PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Quantitative Ultrasonics [and Discussion]

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Quantitative ultrasonics

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[Plate 1]

Ultrasonic non-destructive testing, as currently used in industry, is limited by its non-quantitative capabilities. In this sense, non-quantitative means that current technology is capable only of producing a signal that indicates the presence of a flaw, but it is unable to say anything about the characteristics of the flaw, e.g. its size, shape, orientation, and the material of which it is composed (void or inclusion). This limitation has been brought into sharp focus in recent years with the advent of fracture mechanics as a major structural design and maintenance philosophy. Since fracture mechanics is quantitative in nature, its effective utilization as an accept/reject criterion for flaws in materials and structures thus requires that quantitative information be available from the non-destructive test procedures used to assure the design.

With this limitation in mind, the Defense Advanced Research Projects Agency (Darpa) and the Air Force Materials Laboratory (A.F.M.L.) jointly initiated work at the Science Center, Rockwell International, to explore and to improve this situation. The work is structured to include both Science Center and university participants, and includes research and development in several areas necessary to achieve a quantitative capability. These areas include transducers, acoustic imaging, and defect characterization.

In this paper principal emphasis is placed upon the defect characterization work that has been done. The approach that has been used is that of ultrasonic scattering, an approach which recognizes that several measurements must be taken at different angles and frequencies in order to acquire sufficient information to characterize a flaw. Items that are discussed include the design and preparation of a set of flawed samples in which the flaws are well characterized, theoretical developments that describe the ultrasonic scattering interaction with these flaws, experimental verification of these models, and inversion processes that have been developed to process the data and deduce flaw parameters from the ultrasonic measurements. A comparison of the deduced flaw parameters with the initially known values is given.

Two other topics are discussed. One of these concerns recent developments in the analysis of long wavelength scattering which suggest that it should be possible to obtain stress intensity factors from ultrasonic measurements. The second item is concerned with recent developments in non-contact transducers (electromagnetic acoustic transducers (e.m.a.ts)) that are particularly related to weld inspection.

1. Introduction

An increasing awareness of the need for a significantly improved non-destructive testing technology has developed over the past decade. In the U.S. this first arose within the high technology mission agencies of the federal government charged with the procurement and maintenance of high performance systems (e.g. weapon delivery systems) and are constrained by the aim of reducing the costs of such systems. There are several important limitations of the current technology which have restricted the realization of benefits from parallel engineering advances. These limitations include inadequate training for operators, unreliable equipment, non-quantitative nature of all current non-destructive testing technology, lack of understanding of the signals in terms of material property fundamentals, and lack of accept/reject criteria. Perhaps the most basic of these is that they are not capable of giving the size, shape and orientation of the flaw in the stress fields which surround it or the value of a physical property which may govern material performance. In the authors' opinion the introduction of quantitative test equipment coupled with rational accept/reject criteria may significantly reduce the effect of the other limitations noted above.

The full potential benefits to be derived from the advent and use of fracture mechanics, both in design and as an accept/reject criterion, simply cannot be realized, because of this lack of quantitative data. Fracture mechanics provides a quantitative tool for maximizing system performance at a given cost or it provides a specified performance at a minimum cost, and is the tool whereby the safe remaining life of a system may be predicted.

The deficiencies of current methods have been identified in several national advisory reports (*Nondestructive evaluation; Material needs and the environment today and tomorrow; Material and man's needs*). As a result, an interdisciplinary programme for quantitative flaw definition was established in June 1974 at the Rockwell International Science Center under the joint sponsorship of the Defense Advanced Research Projects Agency and the Air Force Materials Laboratory. Arising from the successful collaborative efforts with several major universities and industrial laboratories, substantial advances have been made toward the goal of developing a quantitative ultrasonic technology which will yield measures of the size, shape and orientation of a flaw in a solid. It is the purpose of this paper to present a summary of the highlights of this work.

2. Quantitative ultrasonics

(*a*) *Fundamental approach*

A goal of the Darpa/A.F.M.L. programme has been the development of a quantitative ultrasonics technology that will provide a direct coupling to fracture mechanics so that it may be used effectively as a rational basis for accept/reject criteria (Thompson & Evans 1976). Since the measurement of a single parameter is not sufficient to characterize a flaw and accomplish the above goal, it is necessary to record additional details of the scattered ultrasonic fields, as might be detected, for example, by a transducer array. Another source of information is the spectral character of the ultrasonic signals. After detection of some combination of these parameters, signal processing may be required to correct for degradation of information due to various experimental shortcomings such as transducer variations and bandwidth, and diffraction effects. Finally, signal interpretation is a major function whereby flaw parameters are defined from the measured and corrected data.

The Darpa/A.F.M.L. programme has been concerned with each element of this system. Although this paper is restricted to the signal interpretation aspects, it should be noted that substantial efforts have been made in each of the other areas as well. Included is the development of ultrasonic imaging systems by G. S. Kino of Stanford University (Waugh & Kino 1976), investigations of techniques for constructing inverse filters to compensate for variations in the spectral response of ultrasonic transducers by R. M. White of the University of California at Berkeley (Kerber *et al.* 1976), and the development of quantitative approaches for calibrating ultrasonic transducers by K. M. Lakin at the University of Southern California (Lakin & Fedotowsky 1976).

A set of procedures has been established whereby a defect characterization capability is built up from fundamental building blocks. The first element is an understanding of the details of the ultrasound defect interaction. This is accomplished by a close interaction between the development of scattering theories and the performance of verifying and/or guiding experiments. These experiments must be performed on controlled samples in which there are defects of predetermined sizes and shapes. In this programme the development of approximate theories has been emphasized because the number of flaw shapes that can be treated by exact techniques is extremely limited. Techniques that can be generalized to the complex shapes of real flaws are much more suitable. Even if a complete understanding of this ultrasound–defect interaction has been developed, it does not immediately follow that a flaw can be characterized from a set of experimental data. In order to accomplish this step, inversion techniques are needed. An analogy to an integral equation has been used. The theory can be viewed as the kernel of this integral equation, which relates ultrasonic measurements to physical parameters of the flaw. By solving the equation by whatever means is appropriate, a relation that predicts the size, shape and orientation of the defect in terms of certain measurables can be developed. This relation must then be verified by using experimental data and the predictions compared with independent knowledge of the flaw parameters. The structure of the loop for the demonstration of the defect characterization capability is then complete and the predictive relation is then available for use with fracture mechanics or other failure predictive disciplines.

Selected details concerning the individual steps in this loop are discussed below.

(*b*) *Theory*

The development of theoretical models has been governed by two considerations. First, it is necessary to base the models upon correct solutions to elastic wave scattering problems in solids as opposed to the use of analogies to scalar models developed for fluid media. An extensive literature exists for the latter because of the practical importance in sonar. However, this information cannot be directly transferred to the solid case in which such effects as mode conversion play an important role. Secondly, approximate models have been emphasized. Exact solutions are available for a few simple geometries, but these theoretical models are not readily generalized to more complex shapes. Since it is the intention to provide the theoretical techniques necessary for the characterization of real flaws, the model development and approximations have been closely guided by the experiments reported below.

The major theoretical effort has been performed at Cornell University by J. A. Krumhansl and several students. They have used an integral equation formulation of the scattering problem (Gubernatis *et al.* 1977*a*) and developed a series of approximate techniques. The first, and simplest, is the Born approximation (Gubernatis *et al.* 1977*b*). In this approach the incident plane wave solution to the wave equation is used as the first approximation to the solution and the scattered fields are derived by substituting this for the actual solution within the integral. The results are rigorously correct only for weakly scattering defects, i.e. inclusions whose properties do not differ too greatly from those of the host medium. However, as will be discussed in § 1*c*, the results agree well with many experimental features over a much broader range of conditions.

In a series of papers (Gubernatis 1978; Domany *et al.* 1979), Krumhansl and coworkers have explored a series of other approximations for both three-dimensional volumetric and two-dimensional, crack-like, flaws. Included have been the quasi-static approximation which gives the rigorous result in the limit of long wavelength, and an extended quasi-static approximation which is a combination of some of the features of both the Born approximation and the quasi-static approximation to extend the range of validity of each. Each of these approaches is primarily applicable when the wavelength is comparable to, or greater than, the dimensions of the flaw. At the other end of the spectrum, Adler & Lewis (1976) and Achenbach & Gautesen (1977) have studied application of the geometrical diffraction theory of Keller to elastic waves.

The simplicity of the Born approximation has led to a number of important insights. For example, when a plane longitudinal wave is incident on a flaw, the far field scattered displacement U^s is defined by

$$U^s = r^{-1}\boldsymbol{A}\,\mathrm{e}^{jk_1 r} + r^{-1}\boldsymbol{B}\,\mathrm{e}^{jk_t r}, \tag{1}$$

where A and B, the amplitudes of the scattered longitudinal and transverse waves having wavevectors k_1 and k_t respectively, are given by

$$A = \frac{k_1^2}{4}\left[\frac{\delta\rho}{\rho}\cos\theta - \frac{\delta\lambda + 2\mu\cos^2\theta}{\lambda+2\mu}\right] F\left[\frac{f\sin\theta}{V_1}, 0, f\frac{\cos\theta - 1}{V_1}\right] \tag{2}$$

and

$$B = \frac{k_t^2}{4\pi}\left[\frac{2V_t\,\delta\mu\cos\theta\sin\theta}{\mu V_1} - \frac{\delta\rho\sin\theta}{\rho}\right] F\left[\frac{f\sin\theta}{V_t}, 0, f\left(\frac{\cos\theta}{V_t} - \frac{1}{V_1}\right)\right] \tag{3}$$

where

$$F(u, v, w) = \int_{-\infty}^{\infty}\mathrm{d}x\int_{-\infty}^{\infty}\mathrm{d}y\int_{-\infty}^{\infty}\mathrm{d}z\, f(x, y, z)\,\mathrm{e}^{-2\pi\mathrm{i}(ux+vy+wz)} \tag{4}$$

and

$$f = 1 \text{ for an inside flaw} \quad \text{and} \quad f = 0 \text{ for an outside flaw.} \tag{5}$$

It will be noted that these expressions consist of the product of three factors, one proportional to the square of the frequency, one determined by the elastic constants of the material, and one determined by the shape which can be recognized as the spatial Fourier transform of a characteristic function defining the shape of the flaw. This result defines a clean path for reconstructing the flaw shape form experimental data, since the process can be directly related to the evaluation of the inverse Fourier transform.

Some of the implications of (1)–(5) are illustrated in figure 1. Here, isographic projections of equal scattered amplitudes are plotted for the scattering of a broadband longitudinal wave pulse from a sphere and an oblate spheroid at 45° incidence. The differences in the signatures of the direct, longitudinal–longitudinal scattering and the mode converted, longitudinal–shear wave scattering are striking. From the information such as that presented in (1)–(5) and figure 1, it is possible to estimate the apertures required to differentiate between various flaw types and orientations.

(c) *Experimental technique*

To evaluate the theoretical approximations, it is necessary to make measurements on samples in which flaws of known shape and orientation have been placed. A procedure with the use of diffusion bonding was selected to achieve this purpose. In this procedure, developed by Paton (1977), two pieces of titanium alloy were carefully prepared with mating surfaces flat to within four optical bands. The desired defect was then machined accurately into the mating surfaces; the two halves of the sample were carefully assembled in a mating jig and placed under pressure at approximately 830 °C. The bonding pressure was kept low to limit the specimen strain, thereby preventing significant distortion of the defect geometry. Under these conditions, grain growth occurs across the bonding plane and produces a bond line which is indistinguishable from the parent metal both ultrasonically and metalallographically. For most of the samples the

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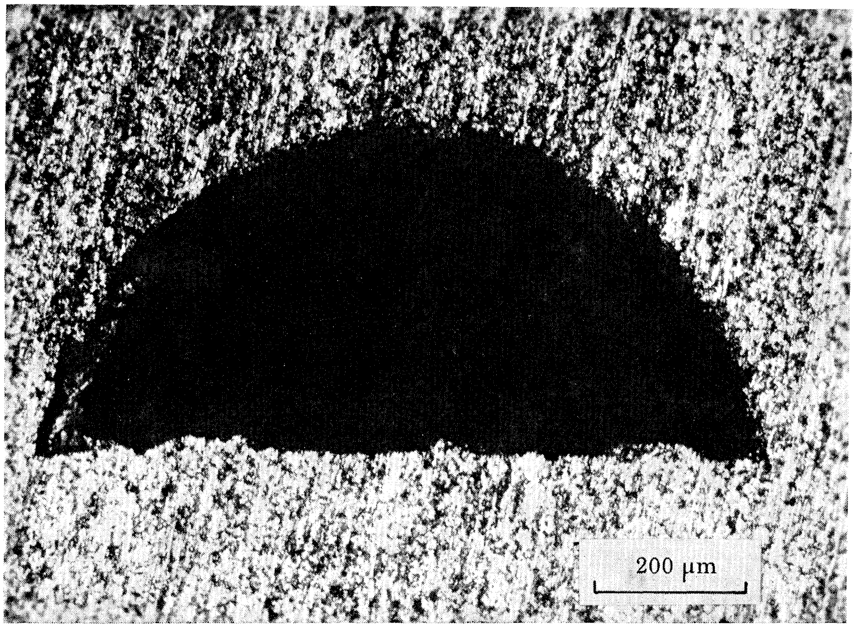

FIGURE 2. Micrograph showing cross section of a hemispherical cavity at a diffusion bond plane. Grain growth occurs across original interphase.

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titanium alloy Ti-6Al-4V was used since it is an aerospace alloy of interest and because of the fact that at the bonding temperature it dissolves residual surface oxides, thus assuring a good bond. Special techniques have also been developed for producing such intentionally defective specimens from steel and aluminium alloys.

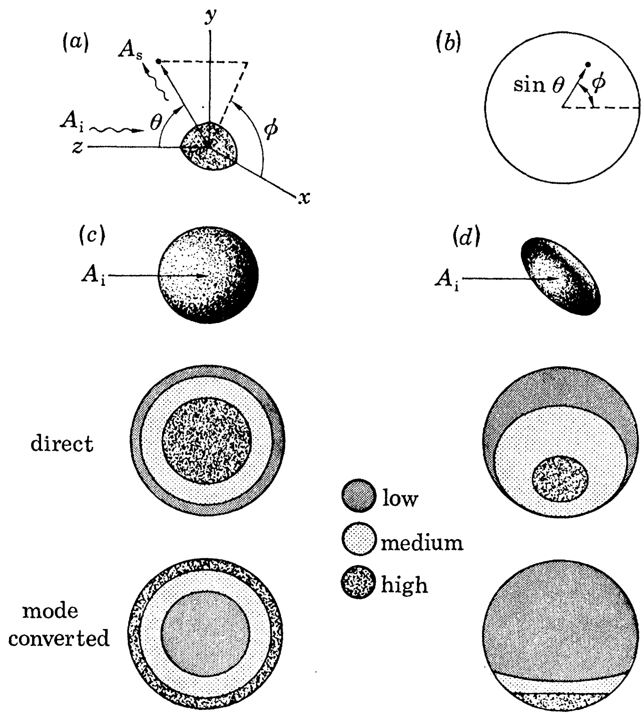


FIGURE 1. (*a*) Scattering geometry; (*b*) coordinates of polar representation of scattered fields; (*c*), (*d*) contours of equal scattering powers for direct and mode converted signals, showing the difference in response of a sphere (*c*) and oblate spheroid (*d*).

A micrograph of a section through a finished sample with a hemispherical void is shown in figure 2, plate 1, and various kinds of cavity retaining one axis of symmetry are illustrated in figure 3. The set includes spherical cavities of different diameters and spheroids of revolution (both prolate and oblate). The size range varies from a 200 by 800 μm oblate spheroid to a 1600 by 400 μm prolate spheroid, thus producing a significant range in the aspect ratio of the spheroids, which permits an examination of the limit as the spheroid of revolution approaches a crack-like flaw.

These defects have been placed in two sets of samples with different exterior shapes. One set is a right circular cylinder 2.5 cm high and 10.2 cm in diameter. The other set has a 'door-knob' or 'trailer hitch' shape as shown in figure 4. In these samples, the exterior surface is a sphere of 2.8 cm radius with the defect at its centre. This feature makes it possible to perform fundamental measurements of the angular dependence of the ultrasonic scattering since transmitting and receiver transducers can be placed at nearly arbitrary angles without changing the ultrasonic path length. These measurements are further facilitated by a precision goniometer and the use of machined buffer caps which match the flat end of the transducers to the curved surface of the sphere. The data obtained in this idealized geometry are used both as a check on the theory and as a reference against which the data on the cylindrical samples can

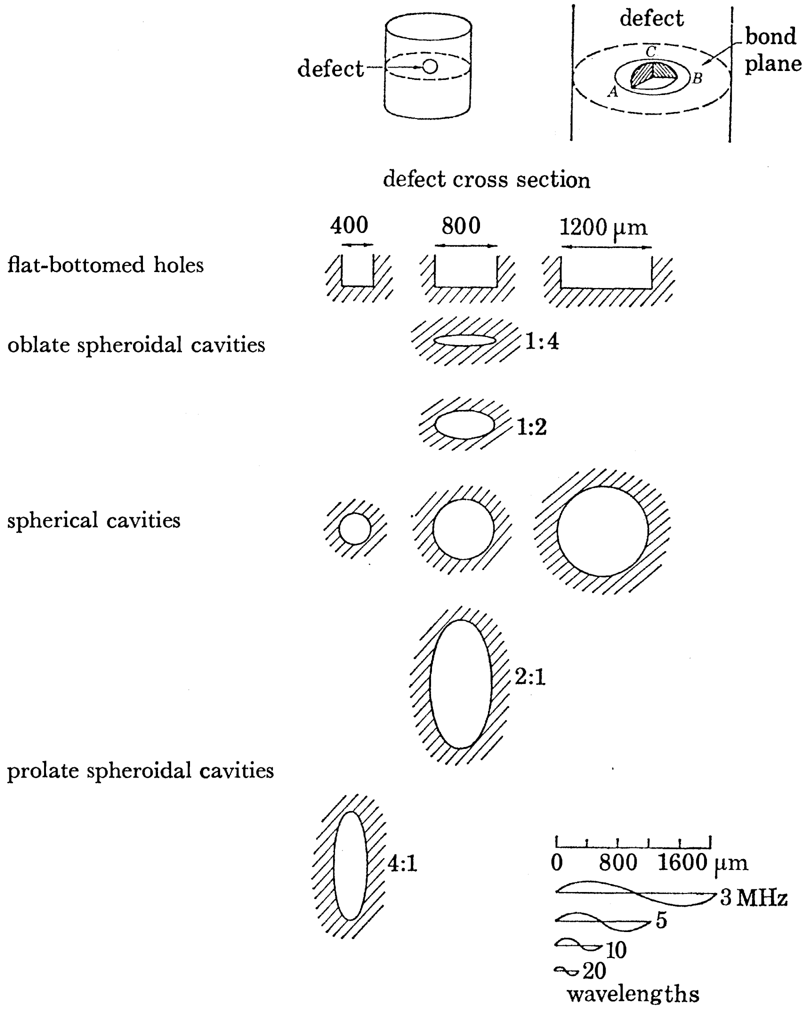


FIGURE 3. Dimensions of flaws placed in diffusion bonded samples.

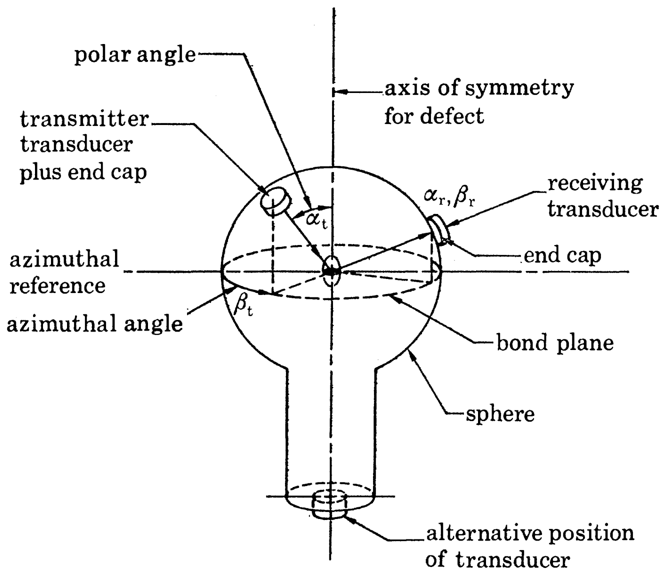


FIGURE 4. 'Trailer hitch' sample used for measurement of angular variation of ultrasonic scattering.

be tested to ensure that corrections for refraction and diffraction effects have been properly made. The development of such corrections is a crucial step in transferring the basic research results from the laboratory into techniques for use on parts of complex shape in the field.

Measurements of the frequency dependence of the ultrasonic scattering have also been made by using a transient signal recorder to digitize the r.f. waveforms, which are subsequently Fourier analysed on a minicomputer.

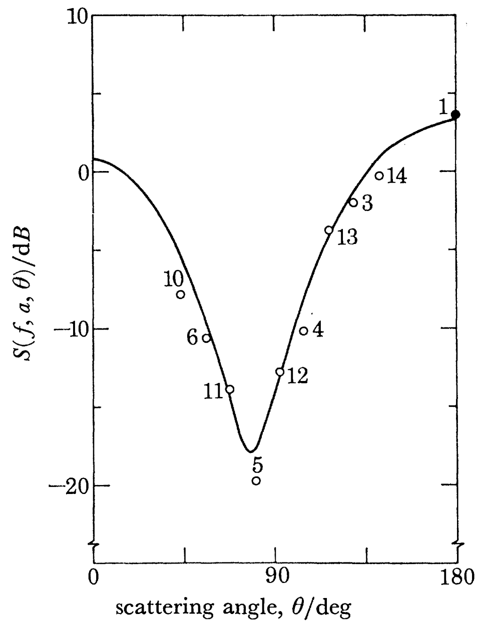


FIGURE 5. Absolute comparison of experiment (∘, two transducers; •, pulse–echo) and theory (——) for ultrasonic scattering from a spherical inclusion (Ti alloy polygon; 800 μm WC sphere; 4.0 MHz).

(*d*) *Experimental results*

Detailed measurements have been made by B. Tittmann at the Science Center and L. Adler at the University of Tennessee on samples containing all of the defect geometries shown in figure 3. Figure 5 illustrates the excellent agreement between the exact theoretical predictions of the angular dependence of the scattering from a spherical inclusion and the experimental measurements (Tittmann & Thompson 1977). This agreement established that an exact calculation based on isotropic elasticity models applies satisfactorily to the polycrystalline, two-phase titanium alloy used in this work and that measurements could be made with great precision. This latter point is strengthened by the fact that there were no adjustable parameters in the comparison. The data were corrected for the efficiency of transduction, attenuation of ultrasound, and diffraction, to yield an absolute measure of scattering amplitudes. In this regard, it should be noted that experimental points are presented that were taken with either a single transducer in the pulse–echo mode (solid point at 180°) or a pair of transducers (open points). In addition to illustrating the agreement between experiment and exact calculations, the results demonstrated a calibration procedure that can be used to ensure that a quantitative experimental system is functioning properly.

For more general defect types, exact calculations become increasingly difficult, and approximate theories have been developed as discussed in §2*b*. The spherical geometry has been used as a reference in which these models can be compared against the well established exact result. As noted, the Born approximation is rigorously valid only for inclusions whose properties are similar to those of the host medium. However, it has been found that it makes many useful predictions outside this régime. For example, even for a cavity, it is found to make good predictions for the angular variation of scattering for angles near the back-scattered direction and for relatively low frequencies, i.e. $ka \approx 1$, where a is the radius of the sphere. The detailed frequency dependence of the result is found to have systematic errors but, when averaged over a set of frequencies which comprises the broadband ultrasonic pulse, the results were again quite useful (Tittmann 1975).

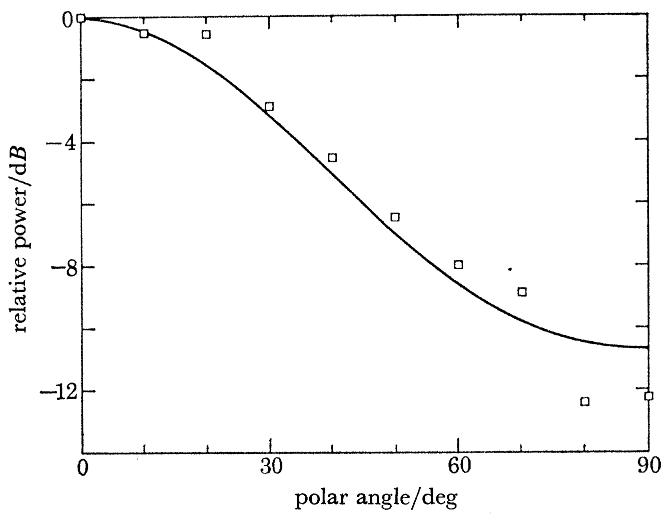


FIGURE 6. Graph of back-scattering against angle for an oblate spheroidal cavity (800 μm × 400 μm). ——, Born approximation synthesized to transducer; □, data points.

These results, deduced for the sphere by comparison of experiment with both exact and approximate models, have been further investigated in the spheroidal geometry by a direct comparison of experiment and the approximate theory (Tittmann 1976; Adler & Lewis 1977). In general, the same conclusions have been reached. For example, figure 6 is a comparison of the back-scattered power from a 800 × 400 μm oblate spheroidal cavity. In this case the theoretical predictions were averaged over a range of frequencies corresponding to those produced by the transducer, and excellent agreement was obtained.

Other measurements at higher frequencies on crack-like flaws have established bounds on the geometrical diffraction theories (Adler & Lewis 1976). Theoretical and experimental work are both continuing to increase the régime in which satisfactory agreement exists.

(*e*) *Inversion*

The end objective of this work is the solution of the inverse problem wherein defect parameters are directly deduced from experimental data. Three approaches have been examined. One, of which imaging is the most familiar example, endeavours to reconstruct the defect shape function from measured spatial Fourier components. Work devoted to the development of imaging systems in which the signal processing algorithms are based upon scalar models for the ultrasound–flaw interaction have been undertaken by Waugh & Kino (1976) and Lakin &

Fedotowsky (1976). In addition, others have given greater attention to the development of data inversion techniques more closely related to rigorous solutions of the wave equation. N. Bleistein and J. Cohen of Denver University are considering the application of algorithms previously developed for the processing of seismic data to ultrasound (Bleistein 1977). Rose & Krumhansl (1978) have developed a conceptually similar approach based upon the Born approximation for elastic waves. As illustrated in (1)–(5), measurements of the ultrasonic power scattered at various angles may be viewed as defining specific components of the Fourier trans-

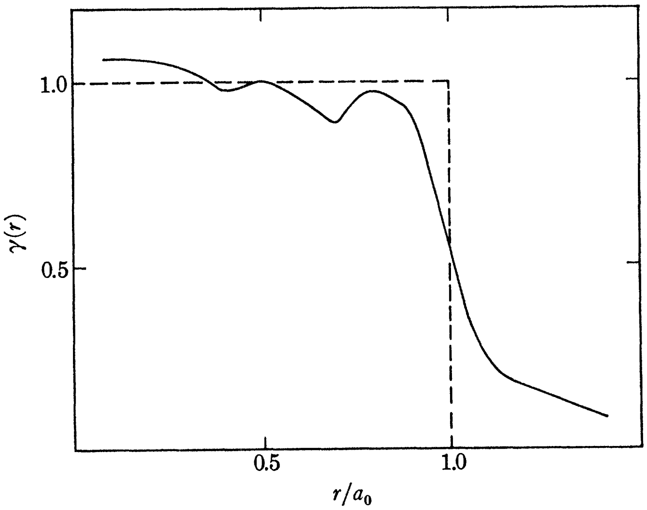


FIGURE 7. Reconstruction of characteristic function of a spherical cavity in Ti from back-scattered data for wavelengths greater than the radius.

form of the defect shape function. This concept was tested by developing inversion formulae based upon the approximate formulae of (1)–(5) and testing them by using numerical results produced by exact theoretical calculations as input data. One of the results is shown in figure 7 for a spherical cavity. Here the shape function is plotted as a function of radius. The reconstructed value is seen to approach very closely the correct value, even though the input data were truncated for $\lambda < a$. Furthermore, addition of 50 % random noise to the data produced very little degradation of the result. Further work is needed to define the limits of this approach for shapes lacking such a high degree of symmetry. However, these results are quite promising, particularly in view of the relatively long wavelengths required for reconstruction.

The reconstruction techniques all rely upon some form of linearization of the scattering problem. However, in fact, the scattering process can be highly nonlinear; for example, the scattering from adjacent facets of a flaw is not necessarily the superposition of the scattering from the facets considered individually. Analytical techniques are not yet sufficiently developed to address the inversion of such a nonlinear problem. However, empirical adaptive learning techniques have proved quite successful as demonstrated by Mucciardi *et al.* (1977). The basic problem is to define functional relations between particular features of the scattered ultrasonic fields, e.g. the energy scattered at a given angle into a given frequency band, and particular parameters of the flaw. To accomplish this in practice, it is necessary to represent the flaw by a small number of parameters. In this case, an oblate spheroid having major and minor semi-axes of length B and A, respectively, and elevation and azimuthal angles α and β with respect to the measurement aperture, was assumed. In order to develop the prediction, it is necessary to have an extensive 'training' base for the purpose of establishing correlations. This was done by using the Born approximation to generate theoretical data corresponding to ellipsoids having a wide range of the parameters defined above. Once the functional form of the predictor had been established, it was tested by using experimental measurements on the previously discussed samples as the input parameters. The data were restricted to 17 transducer locations in a circular aperture having a half-angle of 60° with respect to the flaw. No use of the detailed frequency dependence of the signals was made because of known systematic errors in the theoretical model.

Table 1. Performance of spheroidal defect measurement system, synthesized from theoretical data, on actual scattering data from real defects

	size/µm				orientation/deg			
	A		*B*					
defect no.	true	measured	true	measured	true	measured	true	measured
1	200	154	400	493	0	37	—	197
2	200	163	400	528	30	2	225	215
3	100	100	400	506	80	68	160	165
4	100	114	400	521	0	0	—	—
5	200	202	400	533	80	22	160	174
6	100	126	400	599	30	60	180	196
7	200	114	400	569	30	21	180	178
8	100	130	400	645	30	42	225	218
average absolute error		30		149		23		8
percentage average absolute error		15.0		37.3		25.6		2.2

A comparison of the predicted and known flaw parameters is given in table 1. It will be noted that the agreement is quite good, particularly in view of the approximate nature of the theory used in the training process. It can be expected that the use of more accurate approximations in the future will improve this performance.

A third approach to the inversion problem has been made in the régime where the ultrasonic wavelength is large with respect to the flaw size. Here the problem is again nonlinear, but analytical techniques can be used in the limit of long wavelength to solve the forward scattering problem in closed form. In particular, for a general flaw, it has been shown by Gubernatis (1978) that there are 22 independent parameters which can in principle be deduced from scattering measurements.

Interest has been great in the long-wavelength régime for several reasons. The fact that many flaw parameters are available in a régime where the theory is well developed and inversion problems can be attacked analytically is very attractive. The fact that the technique may give an average representation of the flaw as needed to use simple fracture prediction models rather than a detailed picture with more information than is desired, could be of great practical importance. This interest was sharpened by B. Budianski & J. R. Rice (unpublished results) who demonstrated that, for an elliptical crack, the maximum stress intensity factor could be directly deduced from long wavelength scattering data, to a large extent independent of the eccentricity of the crack. Further analysis has been presented by G. S. Kino (unpublished results). The most recent implementation of the techniques, as developed by Elsley *et al.* (1978), requires that the frequency dependence of the ultrasonic scattering be deduced from measurements made at a number of transducer positions. From these data, the coefficient A_2 of the leading ω^2 term in a power series expansion of the scattered amplitude is determined. The parameters of the flaw are then deduced from the set of coefficients A_2 by using an estimation theory approach. This methodology has been applied to one of the 800×400 μm ellipsoidal cavities. Measurements were made of the backscattered signal at angles of 0, 15, 30, 45, 60, 75 and 90°, with respect to the symmetry axis of the ellipsoid. The results of the prediction of the ellipsoid dimensions and orientations are given in table 2 and the variances in these estimates are presented in table 3. It can be seen that the results are very accurate, which clearly demonstrates the potential of this new approach for defect characterization.

Table 2. Estimates of spheroid size and orientation based on pulse–echo measurements

parameters	exact	estimates: experimental data	estimates: theoretical
B	0.0400	0.03947	0.04000
A	0.0200	0.01999	0.02000
x	0	-1.24×10^{-5}	2.3×10^{-6}
y	0	0	0

Table 3. Normalized standard deviations (*a posteriori*) based on pulse–echo measurements

quantity	r.m.s. meas. error $= 0.46 \times 10^{-5}$: experimental data	r.m.s. meas. error $= 0.46 \times 10^{-5}$: theoretical test data	r.m.s. meas. error $= 1 \times 10^{-5}$: experimental data	r.m.s. meas. error $= 1 \times 10^{-5}$: theoretical test data
s_B/B	0.0168	0.0156	0.0364	0.0340
s_A/A	0.0608	0.0608	0.1320	0.1320
s_x	0.1120	0.1057	0.2434	0.2295
s_y	—	—	—	—

Standard deviation is denoted by s.

(*f*) *Discussion*

Three new approaches to flaw characterization involving generalized imaging, adaptive learning and long wavelength scattering have been developed. Each is built upon results traceable to first principle interactions, and in each, preliminary results that demonstrate the feasibility of the approach have been obtained. Further work must be designed to make specific improvements in each and to deduce their relative advantages and ranges of applicability. In the first category lies the need for improvement of the basic models which form the foundation of the techniques. In the second category, the effects of practical constraints (such as material attenuation and geometric limits) will be considered. The work is sufficiently far advanced, however, that limited applications are being sought. Further details may be found in *Semi-annual and special yearly reports of the Interdisciplinary Program for Quantitative Flaw Definition* and *Proceedings of the Darpa/A.F.M.L. reviews of quantitative NDE.*

3. Electromagnetic transducers

(a) *Principles*

One of the major problems that hinders the implementation of these and other newly developed ultrasonic testing techniques is a lack of reliability in the transduction process. When a piezoelectric transducer is used to excite ultrasonic waves in a solid, it is necessary to establish mechanical contact between the transducer and the sample. Variations in the coupling parameters can degrade the ultrasonic information transmitted from the transducer to the part and back, and the necessity to carefully establish and control the coupling can add extra cost to the inspection.

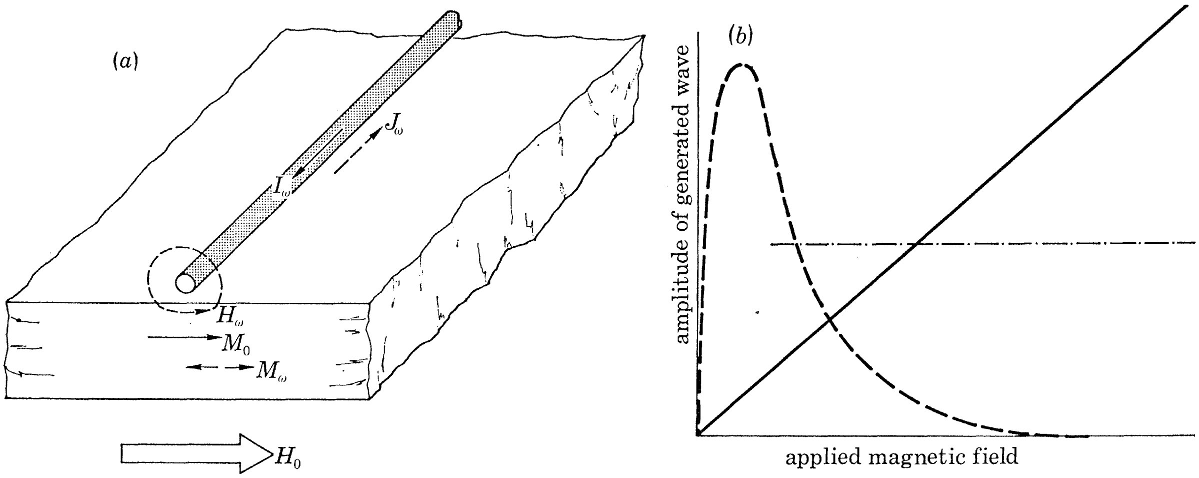


Figure 8. Principles of electromagnetic transducers. (*a*) Elementary forces: forces on lattice are Lorentz force and magnetostriction. (*b*) Field dependence of different mechanisms: ——, Lorentz force on induced eddy currents; – –, equivolumetric magnetostriction (M_s constant); – · –, forced volume magnetostriction ($\partial M_s / \partial H > 0$).

The electromagnetic–acoustic transducer (e.m.a.t.) has recently shown great promise for overcoming this problem. The principles are well known, as illustrated in figure 8*a*, where a single wire is shown. It is driven by a dynamic current and placed adjacent to a metal surface in the presence of a static magnetic field. Early interest in this configuration was stimulated by the fact that, for single crystals at low temperatures, such a structure could couple to helicon waves or other excitations and thereby provide important information about the fundamental structure of the solid Dobbs (1975). However, during studies of such effects, it was found that even at room temperatures and in polycrystalline metals, elastic waves were excited at the frequency of the dynamic current. It was further established that the generation process could be phenomenologically described in terms of the lattice response to body forces equal to the Lorentz forces ($\boldsymbol{J} \times \boldsymbol{B}_0$) exerted on the induced eddy currents, $\boldsymbol{J}$, by the static magnetic field. It is this elementary process which can be utilized in the construction of practical transducers for the ultrasonic testing of materials.

Before addressing the details of transducer structures, it is important to note that in ferromagnetic materials other mechanisms exist in addition to the Lorentz forces. One of the most important in structural alloys is magnetostriction. When the wire shown in figure 8*a* is placed near the ferromagnet, stresses are created by the modulation of the static bias magnetic state by the dynamic field and the resulting coupling to lattice deformation via spin–orbit coupling.

Figure 8*b* shows the field dependence of the amplitude of the ultrasonic wave generated by those mechanisms. The Lorentz force generation is linear in the applied field, whereas the magnetostrictive generation has a peak (at about 300 Oe (*ca.* 24 kA m^{-1}) bias in iron). At higher fields the material becomes saturated and magnetostrictive generation is no longer significant in most materials. Exceptions do exist, however, in which there is a forced volume magnetostriction which can generate waves at substantially higher fields; an example is Invar. A detailed discussion is given in Thompson (1978*a*, *b*). In each of these, reciprocal processes exist whereby the same structure can detect as well as excite ultrasonic waves.

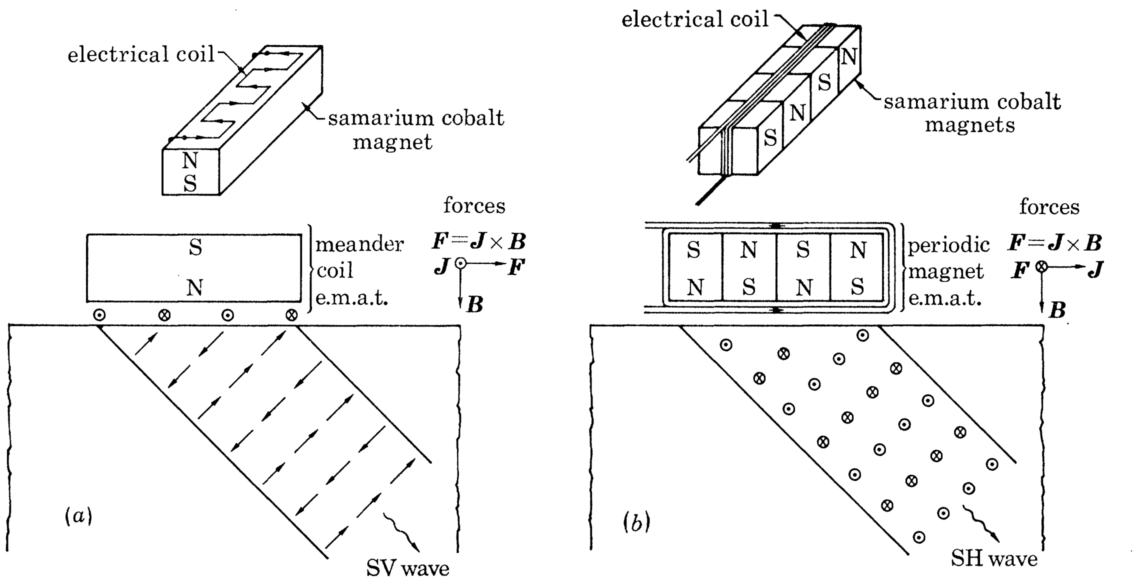


FIGURE 9. Transducer configurations: (*a*) meander coil transducer showing generation of vertically polarized shear wave; (*b*) periodic magnet transducer showing generation of horizontally polarized shear wave.

Practical transducers (Thompson 1976) consist of combinations of the elementary components shown in figure 8. Figure 9 shows two configurations which have found recent application. Figure 9*a* is the meander coil configuration in which the wire is wound back and forth in a serpentine and the magnet is uniformly polarized normal to the metal surface. The resulting Lorentz force is in the plane of the metal surface and spatially periodic with period D equal to that of the coil. If driven with a current of frequency f, where $f = V_R/D$, this structure will excite a surface wave (V_R is the Rayleigh velocity). If driven at a higher frequency, longitudinal or shear waves can be generated inclined to the surface normal at an angle (Moran & Panos 1976)

$$\phi = \arcsin(V/fD), \tag{6}$$

where V is the wave velocity. For shear wave generation, the wave is polarized in the sagittal plane, i.e. that plane defined by the direction of propagation and the surface normal.

A second transducer configuration is shown in figure 9*b*. This differs in two important respects. First, a periodic stress is produced by alternation of the bias magnetic field rather than the dynamic current (Vasile & Thompson 1977). Secondly, the direction of the force is normal to the sagittal plane. Such a transducer will not generate either surface or longitudinal beams because the force direction is orthogonal to the motion of those waves. However, it will generate horizontally polarized shear waves which have a number of advantages in non-destructive testing as discussed below.

(*b*) *Weld inspection*

The efficiency of these transducers is somewhat less than that of piezoelectric transducers. However, careful design (Fortunko & Thompson 1976) has raised it to a more than satisfactory level for many applications in which the unique properties of no contact or couplant required, operation at elevated temperature or at high speeds, and coupling to waves of controlled polarization can be utilized. An example which combines several of these features is the inspection of thick welds (Fortunko *et al.* 1977). Figure 10 illustrates the basic concept. A periodic magnet e.m.a.t. is used to excite shear waves travelling at an angle to the surface of the part. These beams can be used to interrogate a weld by changing the frequency so that the beam angle is swept through the material in accordance with (6). This electronic scanning offers substantial time advantages over the usual procedure of mechanically translating a piezoelectric transducer which sweeps a fixed angle beam through the material.

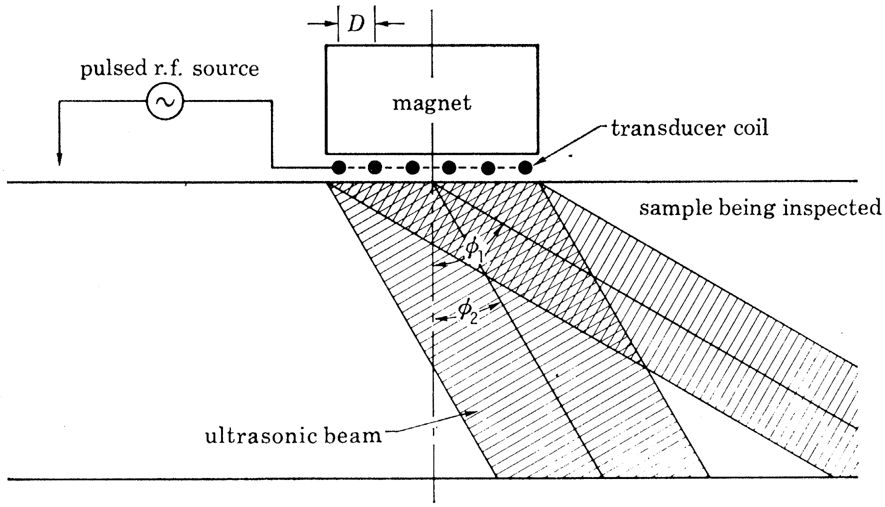


FIGURE 10. Use of a periodic magnet transducer to inspect a weld: the beam can be scanned by changing frequency; $\phi = \arcsin V_s/fD$.

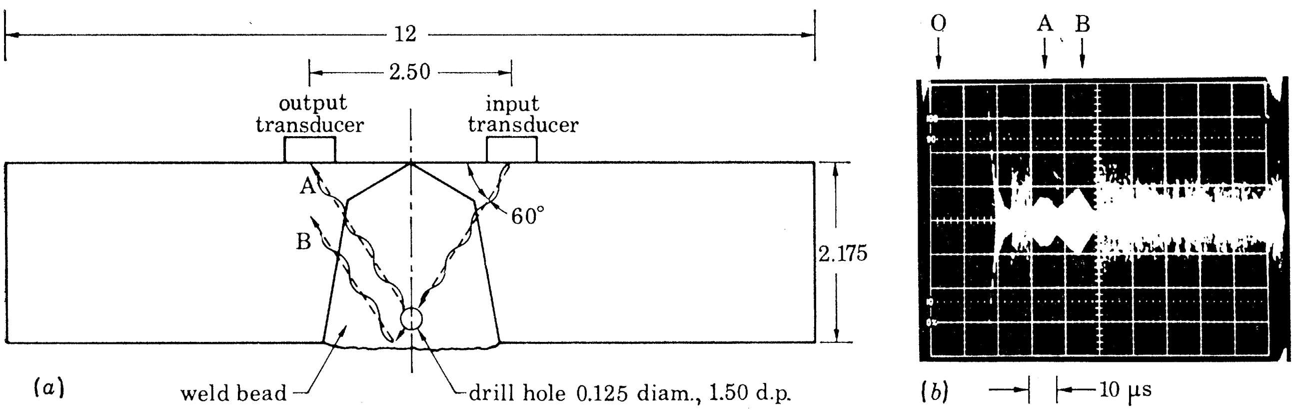
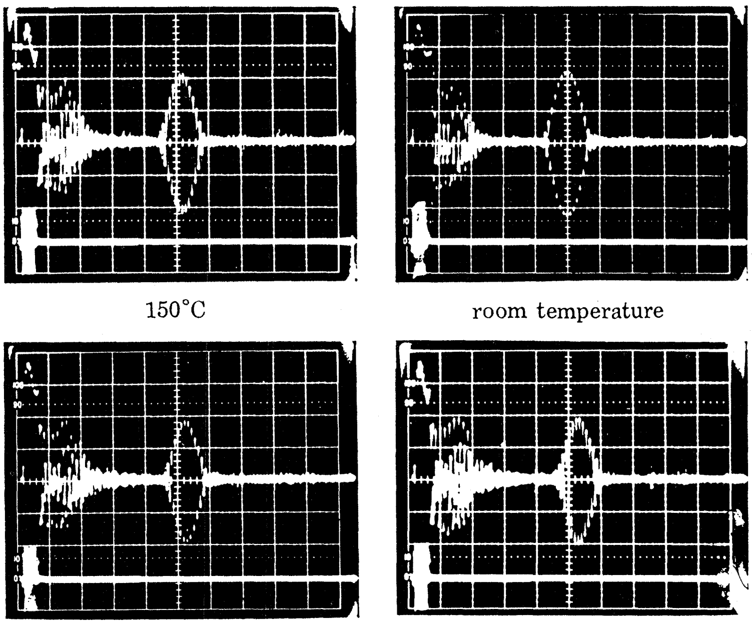


FIGURE 11. Ultrasonic signals in m.i.g. welded, Fe–$2\frac{1}{2}$%Cr–1%Mo plate. (*a*) Experimental configuration: A, signal reflected from drill hole; B, signal reflected from bottom of weld bead. Dimensions in centimetres. (*b*) Ultrasonic signals from calibration hole and plate bottom. In the dual exposure, the high gain is 0.05 V per division and the low gain is 0.5 V per division.

Another important feature of the periodic magnet e.m.a.t. is its convenient ability to excite the horizontally polarized shear waves (Vasile & Thompson 1977). These waves have a number of advantages over longitudinal or vertically polarized shear waves in the inspection of welds. If the weld has a counterbore, the horizontal shear wave will be perfectly reflected. The other waves will produce mode converted signals upon reflexion (e.g. vertically polarized shear waves can convert to longitudinal waves for counterbores greater than a certain angle) which can produce complex signal trains which are difficult to interpret. Also, the horizontal shear wave has a generation efficiency which varies with angle much more slowly as the beam is scanned. Figure 11*a* shows the experimental configuration which incorporates separate transmitting and receiving transducers; figure 11*b* shows the ultrasonic wave forms observed. This is a dual exposure in which a high gain and low gain oscilloscope trace have been superimposed to show both the signal strength and the noise level. Two signals can be seen: the first is the reflexion from a 0.32 cm cylindrical calibration hole drilled parallel to the weld; the second is the reflexion from the bottom of the weld. The fact that the two are clearly resolved is quite significant. In similar measurements with vertically polarized shear waves, the hole signal was obscured by multiple signals produced by mode conversion at the irregularities on the bottom of the weld.



150°C   room temperature

215°C   270°C

FIGURE 12. Ultrasonic signals as a function of temperature on Fe–$2\frac{1}{2}$%Cr–1Mo plate.

A final advantage of these transducers is the ability to operate at elevated temperatures. Figure 12 illustrates this by showing the ultrasonic signals transmitted between two transducers on the same Fe–$2\frac{1}{2}$%Cr–1% Mo plate. Very little change in signal strength is observed between room temperature and 271 °C, and it would appear likely that considerably higher temperatures can be tolerated. This has major practical consequences, since thick sections joined by multipass welds can be inspected at the elevated preheat temperatures. Flaws can be repaired as they occur and while they are near the surface rather than after the entire weld has been finished and cooled to room temperature.

A more comprehensive review of the topics in this paper may be found in Frost (1978).

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Discussion

A. F. BROWN (*Physics Department, The City University, St John Street, London EC1V 4PB, U.K.*). Dr Thompson mentioned work where good characterization of flaws was achieved when the ultrasonic wavelength was about the same as the characteristic flaw dimension. This is what one would expect and is possible provided the necessary wavelength is available in the frequency band of ultrasonic pulse. The way to ensure this is to use broad-band techniques. I believe broad-band to be one of the methods of quantitative ultrasonics under study in Dr Thompson's Institute but am happy to report that both it and its offspring, ultrasonic spectroscopy, are alive and well in England too. However, broad-band techniques are not very popular commercially since it is easier and more efficient to operate transducers at their resonant frequency while the electronics is simplified by the use of tuned circuitry. In pulse–echo techniques, broad-band pulses give problems with paralysis.

For both non-destructive testing and medical diagnosis, broad-band techniques give a means of generating short pulses which improve resolution in depth. A pulse of length T can be produced without the use of frequencies much higher than $1/T$ provided all lower frequencies are available. With narrow band techniques the frequency required would approach $3/T$. We have been using pulses about 0.2 μs long with a centre frequency of 4 MHz and a bandwidth of about 0.5–7 MHz. The corresponding narrow band pulses would require a frequency of perhaps 15 MHz which is too high to be transmitted in most engineering materials and much too high for transmission in biological material. There is of a course a snag in that such short pulses give less power than larger pulses since the amplitude of any pulse is limited by breakdown of the transducer material.

The availability of broad-band transducers and electronics give the possibility of frequency analysis of the scattered pulses. The first application of this is to give a method of time measurement from the modulation of the spectrum of the input pulse. This is much more sensitive than is available in the time domain. A second application has been to the non-destructive testing of layered structures such as the glued aircraft joints to which Dr Thompson referred briefly and which have been extensively studied in our laboratory as well as in his own. Again, the C.E.G.B. use ultrasonic spectroscopy to monitor the growth of corrosion layers on the inaccessible surfaces of nuclear reactor vessels. In a third application we have used broad-band techniques to characterize surface-breaking cracks by methods which owe a lot to seismology. Finally I have heard of the use of ultrasonic spectroscopy as a diagnostic, and presumably also research, tool in medicine. All of these applications require extension of the theoretical work which Dr Thompson described and for which Mr Sharpe pleaded earlier.

A by-product of the availability of frequency analysis is the ability to test commercial resonant transducers. Here it is rather shattering to find that few, if any, emit pulses at their nominal frequency. For many applications this may not matter but where conclusions are drawn from the different response of a given structure to a series of such transducers with differing nominal frequencies, it is as well to be wary.

D. O. Thompson. We certainly agree with the commentary of Professor Brown that the application of wide-band, well characterized transducers is necessary to obtain sufficient information to characterize flaws in materials. Our standard procedures are to measure the frequency response of the transducer and then to apply deconvolution procedures to enhance the information content of the signals.

L. J. Bond (*Department of Physics, The City University, St John Street, London EC1V 4PB, U.K.*). Dr Thompson mentioned in the early part of his paper that he had an experimental programme, backed by approximate theoretical techniques. What programme of mathematical support does he have? I was wondering especially if he had adopted techniques, such as finite difference modelling for pulsed elastic wave propagation, that have been used for some years in mathematical seismology. We have found finite difference methods most useful when applied to model both Rayleigh and compressional wave propagation and scattering by features including steps and both open and filled slots, in support of our ultrasonic non-destructive testing work.

D. O. THOMPSON. The procedures that we have used in our theoretical work are primarily analytical in nature. Most of the work in this area in our programme has been done by Professor J. A. Krumhansl and his students at Cornell University. We have not, as yet, used finite difference modelling for describing elastic wave interactions.

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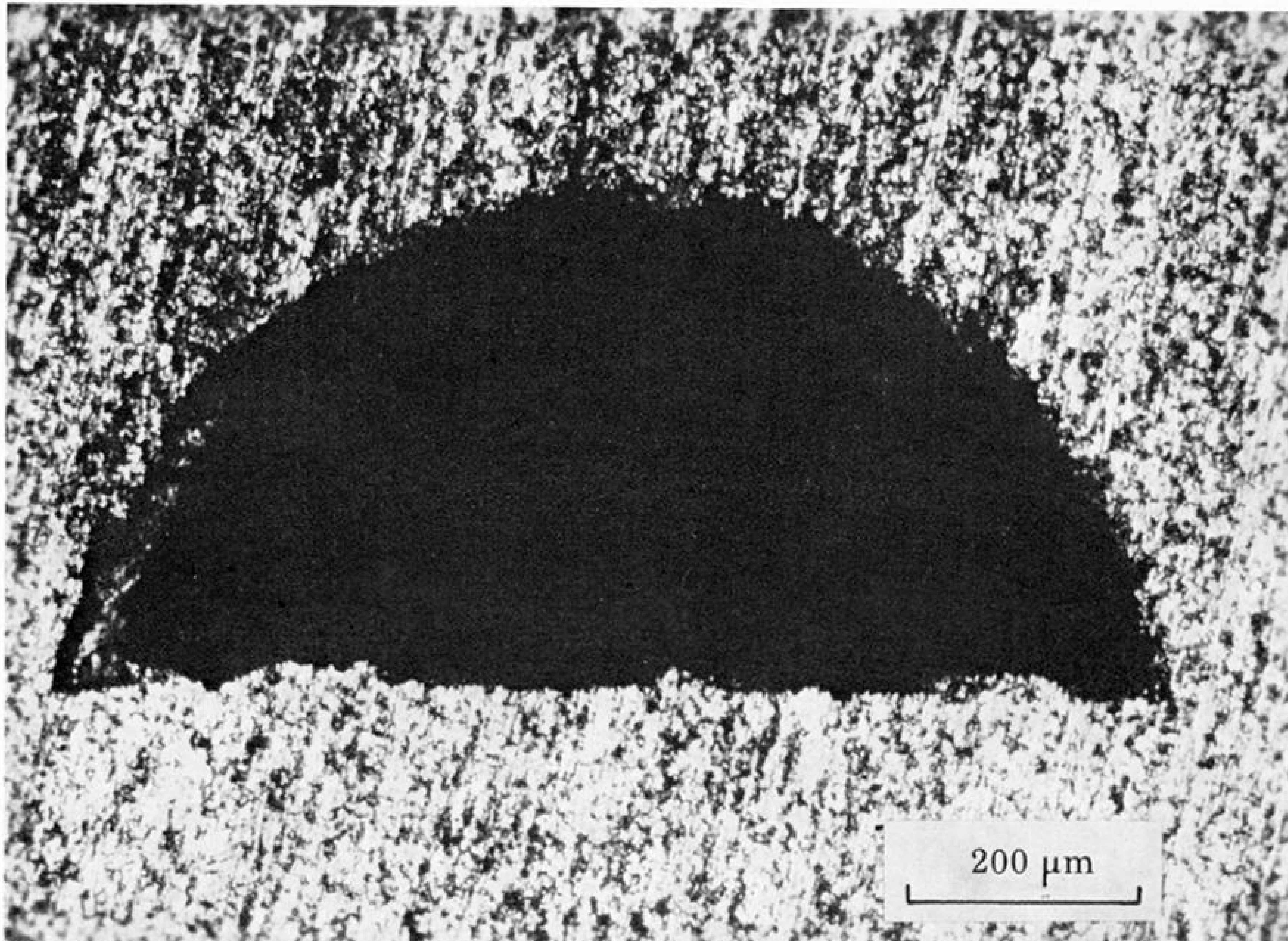

IGURE 2. Micrograph showing cross section of a hemispherical cavity at a diffusion bond plane. Grain growth occurs across original interphase.