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MEASUREMENTS OF SCATTERING FROM BULK DEFECTS

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ABSTRACT

This report presents results of measurements of longitudinal wave ultrasonic scattering from complex defects embedded in Ti-alloy by the diffusion bonding process. The defects examined are: circular and elliptical cracks, two overlapping voids consisting of a sphere and a prolate spheroid, two adjacent spherical voids, and a spherical void with an encircling crack. Representative plots are given for the raw waveforms, magnitude (and sometimes the phase) of the deconvolved Fourier transform, and in some cases the time impulse response function. The data are compared to or analyzed in terms of several current theories. While good quantitative agreement was observed over certain ranges, the comparisons point to definite (in some cases not unexpected) limitations in either the pertaining theory or experiment or both. Finally, the results are discussed with an eye toward applications.

OBJECTIVES AND APPROACH

The objective of this work was to carry out experimental studies on metallic components containing defects in its interior with the aid of bulk wave ultrasonic nondestructive evaluation. The investigation had the goals of (1) the design of specimens containing a variety of complex flaws and their size, shape, and orientation; (2) the characterization of the flaws in experiments which guide and evaluate theoretical scattering models; (3) the testing of inversion algorithms; and (4) the prediction of fatigue lifetime and failure.

The approach was to use diffusion bonded samples as primary test medium. Measurements were made of the angular and frequency or time domain variations of the scattered signals. The results were employed to guide the development of theoretical approaches and to test specific theoretical predictions for the cases of multiple and irregular flaws. As a guide, experimental comparisons of the differences and similarities of the scattering properties of irregularly shaped flaws and ellipsoids were used to identify those aspects of the theory which needed further work and to indicate what physical approximations seem most appropriate. Approximate theories were then checked after development. Similarly the experimental data were used to guide and check inversion algorithms in their attempt to reconstruct the shape, size, and orientation of the flaws. This information was then inserted into fracture mechanics to predict fatigue lifetime and failure, predictions which for selected samples were tested in actual fatigue cycle experiments.

SAMPLE PREPARATION

In close collaboration with the various theoretical groups representing different inversion algorithms, a unique set of diffusion bonded samples were designed and built. These samples containing a variety of irregular and multiple flaws whose scattering characteristics were being obtained in order to guide and evaluate developments of theoretical approaches and to test specific theoretical predictions.

The work was divided according to flaw type. Two flaws were simulated cracks, circular and elliptical in shape, respectively. These flaws were unique in that they possessed zero thickness yet experimentally exhibited a reflection coefficient whose imaginary term was comparable to an air-metal interface. These flaws were investigated in collaboration with Achenbach, who recently solved the inverse problem on the basis of physical elastodynamics for high frequency far-field elastic waves scattered by a flat crack. One of the flaws was a fatigue crack whose growth history was planned to be monitored in fatigue cycle experiments to test predictions of fatigue life and ultimate failure. Another flaw was a perturbation of the spherical void consisting of a small sphere and a modified prolate spheroid. This work was carried out with close collaboration between experiment and theory with the view of identifying key features suitable for data inversion. Two independent theoretical calculations were available: Domany's Distorted Wave Born Approximation and Opsal's adaptation of Visser's Matrix theory. Another flaw was a simple multiple defect consisting of two slightly separated spherical voids of equal radii. Varadan and Varadan have used matrix theory to solve the problem of scattering from similar defects so that a comparison between theory and experiment was feasible. Finally, the important problem of characterizing cracks growing from weldment voids was investigated with a sample consisting of a spherical void and a simulated (Yttria) crack emanating from the void in the form of a "saturn ring."

RESULTS AND DISCUSSION

A. Samples No. 69 and 72, Simulated (Yttria) Cracks

Achenbach et al have developed methods to analyze diffraction of elastic waves by cracks. They showed that good approximations at high frequencies can be obtained on the basis of elastodynamic theory. In the range of frequencies where the wavelengths are of the same order of magnitude as the characteristic length dimension, $a$, of the crack, the frequency dependence of the scattered amplitude shows oscillatory behavior with a period
that depends on \( \alpha \); alternatively, in the time domain the scattered field manifests itself as two waveforms separated by a time increment which depends on \( \alpha \).

As discussed in detail before,9 "trailer hitch" specimens No. 69 and 72 were prepared to simulate circular and elliptical cracks, respectively, by poisoning the bond plane area with yttria powder.10 The yttria was applied in a liquid suspension which was allowed to dry. Figure 1 shows a schematic of "trailer hitch" No. 69 and a photo of the dried yttria disk just before diffusion bonding. Ultrasonic tests of the bond plane area after diffusion bonding revealed the absence of a disbond anywhere except in the yttria area. Here, observation of complete phase reversal showed that the waves encounter a discontinuity equivalent to a metal-air interface, demonstrating the absence of any transmission through the powder to the opposite face of the simulated crack. The thickness of the yttria layer is estimated to be several yttria grain diameter, or 50 microns.

Specimens No. 69 and 72 were interrogated in pitch-catch with the transmitting transducer normal to the crack plane while the receiver transducer were placed at 0°, 15°, 30°, 45° and 55° to the crack plane. The transducers were 15 MHz, 6.35 mm diameter broadband Panametrics transducers. Figure 2a shows the pulse echo signal from the crack normal to the crack plane, while 2b, 2c, 3a, 3b, and 3c show the pitch-catch signals at 0°, 15°, 30°, 45° and 55° from the crack plane, respectively. Table 1 is a list of the time signal minima, maxima, and the time between them.

In qualitative agreement with Achenbach et al, the sound field scattered by the crack exhibited two phase inverted waveforms separated by a time interval which decreased as the receiver angle increased. An interesting feature of Table 1 is

Fig. 2 Time domain waveforms for Sample 69: Circular crack. (a) Pulse-echo signal from crack normal to crack plane. (b) Pitch-catch with transmitter at 90° and receiver at 0° with crack plane. (c) Pitch-catch same as in (b) but receiver at 15°.

Fig. 3 Pitch-catch time domain waveforms for Sample 69 circular crack. Transmitter normal to crack plane, detector at angles (a) 30°, (b) 45°, and (c) 55° above crack plane. Note coalescence of two "flash-point" signals.

Table 1

<table>
<thead>
<tr>
<th>Angle</th>
<th>Minima</th>
<th>Maxima</th>
<th>Time Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>0.00</td>
<td>1.20</td>
<td>1.20</td>
</tr>
<tr>
<td>15°</td>
<td>0.20</td>
<td>1.20</td>
<td>1.00</td>
</tr>
<tr>
<td>30°</td>
<td>0.20</td>
<td>1.00</td>
<td>0.80</td>
</tr>
<tr>
<td>45°</td>
<td>0.20</td>
<td>0.60</td>
<td>0.40</td>
</tr>
<tr>
<td>55°</td>
<td>0.20</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Table 1. Time Domain Positions of Waveform Features

<table>
<thead>
<tr>
<th>Angle from Crack Plane</th>
<th>Time of 1st Minima (μs)</th>
<th>Time of last Maxima (μs)</th>
<th>Δt (μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.405</td>
<td>0.463</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>0.425</td>
<td>0.442</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>0.430</td>
<td>0.367</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>0.567</td>
<td>0.299</td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>0.621</td>
<td>0.229</td>
<td></td>
</tr>
</tbody>
</table>

that the arrival time of the first waveform changes dramatically, whereas the second waveform appears to remain stationary with respect to an arbitrarily chosen reference given by the trigger signal. This result may be a consequence of near-field effects playing a role for the crack edge nearest to the receiving transducer.

Despite this complication, the crack diameter was estimated from the time delays, and Table 2 lists the results in good agreement with the dimensions of the micro photograph of Fig. 1. Figure 4 shows the frequency spectra corresponding to the time domain signals in Fig. 2b and 2c. The spacing between the interference minima gave crack diameter estimates in similarly good agreement.

Table 2. Comparison of Estimated and Actual Crack Dimensions

<table>
<thead>
<tr>
<th>Angle (°)</th>
<th>Δt (μs)</th>
<th>Crack Dia. (mm)</th>
<th>Manufactured Dia. (mm)</th>
<th>Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.463</td>
<td>2.87</td>
<td>2.85</td>
<td>+ 0.7</td>
</tr>
<tr>
<td>15</td>
<td>0.442</td>
<td>2.84</td>
<td>2.85</td>
<td>- 0.3</td>
</tr>
<tr>
<td>30</td>
<td>0.387</td>
<td>2.77</td>
<td>2.85</td>
<td>- 2.8</td>
</tr>
<tr>
<td>45</td>
<td>0.299</td>
<td>2.62</td>
<td>2.85</td>
<td>- 8.7</td>
</tr>
<tr>
<td>55</td>
<td>0.229</td>
<td>2.48</td>
<td>2.85</td>
<td>-16.8</td>
</tr>
</tbody>
</table>

Similar data were obtained on "trailer-hitch" No. 72, a simulated (yttria) crack in the shape of an ellipse. Here, the time delays were obtained systematically as a function of angle around the periphery of the ellipse, with the transducer making a 15° angle with the crack plane. Figure 5 shows a comparison between the estimated shape and the outline of the yttria deposit before diffusion bonding. The systematic overestimate of the dimensions suggests that during the diffusion bonding process the yttria deposit, which may have been too thick, was forced to spread somewhat and caused a somewhat larger disbond area than planned.

B. Sample No. 100, Tensile Fatigue Specimen

Specimen No. 100 was designed to allow the application of the techniques developed in the previous section for failure prediction of a fatigue crack. As shown in Fig. 6, this sample was prepared by introducing a semi-circular slot in each of two blocks which were then diffusion bonded to provide a circular starter notch for crack growth under cyclic tensile fatigue. After diffusion bonding, the block was machined into a "dogbone" geometry with the shape and size shown in Fig. 6.

The sample was inspected with ultrasound before and after machining into the "dogbone" shape. This inspection was carried out in order to have good knowledge of the 6.35 mm diameter starter notch slot. Several experiments were performed in the scanning tank, plus standard pulse echo and pitch-catch experiments. Figure 7a
The specimen was then fatigue cycled but, unfortunately, the threaded section at the grip developed a crack after only 4470 cycles, so that sample No. 100 failed prematurely and was destroyed. Figure 8 shows a micrograph of a cross section through the starter notch and the crack initiated from it. Closer examination of the starter notch revealed that the two halves intended to be mated in the diffusion bonding process were actually displaced by 10% in the bond plane along the diameter. A small displacement probably also occurred along the thickness of the notch. Calculations to estimate the number of cycles to grow the fatigue crack from the starter notch to its actual size gave $N = 3270$ cycles which is in reasonable agreement with the actual $N = 4470$ cycles.

Fig. 8 Micrograph of starter-notch and associated crack.

Unfortunately, the first ultrasonic tests were intended to be performed at 5000 cycles, so that no NDE results are available. Another sample is being readied for new tests. The design has been changed to prevent any future premature failures in the grip section.

C. Sample No. 73, Pinnochio

Previous pitch-catch measurements on the trailer hitches with the goniometer described before have been difficult because of the requirement for strong pressures to be exerted on the goniometer in order to obtain good contact between the "trailer-hitch" sample under test and the end caps which adapt the transducer to the spherical geometry. In order to avoid this problem, the following scheme was devised. First, the transmitting end cap was hard epoxyed to the sample, which resulted in an excellent stationary contact. Second, the goniometer was placed in a water bath, and a focussed transducer was used as a mobile receiver. From the radius of the curvature of the "trailer hitch" and the transducer focal length, the appropriate distance between the sample and transducer could be calculated such that the refracting ultrasonic rays became parallel in the sample. The use of this scheme eliminated lateral forces applied during the rotation of the mobile receiver transducer and still allowed good signals to be obtained without bending or distorting the goniometer.

Figure 9 is a schematic view of the double defect void, nicknamed Pinnochio. Also shown is a
Fig. 9 Sample 73: Pinnochio void. The top view is a schematic presentation of the complex void, while lower figure gives microphoto of one of the defect halves just before diffusion bonding.

Considerable difficulty was encountered in carrying out measurements as a function of angle. In order to demonstrate this problem, the defect was scanned in pulse echo at a 45° polar angle at increments of every 10° in azimuth from 0° to 350°. The results of this experiment are shown in the "waterfall" plot of Fig. 10. The plot shows a succession of time domain waveforms slightly displaced from one another. If the sample had been constructed correctly, the waveforms for azimuthal angles 0° to 180° would have been similar to the waveforms from 360° to 180°. However, in this case there are gross dissimilarities in amplitude, suggesting that the sample was not properly manufactured. Full evaluation of this sample presents yet another challenge to NDE research.

Because of these difficulties, it was decided to carry out our studies in the frequency domain. Figure 11 shows, at the top, a waveform obtained, when the defect was interrogated in pulse-echo from the side, i.e., as a profile of the head and nose. The graph below shows the corresponding deconvolved Fourier spectrum compared with two theories: Domany's Distorted Wave Born Approximation (DWBA) and Vissher's matrix theory. The agreement is reasonably good, especially in the frequency range from 1 MHz to 6 MHz. Above 6 MHz as might be expected, DWBA theory becomes less accurate, since k<a exceeds the range of applicability of the Born approximation approach. Agreement between matrix theory and experiment is reasonable to as high as 12 MHz.

D. Sample No. 95, Double Void

This defect consists of two 800 μm diameter spherical voids separated center-to-center by 1200 μm. Figure 12 shows the defect schematically and in the form of a microphoto just before diffusion bonding. The defect was studied in pulse-echo in a plane containing the axis through the centers of the two defects and the plane normal to the two centers. Figure 13a shows the time-domain waveform for the transducer at 70° from the axis through the void centers. This signal shows two
well-resolved echoes which when Fourier analysed and de-convolved gave well-defined interference minima, as shown in Fig. 13b. Figure 13c is the inverse Fourier transform or the time impulse response function, that is to say, the time-domain waveform of Fig. 13a without the transducer transfer function.

In order to determine the exact phase relationship between these two signals, each signal was windowed, matched according to the waveform centroid and phase compared. Figure 14a is the spectrum of the magnitude ratio and figure 14b is that of the phase difference. It is interesting to note that the phase difference is approximately zero plus or minus 4 degrees over most of the useful frequency range of the transducer. This result is expected because the signals are reflections from identical sources.

Finally, a quantitative comparison was made between the experiment and calculations by Varadan and Varadan. This comparison is shown in Figure 15 which plots the data of Fig. 13b in terms of the scattering cross section versus $ka$, where $a$ is the radius of the sphere. Nearly quantitative agreement was realized over most of the useful range of the transducer.

E. Sample No. 71, "Saturn Ring"

An extension of the crack problem to important applications is the detection and characterization of cracks emanating from voids. This is a frequently encountered problem in weldments. To simulate this situation a "trailer hitch" sample was fabricated consisting of a spherical void 800 $\mu$m in diameter with a yttria powder ring around it having a diameter of 1.5-1.70 mm. Figure 16 shows the bottom half of the trailer-hitch sample with a schematic drawing in the top part of the figure and a photo of the actual defect on the bottom. The microphoto shows one-
Comparison between theory and experiment for double-void. The experimental frequency spectrum is fitted to the theory of Varadan at one point.

This defect was interrogated with longitudinal waves in pulse-echo and pitch-catch and Figs. 17 and 18 are examples of the pulse echo data. A key feature of the data is the appearance of a double echo as shown in Fig. 17a when the transducer is placed at 45° to the crack plane. As expected, the double echo manifests itself in an interference pattern in the deconvolved frequency spectrum, Fig. 17b and as two impulses in the impulse response function, Fig. 17c. This result is a clear-cut indication of the presence of an additional feature besides the spherical void. The two echoes are about 0.40 μs apart corresponding to a distance of \( d = 1.7 \) μm. This value compares favorably with the outer diameter of the yttria ring. Another key feature is illustrated in Fig. 18 which presents a pulse-echo signal normal to the crack plane in Fig. 18a and in the crack plane in Fig. 18b. The main difference between the two signals is the dramatic change in amplitude, a factor of 20. Since a spherical void would give a completely isotropic response, this result shows how much the presence of the crack influences the data.

The data of Fig. 17a were examined more critically to achieve a quantitative comparison with theory. Figure 19 shows at the top the received waveform again and at the bottom the deconvolved frequency spectrum. Also shown are points calculated by J. Opsal using Vischer's matrix theory. The theoretical points are fitted to the experimental data at one point. The comparison is in reasonable agreement, especially for the positions of the nulls and peaks in the spectrum. Notice, that the deep null between 6 MHz and 7 MHz makes this spectrum dramatically different from that of a simple spherical void.
Fig. 18 Saturn Ring defect interrogated in pulse-echo at (a) normal to crack plane (b) in crack plane.

Fig. 19 Frequency spectrum for Saturn Ring interrogated in pulse-echo at 45° to the plane of the crack compared with theoretical calculations.

ACKNOWLEDGEMENT

The authors are grateful to J. Achenbach, V. V. Varadan, V. K. Varadan, J. Opsal, and E. Domany for their calculations allowing the direct comparisons between theory and experiment. They are also indebted to O. Buck for the design and preparation of the fatigue specimen.

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REFERENCES

11. O. Buck, private communication.
SUMMARY DISCUSSION

Bruce Thompson, Chairman (Rockwell Science Center [now Ames Laboratory]): I think we have time to entertain one or two questions.

Anmol Singh (Southwest Research Institute): How did you find the response function?

Bernie Tittmann (Science Center): We found the response function in two ways. We cut the trailer hitch in half so we have the flat face at the diffusion bonding plane and then we set the transducer on the top and let it radiate against its metal interface. The other one that we use is a spherical void for which we have the exact calculations, and we can predict what the radiation pattern should look like and then divide out to get the transducer response.

Bruce Thompson, Chairman: Thank you, Bernie. I think the remainder of the questions should be answered at the coffee break. Dr. Tittmann is chairing the next session.