Inspection of Ceramics Incorporating Size Estimation Methods Using Conventional Ultrasonics

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One of the principal characteristics of the inspection of ceramic materials is the small size of the critical defects involved. In order to meet this challenge, either very high frequency techniques must be developed or conventional (low frequency) techniques must be used in special ways. This paper addresses the latter approach by investigating the use of commercial transducers combined with focusing techniques in a water bath at frequencies in the range of 5 to 20 MHz as well as signal analysis techniques using plane waves in the 30 to 40 MHz range using special order commercial transducers. Although the high velocity of sound in the ceramics used (silicon nitride) put some restrictions on the numerical aperture which could be obtained with acoustic lenses, a focused beam ultrasonic system for use in a water bath was designed and used to produce maps which showed the location and reflecting power of defects in flat ceramic specimens. Subsequent analysis of the reflectors discovered by this focused beam system was carried out by a hand-held ultrasonic probe which irradiated the sample with plane waves. By performing Fourier analysis of the echo signals from the "defects" and comparing the frequency spectrum observed with calculated spectra, it was possible to estimate the effective spherical size of the scattering objects. Analysis of the frequency dependence of the scattered energy in the long wave length limit also provides a measure of an effective spherical volume of the scatterer but this method was found to require additional signal processing methods which will be developed at a later date.

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**BACKGROUND**

As described on Poster 1, the basic problem with inspection of ceramic materials arises from the fact that the critical defects are small (of the order of 100 microns). Thus the ultrasonic reflections are expected to be small and near the noise level not only because of the defect's geometric size but also because the wave length of the sound wave (of the order of 500 microns at 20 MHz) is larger than the defect. Furthermore, the estimation of the size and fracture mechanics parameters of the defect from analysis of the long wave length limit of the reflected energy requires accurate, quantitative data analysis that is a demanding process even with large signals. To overcome these drawbacks, two approaches are available. One is to increase the amount of ultrasonic scattering by increasing the ultrasonic frequency in order to make the wave length equal to or less than the defect dimensions. The other is to enhance the low frequency scattering by focusing more incident energy onto the defect. The former approach is described elsewhere while the objective of this paper is to investigate the latter approach and to demonstrate the capabilities listed on the bottom of Poster 1.

Poster 2 describes the considerations necessary for implementing a focused ultrasonic beam technique for inspection of a ceramic plate. The demanding circumstance here is the unusually high ultrasonic velocity in the silicon nitride ceramic material which causes the outermost rays from the focusing transducer to be refracted strongly to a focus that is closer to the front surface than the focal point for the more centrally located sound rays. In order to minimize this effect (which is equivalent to spherical aberration in optics), the diameter or aperture of the transducer should be kept small or a liquid with a higher sound velocity than water should be used for immersion. For our experiments, it was found that a $\frac{1}{4}$4" diameter transducer had to be stopped down to $\frac{5}{16}$ inches since a water bath was used.

Poster 3 describes a second and very important consideration that appears when low frequency ultrasonic waves are used either for convenience or for obtaining scattering data in the long wave length limit. Under these conditions, the tail of the echo from the top surface of the sample may well still be present at the time of arrival of the defect echo so the two signals appear superimposed on one another and quantitative measurements of the defect echo are rendered very inaccurate. To circumvent this problem and to develop an accurate measure of the defect echo alone, the waveform characterizing the tail of the front surface echo and any other background noise was measured by moving the transducer to a defect free region and the computer was programmed to subtract this background signal from the defect plus background waveform. An example of the waveforms observed, and the results of the subtraction process are shown on the right side of Poster 3.

Once a "defect free" or background waveform had been established and stored in the computer, it could be used to subtract from all waveforms taken at different locations on the sample. Our computer was programmed to deduce and record the peak-to-peak amplitude of any signal found in a time interval chosen to encompass the region in which the sound was focused along with the X-Y coordinates of that region. From this data, a map such as the one shown in Poster 4 was made by printing X symbols with a density proportional to the signal amplitude at each coordinate location.

Following the establishment of the locations and relative scattering powers of the defects, the
ultrasonic inspection system shown in block diagram form on Poster 5 was used to irradiate the defect with high frequency, broad band, plane waves and to digitally analyze the reflected echoes. By using a sapphire buffer rod between the transducer and the sample, more energy could be delivered to the defect and far field approximations could be justified. Note that the transducer used in this system permits scattering versus frequency data to be obtained over a band of frequencies extending from below 10 MHz to above 40 MHz.

Some results of this analysis applied to echoes reflected from voids intentionally placed in silicon nitride samples are shown on Poster 6 where both theoretical and experimental curves of frequency versus reflected intensity are displayed. For voids, theoretical calculations show that the first maximum in reflectivity occurs at \( \pi a = 1.05 \) which corresponds to a frequency of 7.5 MHz for a 500 micron void and 15 MHz for a 250 \( \mu \) void. The experimental data obtained on voids presumed to be of these dimensions are shown at the bottom of Poster 6. The sample containing the 500 micron void was sectioned and the void shown in the photomicrograph was uncovered at the expected location. Its actual diameter was measured to be 580 \( \pm 10 \) microns in reasonable agreement with the expectations based on the scattering data. The conclusions reached by this study were that a commercial transducer could be fitted with a lens for operation in a conventional water bath so that a moderately high resolution map of the interior defects in silicon nitride could be generated. Because the defect echoes were small and not well separated in time from the front surface echo, special signal processing methods had to be incorporated into an on-line computer in order to make these maps. Once the defect locations were determined, the approximate size of the defect could be successfully inferred from the frequency dependence of the reflectivity measured with a specially designed, plane wave transducer equipped with a buffer rod.

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**REFERENCES**


THE INSPECTION OF CERAMIC MATERIALS AT FREQUENCIES BETWEEN 10 AND 50 MHz PRESENTS SEVERAL PROBLEMS TO BE OVERCOME:

- **THE CRITICAL DEFECTS ARE SMALL SO SIGNAL-TO-NOISE RATIOS ARE SMALL.**
- **LOW SIGNAL-TO-NOISE RATIO SIGNALS REQUIRE SPECIAL DATA PROCESSING TECHNIQUES.**
- **DEFECT SIZE ESTIMATION BY LONG WAVELENGTH SCATTERING REQUIRES SUBTRACTION OF LOW FREQUENCY COMPONENTS OF EARLIER REFLECTIONS IN THE SAMPLE.**
- **LACK OF WELL CHARACTERIZED REFERENCE SCATTERING CENTERS IN CERAMICS HINDERS ESTABLISHMENT OF DATA PROCESSING ROUTINES.**

THESE PROBLEMS WERE ATTACKED IN THIS TASK BY THE FOLLOWING TECHNIQUES:

1. **USE FOCUSED TRANSDUCERS TO IMPROVE SIGNAL-TO-NOISE RATIOS AND TO LOCALIZE SCATTERING CENTERS.**
2. **USE COMPUTER CONTROLLED SCANNING OF SAMPLES IN A WATER BATH TO PRODUCE MAPS SHOWING DEFECT LOCATIONS.**
3. **USE DIGITAL SUBTRACTION OF BACKGROUND NOISE TO BETTER DEFINE DEFECT REFLECTION SIGNAL.**
4. **USE DIGITAL FOURIER ANALYSIS OF SIGNALS TO ESTABLISH THE FREQUENCY DEPENDENCE OF THE SCATTERED ENERGY.**
5. **USE THE FIRST MAXIMUM IN THE FREQUENCY DEPENDENCE OF THE SCATTERED ENERGY TO ESTIMATE THE DEFECT SIZE.**

Poster 1 The problem and approach used for the detection, location and characterization of small defects in ceramic plates.
WE WANT TO FOCUS THE ACOUSTIC BEAM TO LOCALIZE THE DEFECT AND DISTINGUISH BETWEEN MULTIPLE DEFECTS

THE CERAMIC SAMPLE IS PLACED IN A WATER BATH AND THE ACOUSTIC BEAM IS FOCUSED WITH A LENSE. THE FOCAL LENGTH OF THE LENS IN WATER IS 38.1 MM (1.5 IN.)

THE RADIATION RAYS OF THE FOCUSED BEAM FOCUS AT A SINGLE POINT. FOR LARGER CONVERGENCE ANGLES, THE RAYS FOCUS CLOSER TO THE LENS. THE RINGING FROM THE FRONT SURFACE ECHO BECOMES MIXED IN WITH THE SIGNAL FROM THE DEFECT AND CAUSES ERRORS IN THE APPARENT PEAK TO PEAK AMPLITUDE OF THE DEFECT SIGNAL.

SOLUTION:

OBTAIN A REFERENCE WAVEFORM FROM A REGION OF THE PART THAT IS FREE OF DEFECTS AND DIGITALLY "SUBTRACT" THIS WAVEFORM FROM THE WAVEFORM CONTAINING THE DEFECT SIGNAL. RESULTS OF USING THIS TECHNIQUE ARE SHOWN BELOW.


THE OTHER METHOD FOR INCREASING THE RESOLUTION IS TO INCREASE THE FREQUENCY. THE ULTIMATE LIMITS THAT CAN BE ACHIEVED IN THIS DIRECTION HAVE NOT BEEN FULLY EVALUATED.

Poster 2 Description of the problems faced when designing a lens for use on silicon nitride samples immersed in water.

Poster 3 Graphic demonstration of the value of correcting the signal waveform for the background "noise" introduced by the front surface and other sources of ultrasonic reflections.
THE FOCUSED TRANSUDER IS SCANNED OVER THE SAMPLE IN A RASTER PATTERN. THE PEAK TO PEAK AMPLITUDE OF THE DEFECT SIGNAL IS EXTRACTED FROM THE WAVEFORM BY USING WAVEFORM SUBTRACTION AND TIME GATING. THE RESULT IS PLOTTED USING A HALF TONE TECHNIQUE TO OBTAIN A COARSE GRAY SCALE. ONE OF THE MAPS OBTAINED IS SHOWN BELOW.

Poster 4 Computer generated map displaying the location of two "defects" within a silicon nitride sample.

TRANSUDER CHARACTERISTICS

DIGITIZATION OF HIGH FREQUENCY WAVEFORMS IS ACCOMPLISHED BY COMPUTER CONTROL OF THE EXTERNAL SWEEP ON THE SAMPLING OSCILLOSCOPE.

Poster 5 Block diagram of the system used to digitize RF ultrasonic signals for the computer and the frequency response of the transducer used for the measurements.
500μ DIA VOID IN Si₃N₄
SAPPHIRE BUFFER
TRANSDUCER

THEORY

DATA (40 MHz)

500μ DIA VOID IN Si₃N₄
SAPPHIRE BUFFER
TRANSDUCER

THEORY

DATA (40 MHz)

500μ DIA VOID IN Si₃N₄
USING A 10 MHz TRANSDUCER
AND AN AL. BUFFER ROD

DATA (10 MHz)

PHOTOMICROGRAPH OF ACTUAL
500 μm VOID

Poster 6 Comparison of experimental and theoretical reflection amplitude versus frequency curves for two voids in silicon nitride samples.