RESONANT SCATTERING AND CRACK SIZING

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INTRODUCTION

Theoretical consideration of ultrasonic scattering from interior cracks has received considerable attention in recent years. These studies have led to scattering amplitude computations for ultrasonic backscatter from circular cracks by the method of optimal truncation (MOOT) (1,2) and by T-matrix techniques (3). A key observation in these results is that a peak in the magnitude of the scattering amplitude is found to occur at approximately ka = 1, where k is the longitudinal wave number and a the crack radius, which is independent of the scattering direction. Up to the present, however, adequate experimental verification of these findings have been impossible due to a lack of suitable laboratory samples.

This paper will present new experimental results obtained from a set of diffusion bonded samples containing simulated circular and square cracks at the bond plane. Good agreement of the data with the theoretical calculations is observed for L-L backscatter. In addition, the experimental evidence also suggests similar phenomena for T-T backscatter from circular cracks and for both L-L and T-T scattering from square cracks, cases for which no theoretical computations are currently available. These findings will be accompanied by an example of their utility in determining the size and orientation of circular cracks from a single ultrasonic measurement.

APPROACH

Figure 1 shows a compilation of theoretically computed scattering amplitudes of a smooth circular crack for several directions of L-L backscatter extending from normal incidence ($\theta=0$) to edge-on ($\theta=90°$). In each a peak is observed at the frequency approximately specified by ka=1, where k is the longitudinal wave number and a is the crack radius. (A similar observation has been made on theoretical calculations for simulated rough circular cracks (4), although these results are not shown here.) Note that only the strength and not the frequency of this peak varies with respect to the angle of illumination. This is in contrast to the other features in the spectra which arise predominantly from diffraction from the crack edges (flash-points).

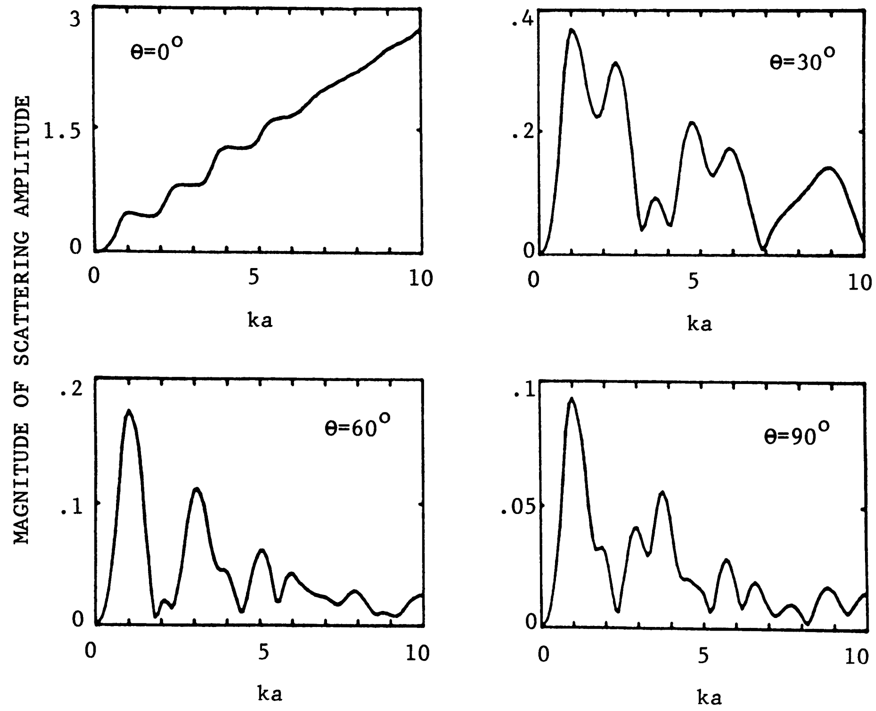


Fig. 1. Theoretical (MOOT) scattering amplitudes for a circular crack at several incident angles showing peaks at ka=1.

Experimental verification of these results has been hindered by inadequate laboratory samples. Preliminary results, of an inconclusive nature, were reported last year (5) concerning experiments performed on laser induced cracks in thermoplastic samples (6). Although some data conformed to the theoretical predictions, particularly at angles approaching edge-on incidence, others did not. The causes of these discrepancies are not well understood, but may be due to partial contact of the crack faces. Therefore, new experiments have recently been performed on diffusion-bonded samples of IN100 and titanium which contain well characterized simulated cracks in the bond plane. Results from these experiments will be presented in the next section.

In order to assess the theoretical expectations, the scattering amplitude for the cracks is required. In fact, the sought after peak at ka=1 may be obscured by the frequency response of the ultrasonic system used. In order to eliminate these systematic effects, the measurement model of Thompson and Gray (7) was used to deconvolve the experimental data. (A further discussion of experiments performed on these samples may be found in Ref. 8 elsewhere in these proceedings.) As an example of the utility of this model, Fig. 2 shows the scattered spectrum at a 30 degree angle from a circular crack in IN100 both before and after deconvolution. Note that the peak at roughly 3 MHz in Fig. 2b is nearly indistinguishable before deconvolution, as seen in Fig. 2a. Also, note that the theoretical MOOT results are superimposed in Fig. 2b on the same absolute scale as the experimental data. All

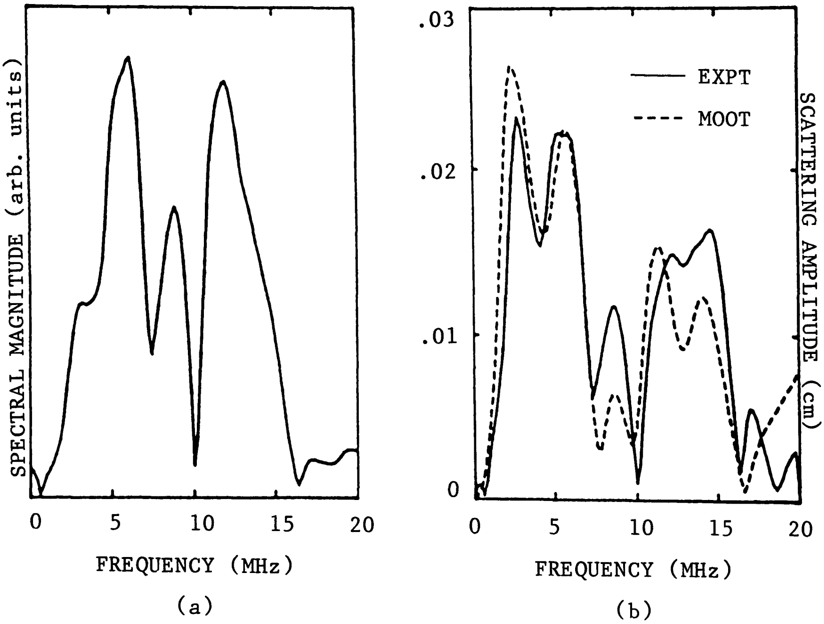


Fig. 2. (a) Raw spectrum from a circular simulated crack in IN100 at a 30° incident angle. (b) Processed experimental spectrum (solid line) for the signal in (a) compared to MOOT calculation (dashed line).

experimental data to be presented here were processed by this measurement model.

RESULTS

Experiments on circular and square simulated cracks in diffusion bonded IN100 and titanium samples were performed in the configuration illustrated in Fig. 3. The circular cracks were nominally .038cm in radius and oriented parallel to the sample surface, as shown, and the square cracks were .070cm on a side and oriented perpendicular to the surface. All defects had a finite thickness of roughly .009cm, and both samples contained nominally identical flaws. Experiments were performed in an immersion tank using a .635cm diameter, 10 MHz transducer with a usable bandwidth of approximately 1.5-15 MHz. The probe was positioned sufficiently far from the samples to assure far field response.

Figure 4 summarizes the results of experiments performed on the circular cracks in both samples for L-L and T-T backscatter. This figure shows the longitudinal wave number $k = 2\pi f/c$, where f is frequency and c the longitudinal wave velocity, as a function of incident angle θ relative to the crack normal. Note that the theoretical expectation of $ka=1$ for $a=0.038$cm corresponds to $k=26.3\text{cm}^{-1}$. The experimental data overestimate this result slightly and exhibit modest scatter.

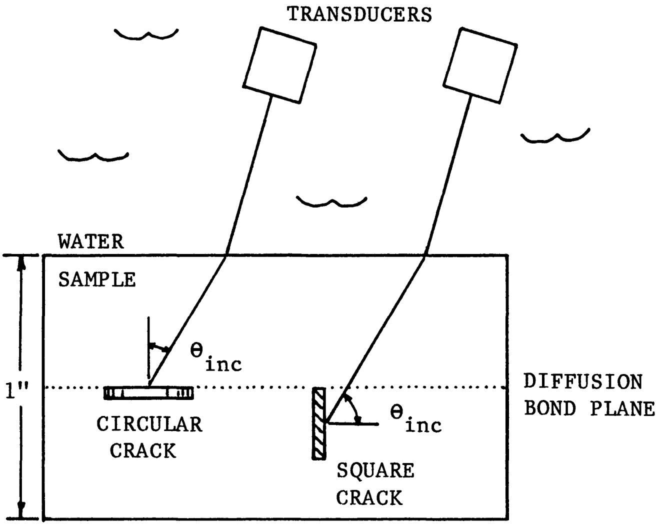


Fig. 3. Experimental configuration.

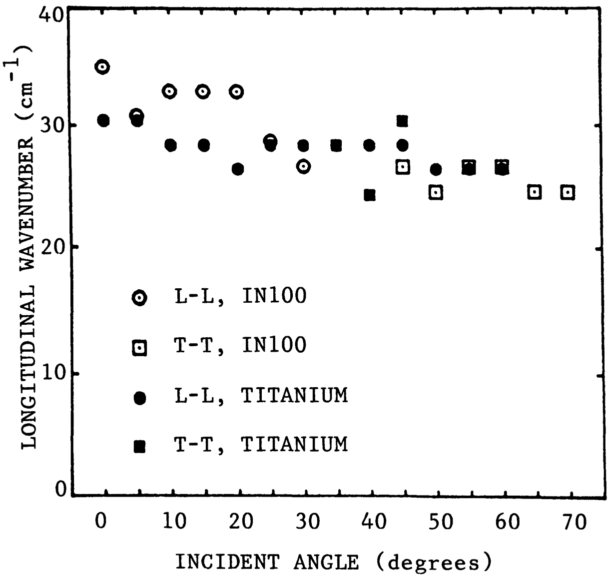


Fig. 4. Longitudinal wavenumber ($k=2\pi f/c_L$) of the first peak in the scattering amplitudes for measurement from simulated circular cracks in IN100 and titanium as a function of incident angle.

Possible explanations for these deviations are experimental error - which was estimated to be roughly $\pm 2\text{cm}^{-1}$ in wave number - and deviation from nominal specifications of the defects, - radius tolerance is specified at ±.0025cm.

Similar experiments were also performed on the square simulated cracks. Figure 5 shows a summary of results from the two samples obtained for L-L backscatter. The results from the samples were quite favorable in that an easily identifiable peak was observed in the scattering amplitudes which exhibited fairly little deviation with respect to illumination angle. No theoretical calculations have been performed to support these data. However, it seems reasonable to speculate a relationship for these square defects similar to that deduced for the circular cracks. A likely such formula may be $kh/2=1$, where h is the length of one side of the square. This would predict $k=28.6\text{cm}^{-1}$ which is quite close to the data shown in Fig. 5. It should be noted that all data were taken in a vertical plane in which illumination was perpendicular to the top edge of the crack. The above result may not hold for different orientations.

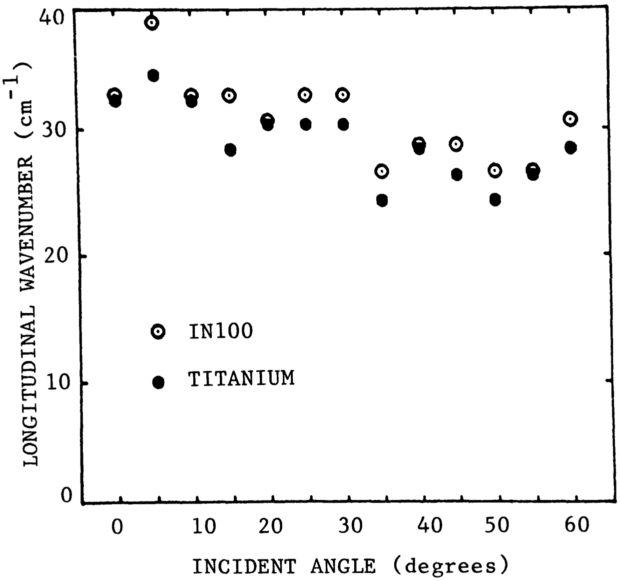
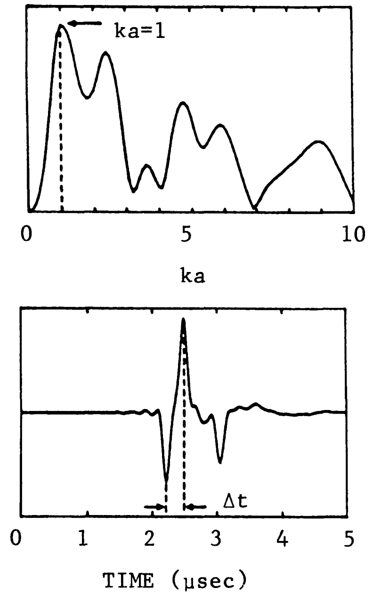


Fig. 5. Longitudinal wavenumber ($k=2\pi f/C_L$) of the first peak in the scattering amplitudes for measurements from simulated square cracks in IN100 and titanium as a function of incident angle.

APPLICATION TO CRACK SIZING

A straight-forward use of the scattering results discussed above provides a simple means for crack characterization, as outlined in Fig. 6. Knowledge of the longitudinal acoustic velocity c and the frequency f of the first peak of the scattering amplitude yields a direct estimate of the crack radius a, namely $a \simeq c/2\pi f$. Additional information may be obtained from the inverse Fourier transform of the scattering amplitude (the impulse response) by identification of the flash-point signals, as shown in Fig. 6. The time delay Δt

between these signals is simply related to the crack radius and angle θ between the backscattered direction and the crack normal by $\Delta t = 4a\sin\theta/c$. (Note that c in this equation is the shear velocity for T-T backscatter measurements.) Thus, if a is determined as above and Δt is measured, θ can be estimated. This combined approach yields both the crack radius and the angle of the crack relative to the incident direction from a single backscatter measurement. Figure 7 shows the results of such an analysis based upon the experimental data from the circular crack in the titanium sample.



$$ka = \frac{2\pi fa}{c} = 1$$

$$\text{SO,} \quad a = \frac{c}{2\pi f}$$

$$\Delta t = \frac{4a\sin\theta}{c}$$

$$\text{SO,} \quad \theta = \sin^{-1}\left(\frac{c\Delta t}{4a}\right)$$

Fig. 6. Technique for estimating the size and orientation of a crack from a single backscatter measurement.

SUMMARY

Experimental evidence has been presented which supports the theoretical predictions of resonant-type peak in the scattering amplitude from circular cracks. These results have been shown to hold promise for determining both the size and orientation of such a crack from a single ultrasonic measurement. The simplicity of these results further suggests that a simple model for scattering from cracks may be feasible and current research is being directed along these lines.

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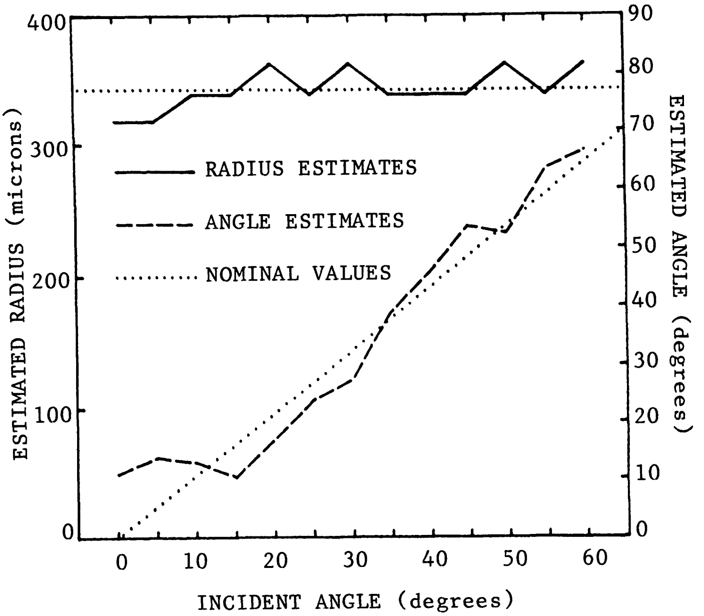

Fig. 7. Results of estimating the size (solid line) and orientation (dashed line) of a simulated circular crack in titanium at various illumination angles.

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