3.2 x 31.8 mm (1/4 x 1-1/4 inch) specimens were cut with the billet thickness as the 6.4 mm (1/4 inch) dimension and with the defect 380  $\mu\text{m}$  (0.015 inches) below the tensile surface.

Figures 6, 7 and 8 show fracture surfaces for specimens that initiated fracture at the ultrasonically detected defects. Figure 6 shows a 25  $\mu\text{m}$  (0.005 inch) tungsten carbide inclusion. The size and material of both these seeded defects were verified by electron microprobe analysis. The portion of the billet containing the other two seeded defects was saved for use as a reference standard as shown in Fig. 4.

To summarize, in the NAVAIR sponsored program TRW has

- 1) Developed the ability to detect defects at least down to 25  $\mu\text{m}$  (0.001 inch) in size in hot pressed silicon nitriding.
- 2) Established a reference standard for hot pressed silicon nitride.
- 3) Demonstrated the ability to correlate ultrasonic inspection results with four-point-bend test data and SEM fractography; and
- 4) Applied the techniques developed to other materials such as hot pressed and sintered silicon carbide and reaction bonded silicon nitride.

The results of this development program are presently being applied to the AiResearch/NAVSEA program to develop a ceramic gas turbine demonstration engine. The plan calls for TRW to inspect:

- 1) seeded billets
- 2) mechanical test specimens
- 3) prototype blade shapes, and
- 4) actual blades.

Item 1 is almost complete and items 2 and 3 are in progress. Figures 9 through 12 show some of the results for item 1. Figure 9 shows the C-scan recording of the 45 MHz longitudinal wave inspection of a billet of NC-350, reaction bonded silicon nitride. The billet was seeded with Fe, Si, SiC, low density  $\text{Si}_3\text{N}_4$ , C and pores in sizes ranging from 125 to 1000  $\mu\text{m}$  (0.005 to 0.040 inches) as shown in the margins. Figure 10 shows the corresponding shear wave inspection results. Not only are the defect indications larger in Fig. 10, but there are a number of defect indications in Fig. 10 which do not appear in Fig. 9. This shows the superior sensitivity of the shear wave techniques. Although there are some blank areas where seeded defects are supposed to be, particularly for the low density  $\text{Si}_3\text{N}_4$  and the smallest size of Si and SiC, there is no way of knowing whether the defects are actually present until the billet is cut up.

Figures 11 and 12 show C-scans of 45 MHz longitudinal and shear wave inspections of a seeded billet of NC-132, hot pressed silicon nitride. In this case the seeded defects are WC, Fe, BN, SiC, Si and C in sizes ranging from 25 to 500  $\mu\text{m}$  (0.001 to 0.020 inches). Once again the shear wave inspection shows more defects than the longitudinal wave inspection. Although the actual defect sizes have yet to be verified by metallurgical evaluation, Fig. 12 offers additional evidence of the ability of high frequency ultrasonics to detect defects at least down to 25  $\mu\text{m}$  (0.001 inches) in size in hot pressed silicon nitride.

In conclusion, the evidence provided, both by inspection of materials containing seeded defects and by SEM examination of ultrasonically detected natural defects, indicates the ability of high frequency (45 MHz) pulse-echo immersion ultrasonic testing using a focused transducer to provide a thorough examination of a large ceramic specimen and to detect defects of a variety of materials at least down to 25  $\mu\text{m}$  (0.001 inches) in size.

LONGITUDINAL WAVE INSPECTION

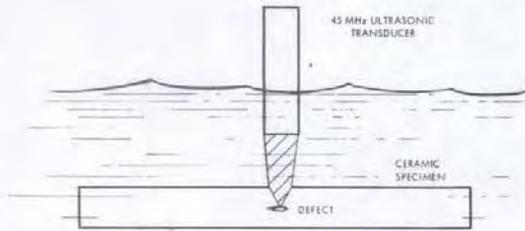


Figure 1. Pulse-echo longitudinal wave inspection is performed at 25 to 45 MHz using a focused ultrasonic transducer immersed in water. C-scan recordings are made of the results. This technique is more sensitive to defects oriented parallel to the surface that is normal to the transducer.

SHEAR WAVE INSPECTION

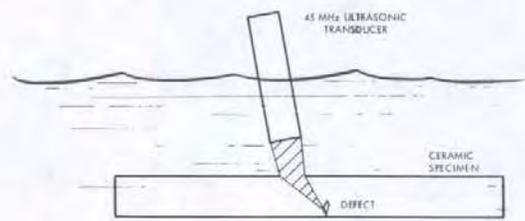


Figure 2. Pulse-echo shear wave inspection is performed using the same equipment, but with the transducer tilted at an angle of about  $11^\circ$  to the surface. This technique is more sensitive to defects oriented normal to the surface.

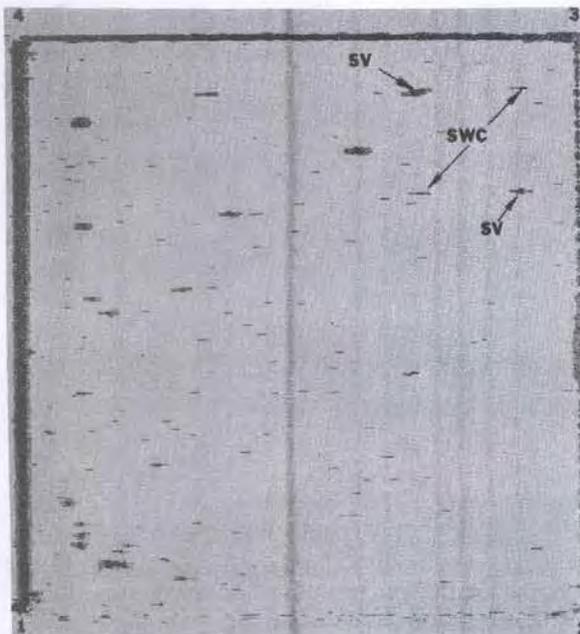


Figure 3. Typical C-scan recording of inspection results for a billet of Cerralloy 147A hot pressed silicon nitride showing seeded low density (SV) and high density (SWC)  $125 \mu\text{m}$  (0.005 inch) defects as well as numerous natural defects.

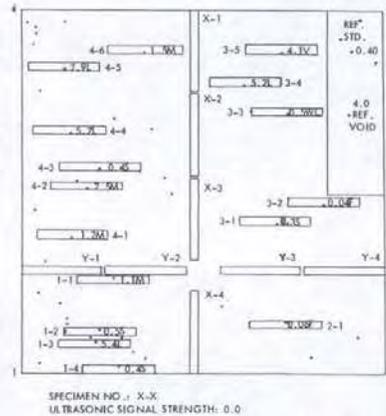


Figure 4. Sketch showing the defects detected in the billet of Cerralloy 147A, the four-point-bend specimens cut from the billet, and the ultrasonic signal strength of the defects located in the specimens.

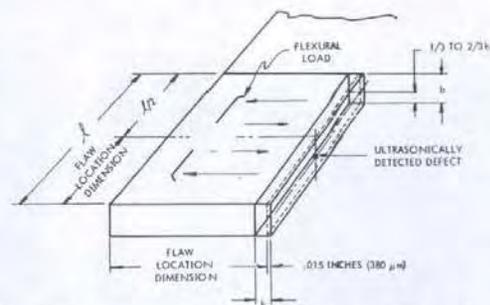
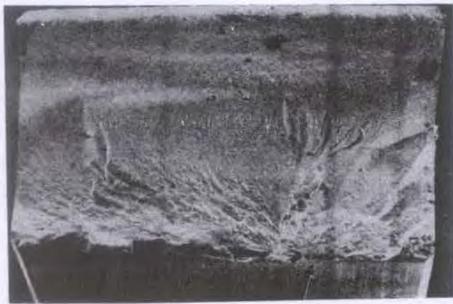
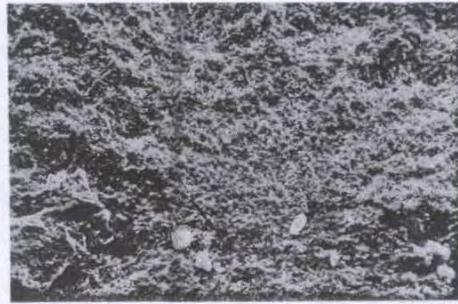


Figure 5. Sketch showing the method by which four-point-bend specimens were cut from the billet of Cerralloy 147A with ultrasonically detected defect located near the tensile surface.



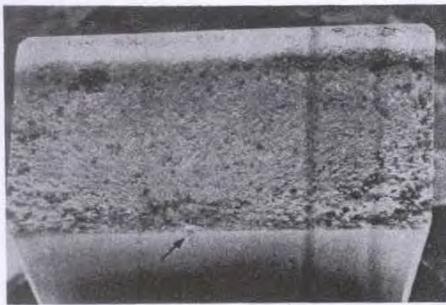
16X



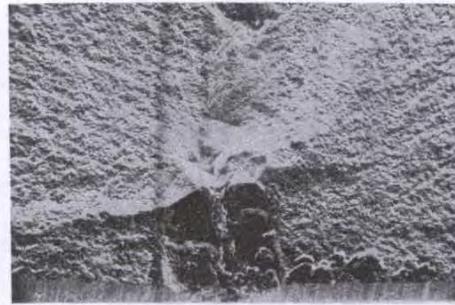
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Figure 6. Fracture surfaces of specimen 1-4, showing fracture origin at ultrasonically detected 25  $\mu\text{m}$  (0.001 inch) void.



16X



200X

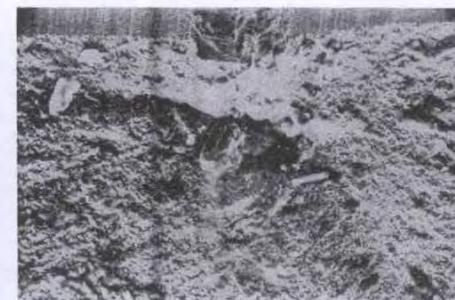
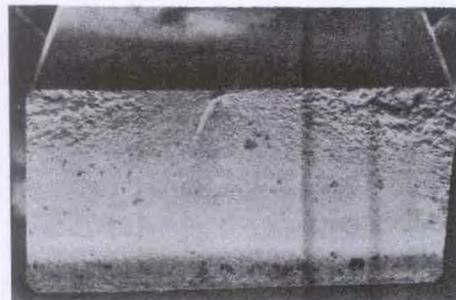
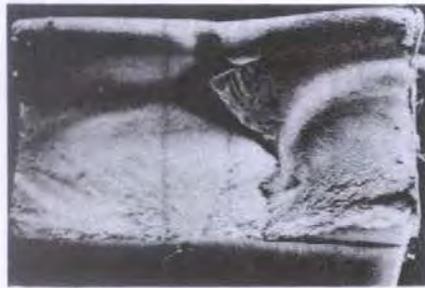


Figure 7. Fracture surfaces of specimen 3-5, showing fracture origin at seeded 125  $\mu\text{m}$  (0.005 inch) simulated void (aluminum oxide inclusion).



16X



WC Seeded Defect

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Figure 8. Fracture surfaces of specimen 3-3, showing fracture origin at seeded 125  $\mu\text{m}$  (0.005 inch) high density (tungsten carbide) inclusion.

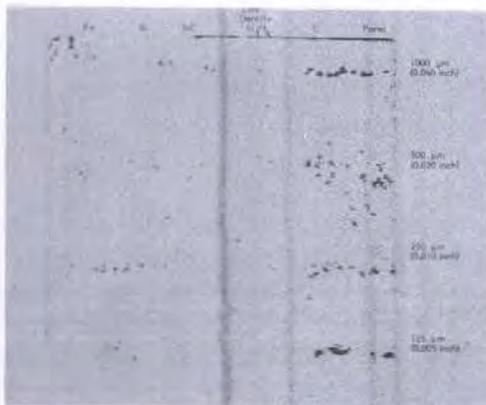


Figure 9. C-scan recording of 45 MHz longitudinal wave inspection results for Airesearch seeded billet of NC-350 reaction bonded silicon nitride.

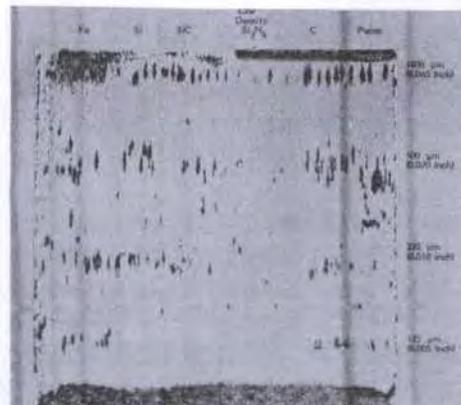


Figure 10. C-scan recording of 45 MHz shear wave inspection results for Airesearch seeded billet of NC-350, showing superior sensitivity of shear wave technique.

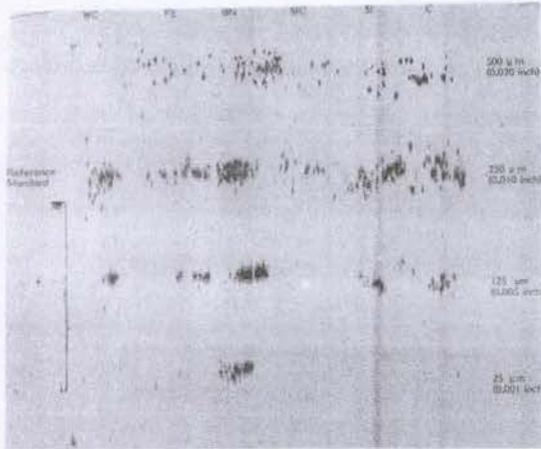


Figure 11. C-scan recording of 45 MHz longitudinal wave inspection results for Airesearch seeded billet of NC-132 hot pressed nitride.

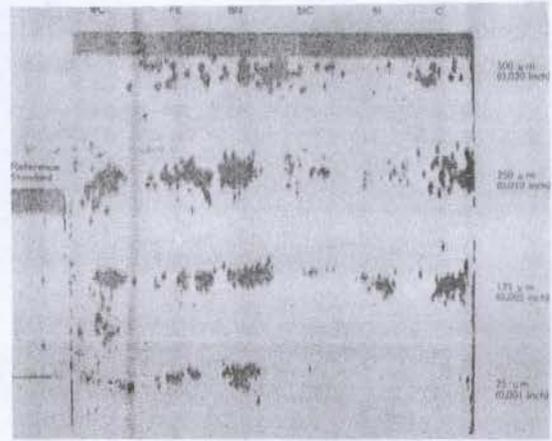


Figure 12. C-scan recording of 45 MHz shear wave inspection results for Airesearch seeded billet of NC-132, showing superior sensitivity of shear wave technique.