FREQUENCY DEPENDENCE OF ULTRASONIC WAVE SCATTERING FROM CRACKS

Laszlo Adler and Kent Lewis
Department of Physics
The University of Tennessee
Knoxville, Tennessee 37916

ABSTRACT

Studies of spectral analysis of the scattered longitudinal and shear waves from crack-like flaws in solids were carried out in the region of $ka \geq 1$. Experimental data are analyzed and compared to two new theories developed recently for elastic wave diffraction from cracks. These theories relate the amplitude spectra of scattered L and S waves to crack parameters such as size, orientation, surface roughness, etc. On the development of the interpretation obtained from phase spectral information the scattered phase from spherical cavities was calculated from exact theory and compared to experimental data.

THEORY

The scattering (diffraction) of ultrasonic waves from circular cracks in metals was analyzed based on two approximate diffraction theories.
(1) Developed by Adler et al.:[1] This theory works for normal incidence. It is based on modifying Keller's geometrical theory of diffraction[2] for the elastic wave problem (modified Keller). The diffraction coefficients for the diffracted shear and longitudinal waves are calculated by using the solutions of Maue[3] for the diffraction of waves by semi-infinite plane. For a circular crack with radius a (Fig. 1) the diffracted L field at a point is given by equations (Fig. 2). Similar expressions may be obtained for the scattered shear waves. Fig. 3 and Fig. 4 are calculated L and S diffracted field amplitude as a function of frequency.
(2) Developed by Achenbach et al.:[4] The so-called elastic dynamic theory (described in detail by Achenbach in this report).

EXPERIMENT

The normally incident L wave diffracted by a circular crack of 2500μ radius is analyzed by both an analog and digital spectrum analyzer system (Fig. 5). The various incident and scattered waves are illustrated by a "time mapping" scheme (Fig. 6). Capability of the signal processing system is shown on Fig. 7 by the transfer function. Correction of the data has to be made because the spectra through the liquid-solid interface changes with angle. This is demonstrated by rotating the sample and recording the transmitted spectra for different angles of orientation (Figs. 8, 9, 10, 11).

RESULTS

Typical scattered L and S data from the 2500μ crack are shown on Figs. 12 and 13. In addition to the RF, the amplitude and phase spectra are shown. The amount of L and S wave produced at various angles at the cavity is shown on Fig. 14. Fig. 12 is corrected by the transmission spectra given by Fig. 11 and compared to both theories (Fig. 15) favorably. The shear data clearly differs from the theoretical prediction given on Fig. 4. The surface ray contribution—predicted by Achenbach's theory—may explain the origin of such irregularities. The radiograph on Fig. 16 gives the side view of a circular crack inside the titanium. The diffusion process introduces a small bending on the top surface of the crack. No significant difference was observed in the spectra by turning the sample around (Fig. 17). This confirms the prediction of the ray theory, i.e., rays originating at sharp corners.

PHASE SPECTROSCOPY

Since digital spectrum analysis gives phase information, the possibility of using phase spectroscopy (in addition to amplitude spectroscopy) to characterize defects is also studied. Calculations for scattered L waves from spherical cavities in titanium based on exact theory of Ying and Truell[5] shows that the scattered phase spectra is size dependent. There is also angular dependence. See Figs. 18, 19, 20. Experimental results compare reasonably well with theory—shown on Fig. 21—to assume that phase spectroscopy coupled with amplitude spectroscopy can be developed to be a powerful tool of flaw characterization.

ACKNOWLEDGEMENT

This research was sponsored by the Center for Advanced NDE operated by the Science Center, Rockwell International, for the Advanced Research Projects Agency and the Air Force Materials Laboratory under Contract F33615-74-C-5180.

REFERENCES

1. Kent Lewis, Peter Szilas, Dale Fitting, and Laszlo Adler, J. Acoust. Soc. of Am., 63, 574 (1978).
2. J. B. Keller, J. Appl. Phys., 28, 426 (1957).
3. A. W. Maue, Z. Für Angew. Math. U. Mech., 33, 1 (1953).
4. J. D. Achenbach and A. K. Gautesen, J. Acoust. Soc. of Am., 61, 413 (1977).
5. C. F. Ying and R. Truell, J. Appl. Phys., 27, 1086 (1956).

Diffraction of Elastic Waves by Circular Cracks in Metals. Modified Keller Theory Developed by Adler et al.

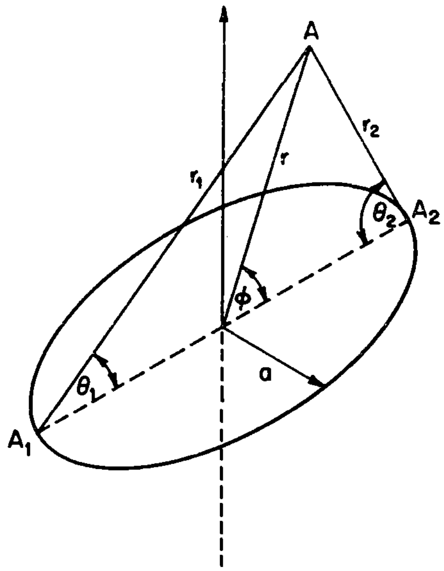


Fig. 1. Circular aperture

The amplitude of the diffracted L wave is given as

$$u_D(P) = f(r)g_k(\phi) \quad (1)$$

where

$$f(r) = -A\,\frac{e^{ikr}}{r} \quad (2)$$

and

$$g_k(\phi) = \frac{k^2}{\sqrt{K}}\,\frac{\cos\phi}{\left(\frac{\sin\phi}{a}\right)^{1/2}}\,\{[\cos(ka\sin\phi)[P(-k\sin\phi)] + P(k\sin\phi)\sin(ka\sin\phi)]$$

$$- i[P(-k\sin\phi)\sin(ka\sin\phi) + P(k\sin\phi)\cos(ka\sin\phi)]\} \quad (3)$$

where

$$P(\lambda) = \frac{1}{2\pi}\left(\frac{K-\lambda}{K}\right)^{1/2} \cdot \frac{F_2(\lambda)}{F_2(0)} \cdot \frac{\left(\frac{K^2}{2} - \lambda^2\right)\left(\frac{K^2}{2}\right)}{\left(\frac{K^2}{2} - \lambda^2\right)^2 + \lambda^2\sqrt{(k^2 - \lambda^2)(K^2 - \lambda^2)}} \quad (4)$$

where $F_2(\lambda) = e^{f_2(\lambda)}$

$$f_2(\lambda) = \ln\frac{\lambda_R - \lambda}{K-\lambda} + \frac{1}{\pi}\int_k^K \arctan\left(\frac{\left(\frac{K^2}{2} - z^2\right)^2}{z^2\sqrt{(z^2 - k^2)(K^2 - z^2)}}\right) \cdot \frac{dz}{z-\lambda} \quad (5)$$

k is the L wave number

K is the S wave number

$\lambda_R = \frac{\omega}{C_R}$. C_R is the Rayleigh velocity.

Fig. 2. Expressions for the diffracted amplitude

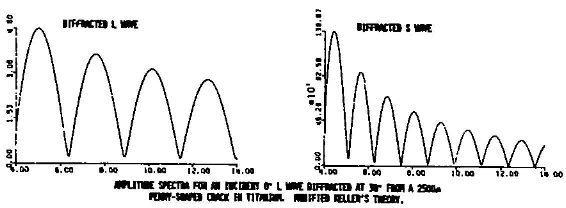


Fig. 3

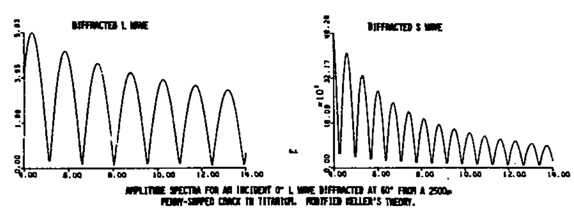


Fig. 4

Fig. 3 & 4. Calculated amplitude spectra for diffracted longitudinal and shear waves

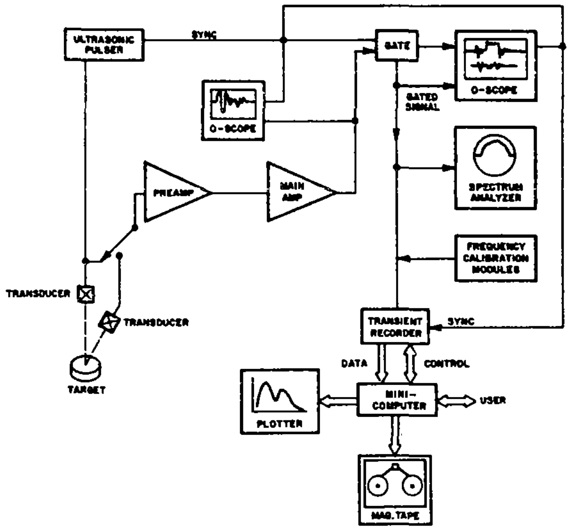
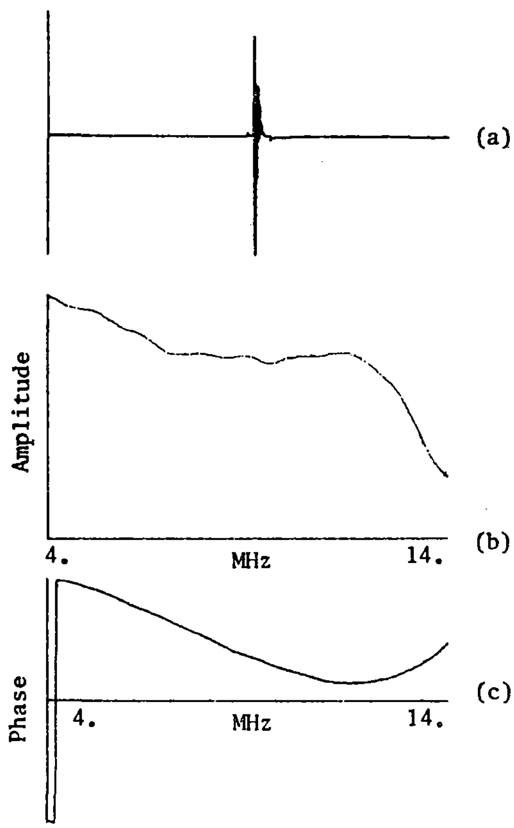


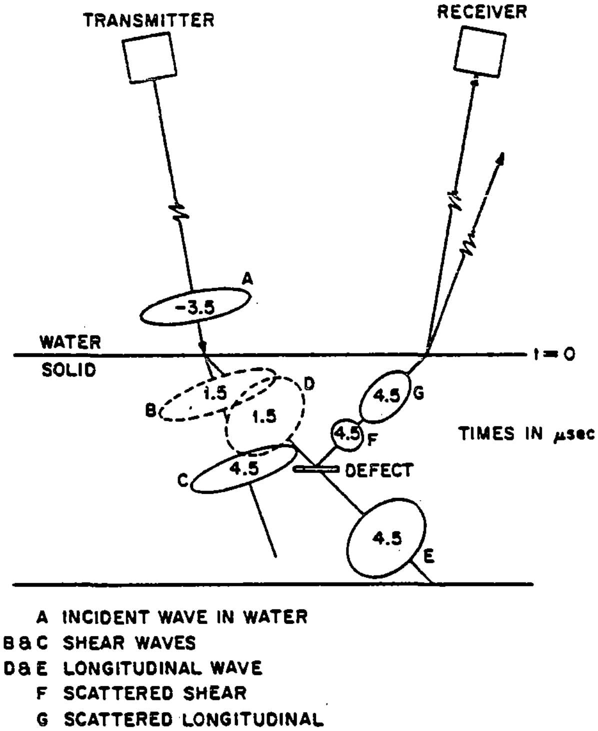
Fig. 5. Lxperimental system for analog and digital spectrum analysis



Transducer Output

(a) R.F. waveform; (b) amplitude spectrum; (c) phase spectrum.

Fig. 7. Transducer transfer function



Time Mapping" of Shear and Longitudinal Waves before and after Interaction with Defect.

Fig. 6. Experimental technique and "time mapping" of incident and scattered pulses

The Distribution of the Transmission Spectra Through Liquid-Solid Interface Changes with Angle

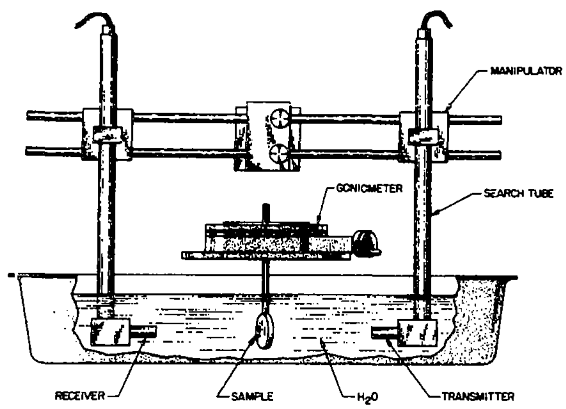
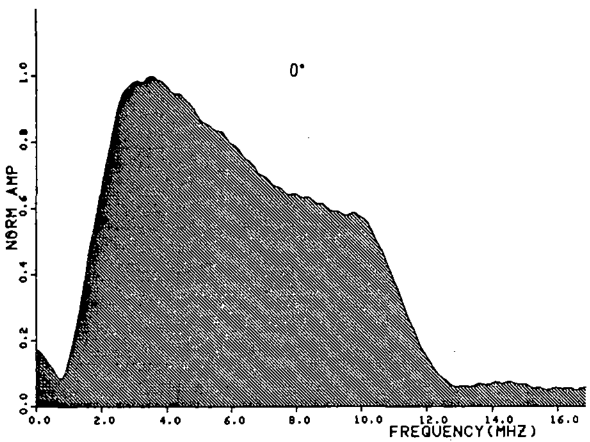
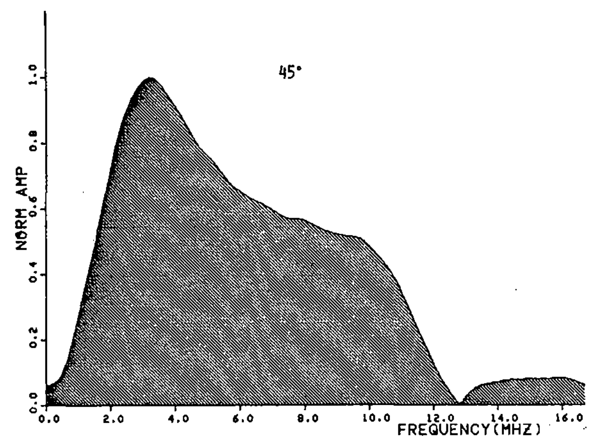


Fig. 8. Experimental system to measure transmitted spectra through titanium sample



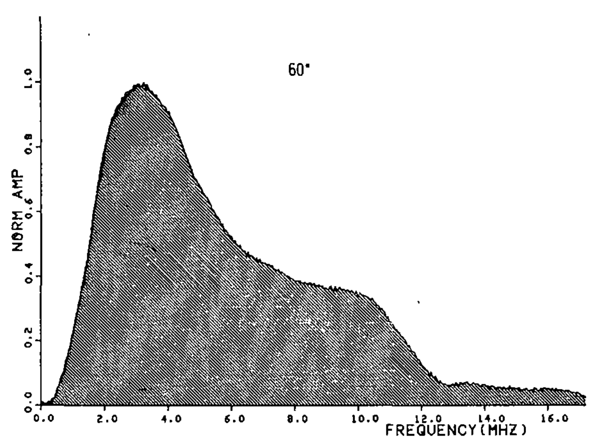
TRANSMISSION SPECTRUM OF AN L WAVE THROUGH A 2.5 CM-THICK TITANIUM DISK IN WATER

Fig. 9



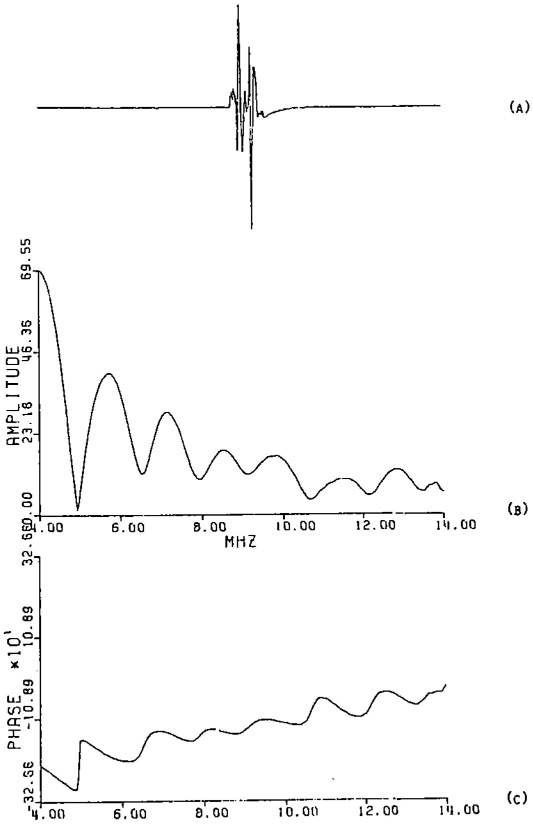
TRANSMISSION SPECTRUM OF AN L WAVE THROUGH A 2.5 CM-THICK TITANIUM DISK IN WATER

Fig. 10



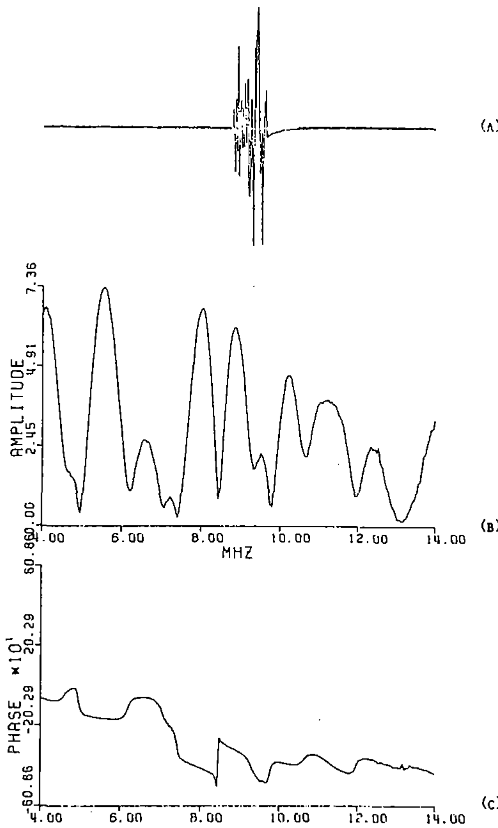
TRANSMISSION SPECTRUM OF AN L WAVE THROUGH A 2.5 CM-THICK TITANIUM DISK IN WATER

Fig. 11



SCATTERED LONGITUDINAL WAVE FROM A 2500μ RADIUS CRACK IN TITANIUM. SCATTERING ANGLE IS 60°. (A) R.F. WAVEFORM; (B) AMPLITUDE SPECTRUM; (C) PHASE SPECTRUM.

Fig. 12. Longitudinal wave



SCATTERED SHEAR WAVE FROM A 2500μ RADIUS CRACK IN TITANIUM. SCATTERING ANGLE IS 60°. (A) R.F. WAVEFORM; (B) AMPLITUDE SPECTRUM; (C) PHASE SPECTRUM.

Fig. 13. Shear wave

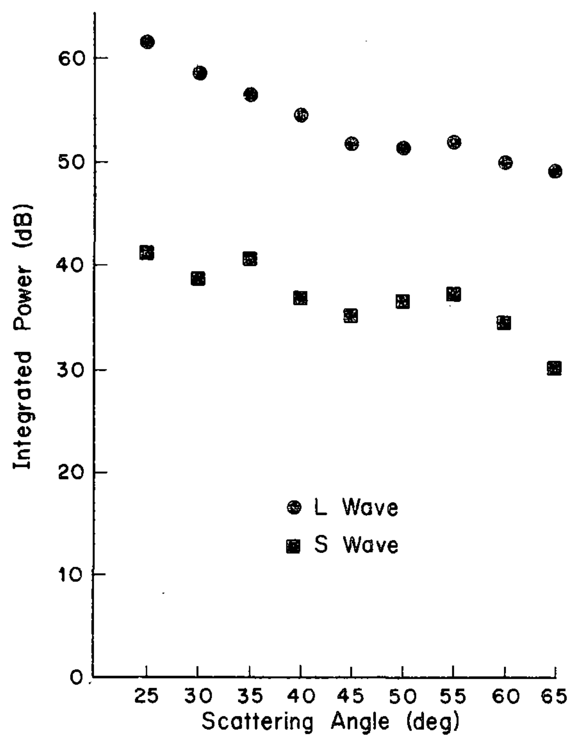


Fig. 14. Incident L wave scattered from a penny shaped crack of 2500μ radius in titanium

Comparison of Experimental Data to Modified Keller Theory (by Adler et al.)
and to Elastodynamic Theory (by Achenbach et al.)

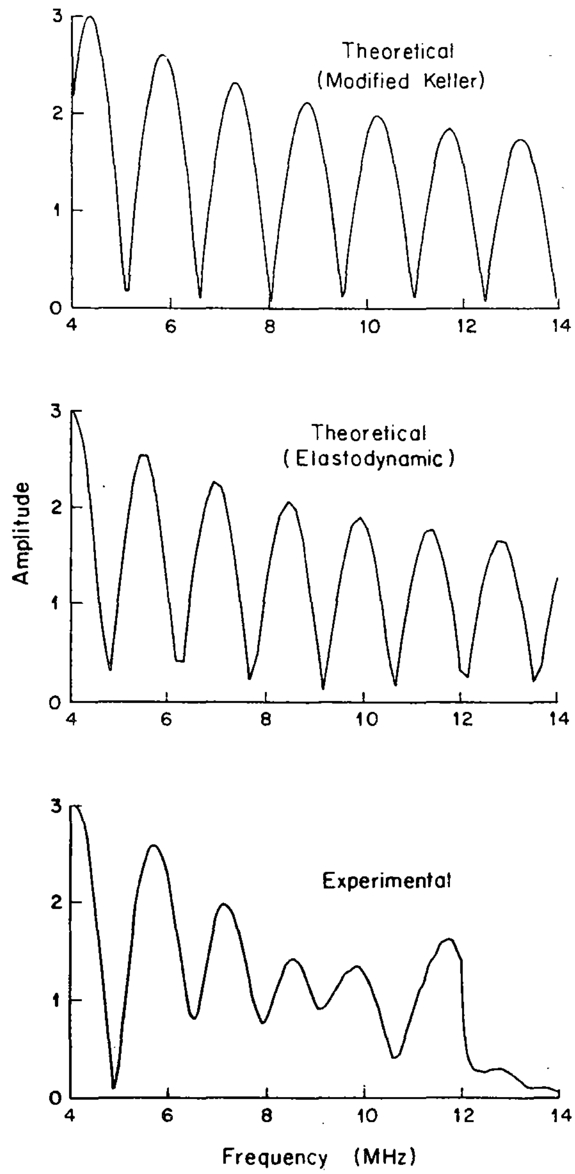


Fig. 15. Scattered longitudinal wave from a 2500μ radius crack in titanium, scattering angle is 60°.

Slight Curvature on the Crack Will Not Affect Significantly the Diffracted Amplitude Spectra

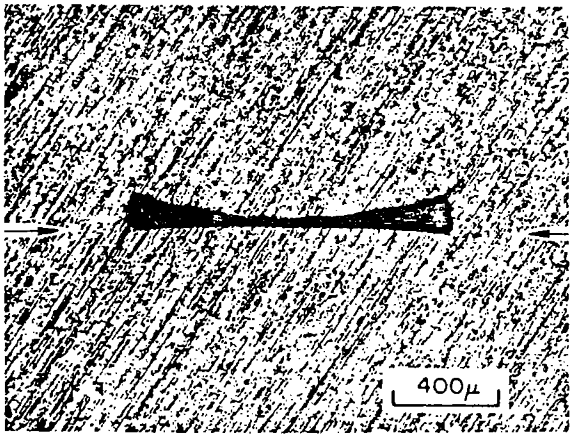


Fig. 16. Side view radiography of the defect

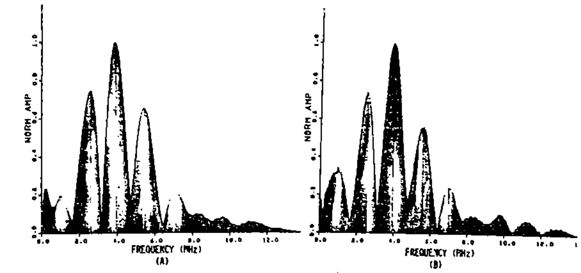


Fig. 17. Amplitude spectra for an incident 0° L wave diffracted to a 60° L wave from a 2500μ penny-shaped crack in titanium alloy. (A) top side; (B) bottom side

Phase Spectroscopy for Flaw Characterization

Exact Theory of Elastic Wave Scattering by Spherical Cavity in Titanium Relates Phase Spectra to Cavity Size.

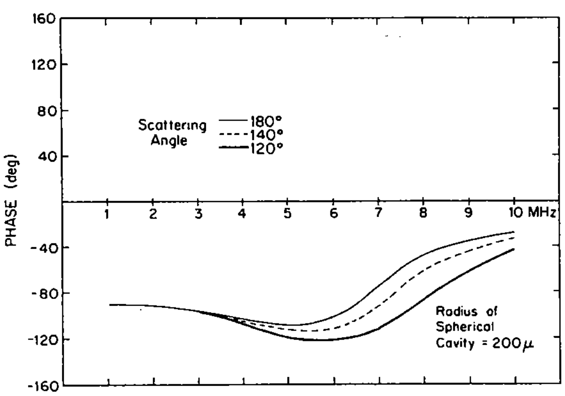


Fig. 18

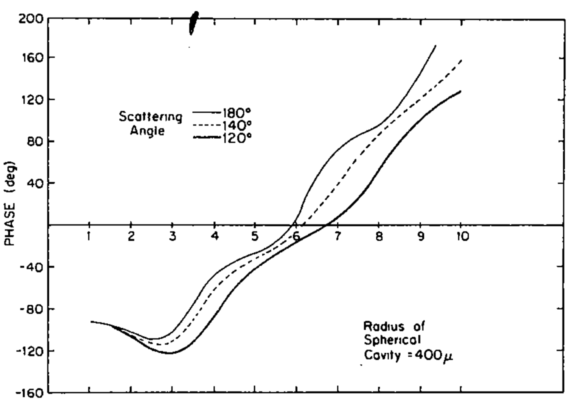


Fig. 19

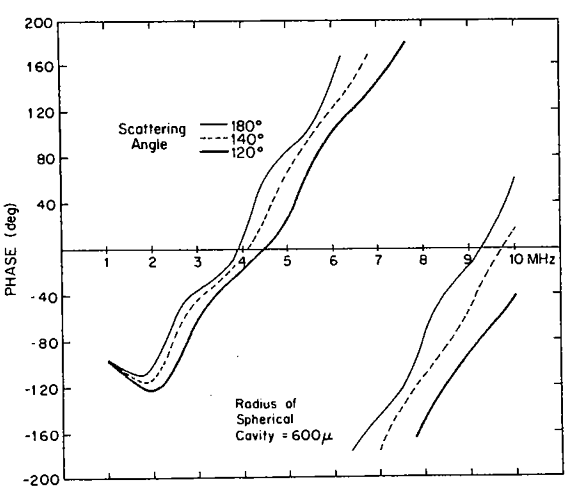


Fig. 20

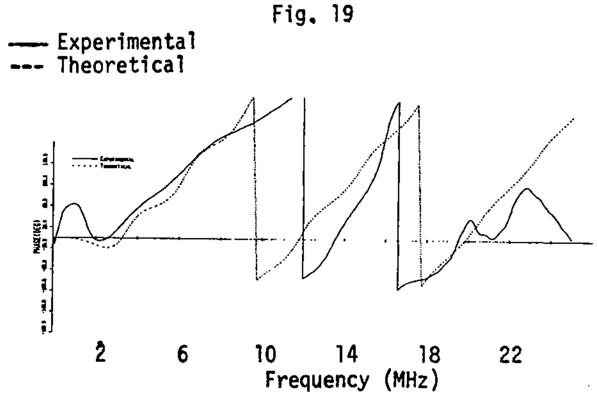


Fig. 21. Phase behavior for a 180° scattered L wave from a 400μ radius spherical cavity in titanium