MICROWAVE NDE OF CERAMICS

A. J. Bahr
SRI International
Menlo Park, California 94025

ABSTRACT

The objective of this work is to evaluate the potential of microwave techniques for detecting, classifying, and determining the dimensions of inclusions and surface cracks in structural ceramics such as Si_3N_4. Experimental results that show the feasibility of detecting various types of inclusions and voids in Si_3N_4 have been obtained, and these results are reviewed. In addition, the question of the quantitative capability of microwave NDE for this application is discussed.

INTRODUCTION

In recent years, the technology for generating and controlling electromagnetic energy at frequencies of 100 GHz and above has improved considerably, and such components are now readily available. In view of this fact, we have undertaken a program to assess the applicability of this technology to the NDE of ceramic materials and components.

We have found that Si_3N_4 is nearly transparent at these high frequencies, which permits the interior of components made from this material to be inspected using microwave energy. The dielectric constant of hot-pressed Si_3N_4 is about 7.5, so the wavelength in this material at 100 GHz is about 1 mm. This electromagnetic wavelength is comparable to the acoustic wavelength of 10 MHz ultrasound in this material. Thus, microwave C-scan images can have resolutions roughly comparable to those produced by commercial ultrasonic equipment, but do not require the use of a water bath or other coupling medium in order to achieve rapid scanning. In addition, electromagnetic and ultrasonic scattering will differ for a given flaw, and thus microwave NDE may provide better flaw discrimination in some cases.

EXPERIMENTAL RESULTS

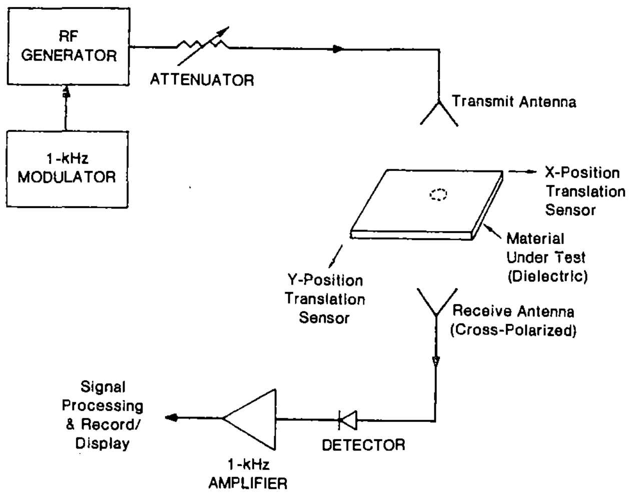
Three typical experimental arrangements that are useful in microwave NDE are shown in Figure 1. All of these schemes make use of cross-polarized scattering in order to suppress the specular scattering from the surface(s) of the part being examined. Fig. 1(a) shows a transmission scheme that is suitable for inspecting low-loss dielectric materials. As indicated, video detection can be used, but, of course, this results in limited sensitivity. Figs. 1(b) and 1(c) show backscatter schemes that eliminate the requirement for precise alignment of the transmit and receive antennas, and which permit the inspection of both dielectric materials and metallic surfaces. The orthomode coupler is used to select the cross-polarized component in the backscattered wave. Super-heterodyne or homodyne detection provides a significant increase in sensitivity, with homodyne detection providing the most information about the scatterer (flaw).

Three different plates of Norton hot-pressed NC 132 containing seeded inclusions and voids were examined using the cross-polarized transmission technique. Fig. 2 shows a microwave C-scan of a portion of a plate containing 0.020" and 0.005" inclusions of WC, Fe, Si, and C. Fig. 2(a) shows the area covered by the scan and the intended flaw locations. Fig. 2(b) shows the portions of the scan area that produce a scattered signal greater than an arbitrarily selected threshold value. Finally, Fig. 2(c) shows the amplitude of the scattered signal as a function of position within the scan area.

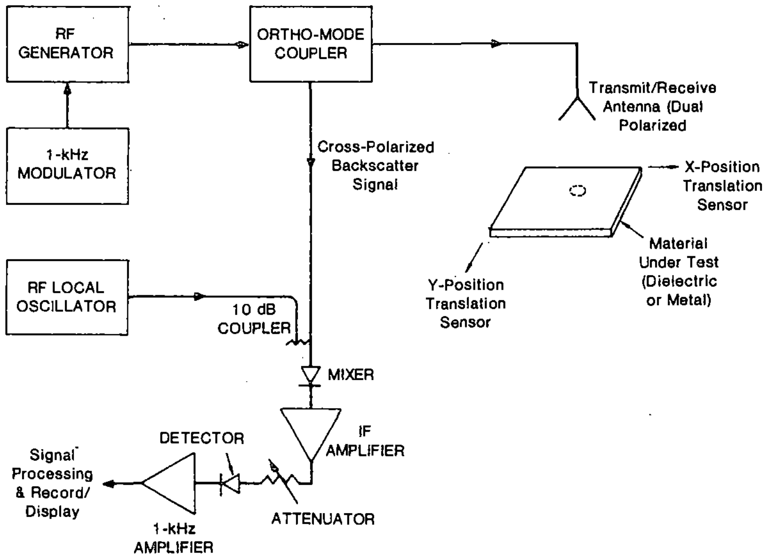
Several features of this C-scan are noteworthy. First, all 0.020" flaws are detected. Iron provides the strongest signal, and is the only 0.005" flaw that is clearly detected in this figure (the other small flaws become more apparent if the frequency is changed). Second, X-rays show that diffusion of the iron inclusion during hot pressing produces an irregularly shaped scatterer that causes the spatial extent for this flaw to appear overly large in the microwave C-scan. Finally, it appears that a crack-like flaw is present between the 0.020-inch diameter iron and silicon inclusions. Apparently, X-ray, ultrasonic, and dye-penetrant examination by AMMRC did not reveal the presence of such a flaw. If this flaw is indeed found to be real, it would indicate the superior sensitivity of the microwave technique for detecting this type of flaw.

Fig. 3 shows a similar microwave C-scan, but for a Si_3N_4 plate containing different types and densities of inclusions. All of the 0.005" inclusions are detected in this scan, but, of course, the closer spacing between inclusions may enhance this detection.

In Fig. 4 we see another scan of the same plate as in Figure 3, but of only the area containing the 0.001" through 0.010"-diameter silicon inclusions. The sensitivity of our technique for the detection of unreacted silicon appears to be good, and may be better for this purpose than other techniques. This feature could be important in process-control application.

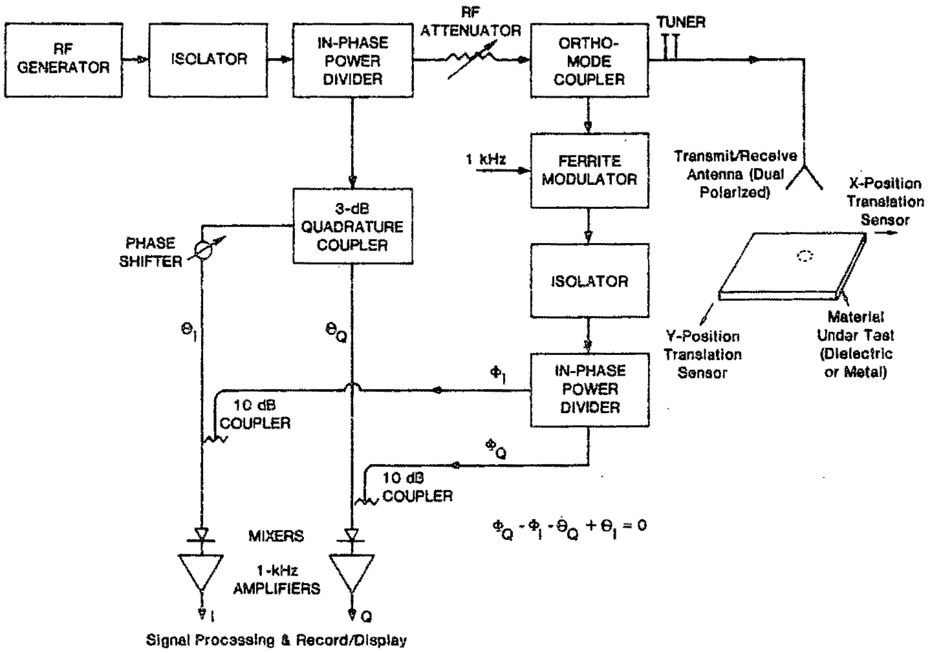


(a) CROSS-POLARIZED TRANSMISSION WITH VIDEO DETECTION (INCOHERENT)



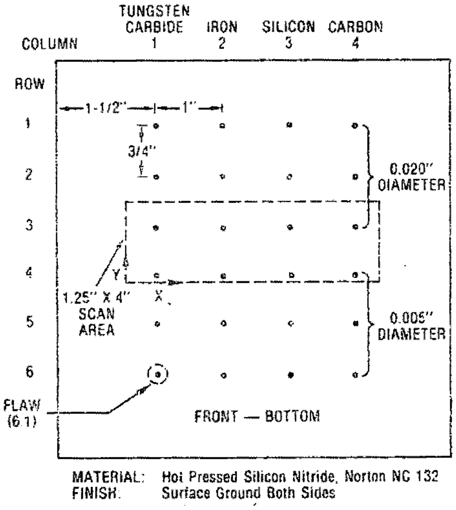
(b) CROSS-POLARIZED BACKSCATTER WITH SUPER-HETERODYNE DETECTION (INCOHERENT)

Fig. 1 Typical microwave NDE schemes

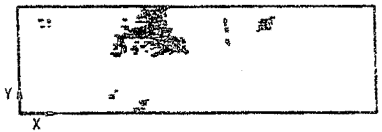


(c) CROSS-POLARIZED BACKSCATTER WITH HOMODYNE DETECTION (COHERENT)

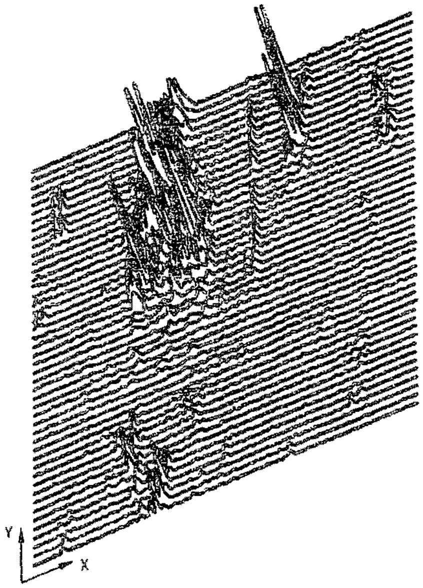
Fig. 1 (Continued)



(a) Map of Intended Flaw Locations Showing Scan Area

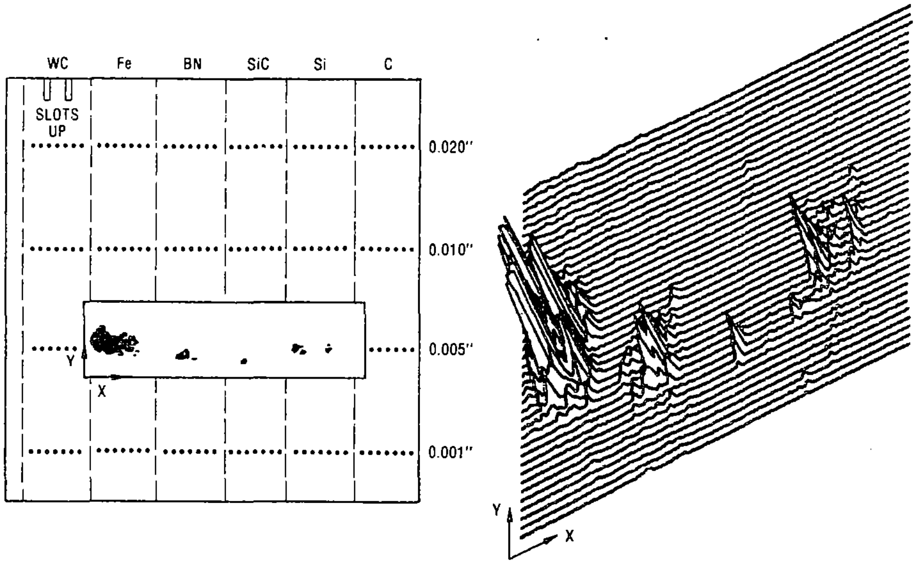


(b) Excess Signal vs. Position



(c) Amplitude vs. Position

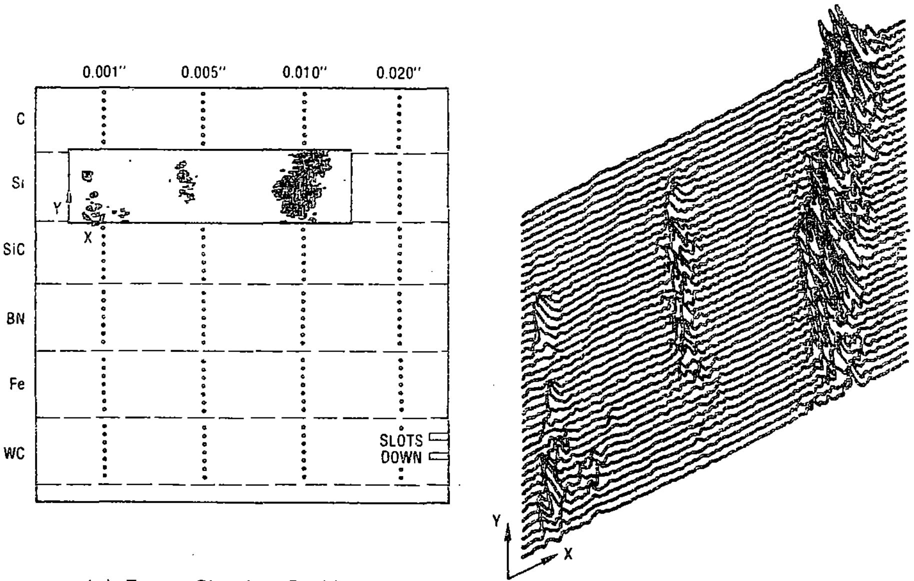
Fig. 2 Microwave cross-polarized-transmission C-scan of four types of inclusions in Si_3N_4 (frequency = 94 GHz)



(a) Excess Signal vs. Position

(b) Amplitude vs. Position

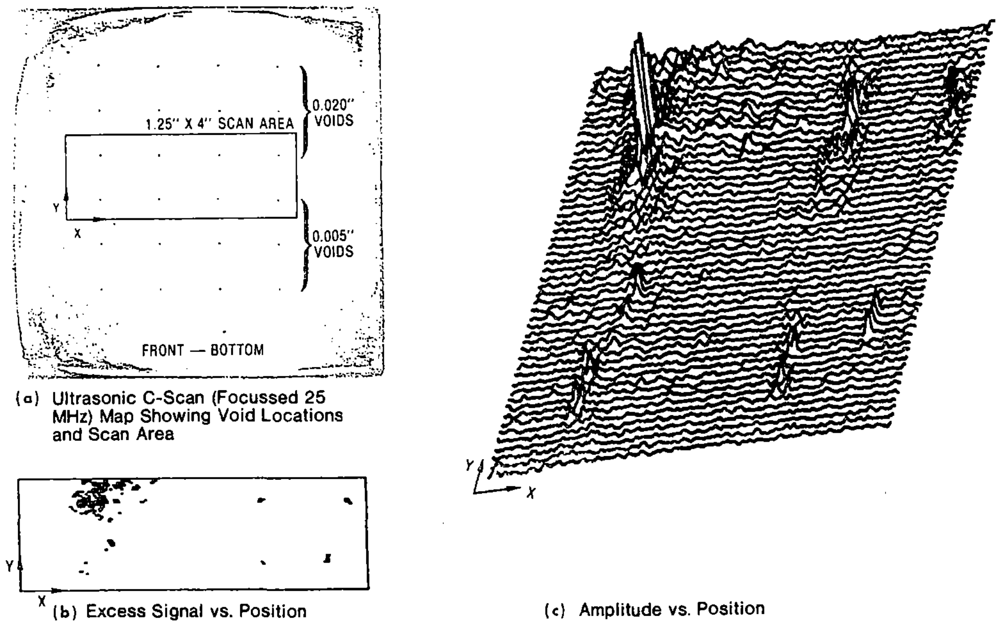
Fig. 3 Microwave cross-polarized-transmission C-scan of four types of inclusions in Si_3N_4 (frequency = 91 GHz)



(a) Excess Signal vs. Position

(b) Amplitude vs. Position

Fig. 4 Microwave cross-polarized-transmission C-scan of silicon inclusions in Si_3N_4 (frequency = 98 GHz)

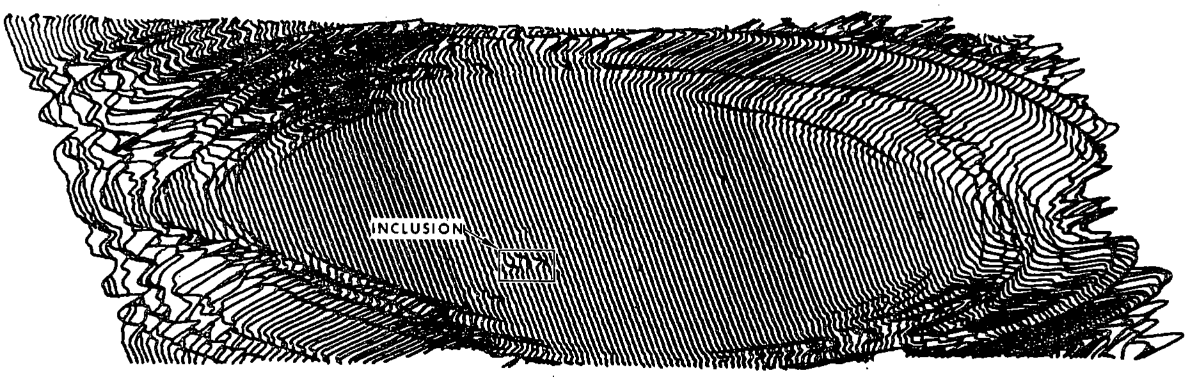


(a) Ultrasonic C-Scan (Focussed 25 MHz) Map Showing Void Locations and Scan Area

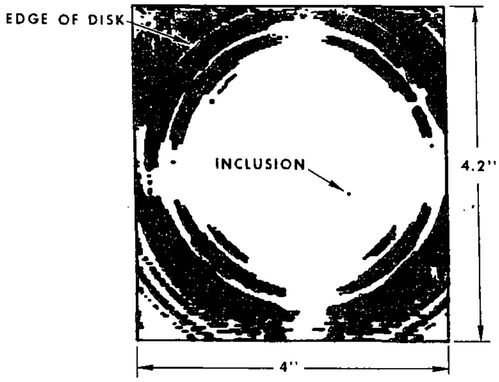
(b) Excess Signal vs. Position

(c) Amplitude vs. Position

Fig. 5 Microwave cross-polarized-transmission C-scan showing voids in Si_3N_4 (Frequency = 94 GHz)



(a) Amplitude vs. position



(b) Excess signal vs. position

Fig. 6 Microwave cross-polarized-transmission C-scan of 4" -Diameter hot-pressed Si_3N_4 disk (frequency = 94.4 GHz)

The data shown in Fig. 5 demonstrates our ability to detect small voids in Si_3N_4, as well as inclusions. The voids were formed in the interior of a 0.250"-thick plate by first drilling small holes in a 0.125"-thick plate, and then diffusion bonding this plate to a second 0.125"-thick plate. The voids that were not detected by microwaves were also weakly imaged in an X-ray, indicating that these particular holes probably were filled with some kind of material.

A hot-pressed Si_3N_4 billet in the form of a surface-ground disk was also examined using microwaves. The results are shown in Fig. 6. X-rays showed the presence of an unintended high-density inclusion in the disk, and this flaw is detected in the microwave C-scan. This experiment also shows the effect of diffraction near a sharp edge. The cross-polarized scattering from an edge is quite strong, and can be detected at a significant distance from the edge.

We conclude from these results that microwave techniques can be used to detect typical flaws that occur in ceramic materials like Si_3N_4, provided that the flaws are not located near a sharp edge.

QUANTITATIVE MICROWAVE NDE

Measurements aimed at assessing the quantitative potential of microwave NDE for ceramics using a homodyne backscatter system are planned for the near future. However, it is possible to make some general statements about the quantitative capability of microwave NDE without having specific experimental results.

In general, there are two basic approaches to the utilization of scattering data. One approach is to measure the scattered power in one direction and at one frequency, i.e., the scattering cross section, and to attempt to gain information about the flaw from this single number. The other approach can be called imaging, where the scattered power (or amplitude and phase of the scattered field) is measured over a range of directions and/or frequencies.

The measured value of scattered power in one direction depends on:

- The dimensions of the scatterer.
- The constitutive properties (dielectric constant, conductivity, etc.) of the scatterer.
- The characteristics of the transmitter and receiver, as determined at a given distance from the scatterer.

Therefore, quantitative NDE using cross section measurements requires either:

- Statistical calibration using characterized flaws in a fixed size and shape of test piece, or
- An accurate scattering theory for the flaws of interest.
- Determination of the transmitter/receiver characteristics by theory or calibration.
- Negligible (or predictable) scattering from the boundaries of the test piece.
- a priori information on all but one of the independent dimensional and constitutive parameters of the flaw.

It would appear that statistical calibration is the more feasible approach in this case.

In the case of imaging, it is sufficient to discuss two types: A-scan and C-scan. A-scan imaging involves the use of a short pulse (or many coherent frequencies) to measure the length and profile of the scatterer along the direction of propagation. Under some conditions the type of flaw may also be deducible from this measurement.

Quantitative A-scan imaging of typical internal flaws in ceramics is not feasible using microwaves. For example, even with a carrier frequency of 100 GHz, the best achievable resolution is still only on the order of 10 mm.

In C-scan imaging the transverse dimensions of the scatterer are measured by scanning the test piece (or the transmit/receive beam) perpendicular to the direction of propagation. With a microwave system it is possible to obtain a focused beam whose width is about one wavelength. For example, this width would be about 3 mm at 100 GHz.

Thus, a CW microwave C-scan imaging system can give a quantitative indication of the transverse dimension of flaws that are larger than about 3 mm and that are located several mm from the test-piece boundaries in the transverse plane. It should be noted again, however, that flaws much smaller in size can be detected by such a microwave system.

ACKNOWLEDGMENT

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