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ACOUSTIC EMISSION SIGNATURE ANALYSIS

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1.0 ABSTRACT

Progress during the past twelve months of the DOE Contract ER-78-C-03-2029 is reported. The principal results obtained in this reporting period include the radiation patterns of the acoustic emission signals that are generated by reproducible fast crack growth in glass, and by the slow, stable transgranular crack growth in 304 stainless steel. The wave forms received have been Fourier analyzed for frequency content of the different displacement modes that arrive at the detector. One 304 stainless steel specimen has been sensitized and electrolytically charged with hydrogen to change the fracture mode from transgranular to intergranular to determine if differences can be detected in the acoustic emissions generalized by these two fracture modes. Preliminary high frequency results (5-20 MHz) are reported for glass.

The "wave momentum" or "fracture momentum" concept discovered during first year has been extended and techniques for measuring it suggested. It appears increasingly attractive as an experimental and conceptual tool. Theoretical estimates suggest that it is most likely to be useful at frequencies above 5 MHz, and that region is now being explored experimentally. Several theoretical results appear to have implications for other areas of ultrasonics. In particular, a hitherto apparently unknown infinite family of surface waves and families of plate curves have been mathematically described, together with suggestions for their generation, detection and application.

2.0 INTRODUCTION

Acoustic emission (AE) signals resulting from crack growth have been studied by various authors (1-4). Most of these studies are particularly concerned with obtaining correlations between the stress intensity factor K and the number of acoustic emission events with the ultimate goal of fatigue life prediction in mind. Acoustic emission is also a viable nondestructive testing tool which can be used in prooftesting to warn of the formation and growth of the flaws and to locate these flaws even on relatively large structures, such as pressure vessels.

In spite of these successes, there are still serious limitations imposed by the absence of a fundamental understanding of the relation between the characteristics of the elastic wave at the transducer and the characteristics of the microscopic source which generated it. A deeper understanding would permit optimization of detector design and should reduce the costly, tedious empirical effort needed to redevelop AE technology for each new alloy and heat treatment and each new structure. Such understanding is necessary for the effective application of the best of current device technology to AE detection, data collection, reduction, and interpretation.

Somewhat more subtle, but no less important, is the problem of confidence in the AE results. The degree of confidence which can be accorded an NDT measurement is strictly limited by the extent of our knowledge of the relation between the observed phenomena and the flaw. Because AE observes genuinely microscopic dynamic processes, it has been difficult to establish this link. This technical difficulty, however, is a potential strength since it gives AE microscopic sensitivity which may be invaluable with the very small critical defect sizes in the next generation high strength materials.

The present program is devoted to a study of the release of strain energy during subcritical crack growth using new acoustic emission sensing techniques based upon sound theoretical grounds. This effort is called "Acoustic Emission Signature Analysis" since both the characteristics of the

strain energy release and the resulting response of the detectors are analyzed. The program utilizes digital data processing methods and recent developments in AE theory to acquire improved fundamental understanding of acoustic emission.

During the first year, crack formation in plate glass was studied primarily because this material is elastically isotropic and thus simplifies the AE signal analysis problem. Although AE experiments on glass are still being done to test new concepts, the main emphasis during the second year has been shifted to crack growth mechanisms in steels as the material of major interest to DOE. There are a number of common problems in many pressure vessels and pipelines where the structure is subjected to high loads and a corrosive (hydrogen containing) environment. In pressure vessels for hydrocarbon cracking, the structure is subjected to cyclic mechanical and thermal stresses which can cause the crack to grow in a slow stable manner. In many cases, this growth is modified by the presence of an environment. The growth rate in gaseous hydrogen, e.g., can be several orders of magnitude faster than in an inert environment. The specific attractions of hydrogen assisted crack growth for the present, fundamental AE studies, in addition to its practical significance, are twofold. First, it permits relatively controlled subcritical crack growth, and the nature⁵ of the crack growth can be altered (e.g., transgranular vs. intergranular by relatively minor changes in the microstructure by change in post-anneal cooling rate for the previous example). Second, the details of the crack growth process in embrittled steel are not fully understood to date. The AE experiments on such a system, therefore, may provide additional information which may contribute to better understanding of the embrittlement mechanism itself. If suitable samples can be obtained, these experiments could be extended to radiation embrittled steel at later stages of the program.

3.0 PROGRESS

3.1 General

Stated in a general way, the fundamental AE problem is the determination of the characteristics of a microscopic process in a solid from its macroscopic elastic radiation measured with ultrasonic transducers at remote points. To appreciate the role this problem plays, it is helpful to divide the applications of acoustic emission into three categories: its use in proof testing to locate defects in large structures like pressure vessels; its use as a monitoring device to warn of potentially hazardous failure of similar structures; and its use as a materials science tool to study the kinetics of the microscopic processes from which it originates. The first is its largest and most successful application, probably because this application does not really require a solution of the fundamental problem. For the second and third applications, however, AE suffers from several deficiencies,⁶ largely due to the difficulty in finding a signature which identifies and characterizes the particular microscopic process occurring. Since realistic applications will have several different kinds of sources present, the ability to distinguish them and interpret them in terms of the specific microscopic characteristics is vital to progress in the second two categories of AE applications. This is a formidable problem to which we will try to find solutions in the course of this program, focussing upon the general problem of acoustic emission accompanying deformation and fracture, the theoretical description of acoustic emission, and the best use of computer signal processing to effectively utilize a combination of sophisticated measurements with rigorous, idealized, theoretical descriptions.

3.2 Acoustic Emission Characterization in Glass

Extensive experiments to characterize acoustic emission signals of propagating cracks have been performed on glass. The experimental set-up used has been described in our first year report.⁷ Briefly, by means of a

hydraulic loading tank that permits direct observation of the cracks initiated, a diamond indenter was pushed into the glass. All signals observed are due to the generation of "radial cracks" of about 1 mm length as described earlier.⁷ A PZT transducer was mounted on the glass plate as shown in Fig. 1. In a first series of experiments, the angular dependence of the acoustic emission events was determined by producing cracks such that they had equal distance (14.2 cm) to the detector; however, the normal to the plane of these cracks varied from 0 to 90° with respect to the direction of the detector location (see Fig. 1). Four examples of the first 40 μsec of these signals detected and recorded with a modified Sony video recorder, that was described earlier,⁷ are shown in Fig. 2. Although these four signals originated at four different cracks, the similarity of shape (in time) of these signals is apparent. In the figure, four different, easily identifiable peaks, have been marked: 1st and 3rd P-wave peaks, the shear wave peak (S) and the Rayleigh wave peak (R). Since S and R are more prominent than the earlier arriving P-wave peaks, we used S and R to draw some conclusions on their common origin. Using a distance of 14.2 cm between the cracks and the detector yields a shear wave velocity of 3.6×10^5 cm/sec and a Rayleigh velocity of 3.1×10^5 cm/sec which agrees very well with the values reported in the first year report.⁷ Furthermore, we find that the event (in time) occurred about 22.5 μsec to the left of each figure. Under those conditions the "direct" P-wave (shortest distance between crack and detector) should arrive at about 0.7 μsec in Fig. 2 (using a P-wave velocity of 5.9×10^5 cm/sec). The signal-to-noise ratio is too large, however, for its unambiguous identification. The 1st and 3rd P-wave peak thus must be caused by multiple reflections at the bottom and top of the glass plate. Furthermore, it is very likely that complex interferences of these multiple reflected P-waves come about since the detector has a finite width, probably causing such features as the 1st and 3rd P-wave peak. In spite of the uncertainties in the exact interpretation of the detected P-wave peaks, we have attempted to obtain the P-wave acoustic emission radiation pattern for the propagating cracks. In Fig. 3, we have plotted the observed angular dependence of the 3rd P-wave

1st SERIES:
ANGULAR DEPENDENCE

2nd SERIES:
INTERFERENCE
EFFECTS

Fig. 1 Experimental arrangement for glass experiments.

Fig. 2 First 40 μs of acoustic emission signals received on glass as a function of crack orientation.

Fig. 3 P-wave amplitude, normalized to S-wave amplitude as a function of crack orientation on glass.

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amplitude, normalized to the shear wave (S) amplitude, in cylindrical coordinates (the P-wave peak is thus internally calibrated). As may be seen from this figure, the P/S wave amplitude ratio is, practically independent of the angle of observation. The scatter around the average line (dashed curve) is mainly due to the uncertainties in measuring the amplitude of the 3rd P-wave peak. Furthermore, we conclude from Fig. 2 that both the S-wave and the Rayleigh wave (R) show little, if any, directionality. Observed small differences in the S- and R-peak amplitude are, very likely, caused primarily by small differences in the production of these cracks (remember that each acoustic emission event shown in Fig. 2 is generated by a different crack).

Another interesting and important feature of the acoustic emission signals, shown in Fig. 2, is their Fourier spectrum. Analyzed were the first 40 μ sec (that means both P-wave peaks, and the shear and Rayleigh wave peaks) in two steps: Fig. 4 shows the Fourier spectrum of all four signals and Fig. 5 the normalization of the 90°, 60° and 30° spectra with respect to that observed at 0°. The latter step was taken to eliminate the inherent detector response as much as possible.

In both Figs. 4 and 5, indications are that there are distinct peaks at about 0.28, 0.52 and about 0.75 MHz with the latter particularly pronounced in the 60° and 90° directions. However, we have to indicate here that in light of a similar experiment, to be discussed in the following, one should not draw any detailed conclusions from the present results in that we have not achieved satisfactory repeatability in these tests.

We believe that the results presented in Figs 2 through 5 can be qualitatively explained as follows: as the crack is generated, the resulting fracture surfaces apparently vibrate not only in a normal (drum head mode, giving rise to P-waves) but also in a shear mode. Those P- and S-waves that strike the surface in the vicinity of the crack, generate a Rayleigh wave, which arrives as a relatively strong signal at the detector, since its energy is very little dissipated in space due to the guided wave character. The

Fig. 4 Fourier spectra of acoustic emission signals on glass.

Fig. 5 Normalized Fourier spectra (from Fig. 4).

major part of the P-wave is strongly attenuated due to both spatial dissipation and partial mode conversion at the free surfaces. The strong shear wave is a surprise and we have no explanation for this phenomenon at the present time.

Furthermore, we may speculate on the radiation pattern that has been observed. Since the major frequency components of the wave received are below 0.6 MHz, the wavelengths of the acoustic emission signals is in the range

$$\frac{3.1 \times 10^5}{6 \times 10^5} < \lambda < \frac{5.9 \times 10^5}{3 \times 10^5}$$

or between 1/2 and 2 cm. Since the crack length is small (1 mm) with respect to the wavelength, the crack can basically be considered a point source whose radiation pattern should be isotropic, as observed. Theoretical estimates of the extent of possible anisotropy are discussed in Sec. 3.4.

As mentioned before, we repeated the experiments described above. We will present the results without going too much into the details. However, it should be pointed out that the signals received were treated somewhat differently from those shown in Fig. 2. After having recorded the signals in the second experiment, each signal was played 250 times into the computer to eliminate random noise during the transfer of the signal into the computer. Example results are shown in Fig. 6. Note the elimination of the background noise. This also had the effect to produce acoustic emission signals that are smoother than those shown in Fig. 2. The radiation patterns are isotropic, as observed in the first set of experiments.

In the latter experiments, the Fourier spectrum over the first 50 μ sec, shown in the normalized form in Fig. 7, was broken down in smaller sections: (a) a section that only includes the P-wave (Fig. 8); (b) a section that includes the first 5 μ sec of the S-wave (Fig. 9); and (c) a section including the arrival of the Rayleigh wave (and chosen again to be 5 μ sec long) (Fig. 10). Qualitatively, features shown in Fig. 7 are similar to those shown in Fig. 5. But it now appears that the low frequency peak (at about

Fig. 6 Signal averaged first 50 μ sec of acoustic emission signals received on glass for two crack orientations.

Fig. 7 Fourier spectra of signal averaged acoustic emission signals on glass.

Fig. 8 P-wave section of Fig. 7.

Fig. 9 S-wave section of Fig. 7.

Fig. 10 S- and Rayleigh section of Fig. 7.

0.13 MHz) is mainly due to the shear wave and that at about 0.45 MHz due to the P-wave. The Rayleigh wave also contains a 0.45 MHz component (probably caused by a P-wave conversion to the Rayleigh wave). The previous conclusions on the generation of these signals are unchanged otherwise.

Again, in reference to Fig. 1, another set of experiments was carried out to test the interference of already present cracks on the signal generated last. A result is shown in Fig. 11. In this case (bottom of Fig. 11) a crack of orientation $\varphi = 90^\circ$ was produced in front of an already existing $\varphi = 90^\circ$ crack, the 1st and 3rd P-wave peak amplitudes are much larger (compare bottom to top of Fig. 11). We believe that the already existing crack acts as a reflector for the P-wave, thus producing a stronger P-wave signals.

Recently, we have performed initial experiments, in which a commercial high-frequency (10 MHz) transducer was used to detect acoustic emission signals originating at cracks in glass. These experiments were designed to check our theoretical hypothesis that high frequency events, indicating very fast events, should exist. Naturally, the modified Sony video recorder cannot be used to record the signals since its bandwidth is limited to 3 MHz. The signals were instead digitized in real time by a Biomation 8100 A-D converter, controlled by a mini-computer. The two left hand records in Fig. 12 show such a high frequency count (in time and frequency). The signals decay very fast (within 2 μ sec) and have frequency components as high as 20 MHz. For comparison, using the same mode of operation, a low frequency event, similar to Figs. 3 and 7, is shown on the right hand side of Fig. 12. In the latter case, all frequency components are below 1 MHz.

At the present time, we do not know the origin of these high frequency events. We conjecture that they correspond to the fracture of small glass particles.

3.3 Acoustic Emission Characterization in Steels

Several unsuccessful attempts to produce acoustic emission events in steels by pushing a microindenter into the material have been made. Even in a

← EXISTING
CRACK

Fig. 11 Indications for interference of older cracks with acoustic emission signals.

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Fig. 12 High frequency event (graphs on lefthand side) in time and frequency, compared with a typical low frequency event.

low-toughness ball bearing steel (52100), only the usual indentation marks (used to measure the hardness) accompanied by some plastic deformation, have been achieved. Pointed experiments, in which we tried to split a grain boundary in the ball bearing steel using an indenter, also failed.

It was thus decided to attempt to obtain acoustic emission data from fatigue cracks growing in compact tension specimens. There are certain advantages and disadvantages to this procedure. An advantage is that a growing fatigue crack in a compact tension specimen actually simulates the "real world" situation. On the other hand, external (and unwanted) noise from the usually used electro-hydraulic systems and fretting noises at the grips may make it difficult to discover actual noise from the propagating crack. In order to avoid these disadvantages, two steps were taken:

- (a) It was decided to build a special hydraulic fatigue machine in which the oil is pumped manually to load and unload the specimen. High frequency vibrations, usually generated at the pump and carried by the oil to the fatigue machine, and thus to the specimen, are totally avoided.
- (b) In order to prevent grip noise from being detected by the acoustic emission transducer, a system that employs three additional detectors was developed. This system is schematically shown in Fig. 13. Close to the grips (G) two slave transducers are mounted. A third one is mounted close to the crack tip. If noise is generated at the grips, slave detectors 1 or 2 detect it before slave detector 3 does. Through the logic of the gate control, the gate is closed and the signal, as detected by the actual acoustic emission detector, is not put on the tape. If a true acoustic emission signal is generated at the crack tip, slave detector 3 detects it before 1 and 2 and the gate will be opened for the signal, detected by the acoustic emission detector and will be recorded.

Fig. 13 Experimental set-up for acoustic emission signals on stainless steel.

The acoustic emission detector can be placed anywhere on the specimen (within the confinements imposed by the set-up of the slave detectors). At the present time, we operate with the detectors placed on the circumference of the circularly shaped specimen, designed such that the angular dependence of the emissions from the growing crack could be determined. A photograph of the specimen is given in Fig. 14 (only one of the slave detectors is shown in this figure).

First tests on this system were performed on 304 stainless steel in the quenched condition. Before going into the results, it is appropriate, however, to discuss the reasons for using this particular material. The crack grows transgranularly in the quenched condition. However, if the material is sensitized (600°C and furnace cooled) and exposed to hydrogen, the fracture mode is changed to intergranular.⁸ At room temperature, the hydrogen diffusion coefficient in this material is small⁹ ($D = 4.7 \times 10^{-3} \exp(12,900/kT)$ or equal to $D \approx 3 \times 10^{-12} \text{ cm}^2/\text{sec}$) which is advantageous in that there will be hardly any loss of hydrogen during the crack propagation studies. On the other hand, the small diffusion coefficient makes it much more difficult to charge a large specimen, as shown in Fig. 14, with the appropriate hydrogen concentration to achieve hydrogen induced crack growth. It was thus decided to apply the following procedure. After sensitization of a specimen (the microstructure of which is shown in Fig. 15) the specimen was charged electrolytically at 290K for 8 hours per day at 2 to 3 milliamps/cm² using a NaOH + NaCN bath, and heated (outside the bath) to about 350°C for 16 hours a day over a period of 4 weeks ($D \approx 10^{-7} \text{ cm}^2/\text{sec}$). Any hydrogen penetrating into the material during charging (penetration depth for 8 hours charging is about 10 μm) should diffuse into the material for an estimated 7 mm during the warm-up period and, hopefully, give rise to transgranular failure. It is thus expected that we should be in a position to make acoustic emission measurements on two different fracture modes of the same material.

Tests were carried out so far on the as-quenched material only. The compact-tension specimen was pre-cracked in a standard electrohydraulic

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Fig. 14 Stainless steel specimen in fatigue test apparatus.

Fig. 15 Micrograph of sensitized 304SS.

fatigue frame, such that the tip of the crack was close to the center of the specimen. Tests were then continued in the manually operated frame described above. Initial experiments concentrated on the occurrence of acoustic emissions as a function of load, as shown schematically in Fig. 16. Accumulated acoustic emission counts (A.C.) with and without gate control were monitored during these tests, which indicate that without gate control, many of the signals originate at the grips. The gate control is, therefore, very important. With gate control some occasional acoustic emission events occurred close to the maximum load. We believe these to be indications of actual crack growth. During unloading, many emissions occur, believe to be due to "crack closure" noise. All the following data have been taken during unloading at 1800 lbs. Data on the events during the loading portion of the stress cycle (occasional events) will be taken shortly.

The angular dependence of acoustic emission signals, as obtained during the unloading (with the receiver angle as defined in Fig. 13) are shown in Fig. 17. In contrast to the angular dependence of the emission signals on glass (Fig. 13) there is very little resemblance between the various signals. At the present time it is not clear to us, whether the various signals should look alike or not, since the events that initiated the signals, may actually be different. As a next step, it is clearly necessary to try to catch the signals from one and only one event by putting a time delay between the detectors and record the signals in succession. Furthermore, it will be necessary to determine P- and S-wave velocities (and, possibly, the Rayleigh velocity), as well as the acoustic attenuation of these modes, as a function of detector angle, to be able to account for a possible effect of texture on the signals detected. As in the case of glass, the signals shown in Fig. 17 have been Fourier analyzed. The major response is observed in the frequency range 0 to 0.4 MHz. Since the experiments are still ongoing, we will report on them together with the results on the sensitized material at a later date.

Fig. 16 Acoustic emission signals as a function of fatigue load.

Fig. 17 First 100 μsec of acoustic emission signals received on stainless steel as a function of crack orientation.

3.4 Progress in Acoustic Emission Theory

Acoustic emissions emitted by a crack under load commonly undergo many boundary reflections before detection. As a result, the detailed form of the signal (e.g., Fig. 2) is sensitive to the precise location of the detector and is very difficult to interpret. One quantity, the total energy of the AE, is independent of the detector location (except for the usually weak attenuation) and is, therefore, much easier to interpret. In fact, phase insensitive transducers have been developed and have found applications in ultrasonic inspection precisely because they measure only this simple, integrated property of the signal (its energy). In the first year of the program, it was discovered¹⁰ that an acoustic emission in an isotropic elastic plate has two conserved quantities in addition to the total energy. The quantities are quadratic in the elastic wave field, like the total energy, and form a vector parallel to the plate surface. This vector is the conserved elastic wave momentum. (A third component exists, but is not conserved on reflection by the surface.) The elastic wave momentum characterizes the source orientation in a way which is insensitive to the details of the propagation path, much as the source magnitude can be characterized by the energy of the wave.

During the present year, the wave momentum concept has been further developed. Measurement techniques have been suggested and provided with an analytical basis,¹⁰ for interpreting the data, though these have not yet been implemented. The momentum P_i is given by

$$P_i = - \int d^3x \rho v_j \frac{\partial u_j}{\partial x_i} \quad (1)$$

where ρ is the density, u the elastic wave displacement, and $\underline{v} = \partial \underline{u} / \partial t$ the velocity. A transducer can measure these quantities only on a surface, say $\underline{u}(x, y, 0, t)$, so the evaluation of the integral over z requires a theoretical basis for extrapolating the surface values into the material.

An important special case of that problem was solved by the observation that knowledge of either the transverse or normal displacement of a Rayleigh wave will tell you everything about that Rayleigh wave. The conditions appropriate for this problem are those of a radially expanding cylindrical wave, for which Rayleigh waves have not been generally treated except for the isotropic case.¹² A previously unstudied infinite family of Rayleigh waves, and later, a similar infinite family of plate waves, were discovered.¹³ The Rayleigh-like waves have radial, azimuthal, and normal displacement components given by

$$u_r(t, r, \theta, z) = \sum_{m=0}^{\infty} \int \frac{d\omega}{2\pi} \frac{\exp[i(m\theta - \omega t)]}{\omega \alpha_L (\alpha_T^2 + k^2)} a_m(\omega) [H_{m-1}^{(1)}(kr) - H_{m+1}^{(1)}(kr)] [(\alpha_T^2 + k^2) e^{\alpha_L z} - 2\alpha_T \alpha_L e^{\alpha_T z}], \quad (2)$$

$$u_\theta(t, r, \theta, z) = \sum_{m=0}^{\infty} \int \frac{d\omega}{2\pi} \frac{\exp[i(m\theta - \omega t)]}{\omega \alpha_L (\alpha_T^2 + k^2)} a_m(\omega) [H_{m-1}^{(1)}(kr) - H_{m+1}^{(1)}(kr)] [(\alpha_T^2 + k^2) e^{\alpha_L z} - 2\alpha_T \alpha_L e^{\alpha_T z}], \quad (3)$$

and

$$u_z(t, r, \theta, z) = \sum_{m=0}^{\infty} \int \frac{d\omega}{2\pi} \frac{\exp[i(m\theta - \omega t)]}{\omega \alpha_L (\alpha_T^2 + k^2)} a_m(\omega) [H_m^{(1)}(kr)] [(\alpha_T^2 + k^2) e^{\alpha_L z} - 2k \alpha_T e^{\alpha_T z}], \quad (4)$$

where $k = \omega/c$ with c the Rayleigh wave velocity, $\alpha_L = (k^2 - \omega^2/c_L^2)^{1/2}$, $\alpha_T = (k^2 - \omega^2/c_T^2)^{1/2}$, the $H_m^{(1)}$ are the outgoing-wave Hankel functions, and the a_m are arbitrary dimensionless functions of ω . An ideal experiment would measure the normal displacement as a function of time at all points on a circle of radius R . A Fourier analysis then extracts a_m , and this can be used to calculate u_r , u_θ , and thus the wave momentum

$$\vec{p} = (p_x, p_y)$$

The rather lengthy analysis has been carried out and will be published in a form suitable for data analysis. In many cases the results simplify to

$$P_x \propto \int_0^{2\pi} d\theta \cos\theta R |u_z(R, \theta)|^2 \quad (6)$$

$$P_y \propto \int_0^{2\pi} d\theta \sin\theta R |u_z(R, \theta)|^2 \quad (7)$$

and

$$E \propto \int_0^{2\pi} dt R |u_z(R, \theta)|^2 \quad (8)$$

This infinite family of Rayleigh waves and the related families of radially expanding plate waves are of interest in their own right. Acoustic emissions are generally fairly complicated combinations of these modes but now that these modes are known and understood, special transducers can fairly easily be fabricated to generate and detect pure modes. They appear to have several potential applications outside of acoustic emission. For example, bolt hole inspection is an important practical problem for which it appears the generation and detection of their radial plate modes may be superior to existing techniques.¹³

Theoretical calculations of the wave momentum for model sources are underway. Because of the sensitivity of the results to the details of the model assumptions, it is premature to comment on the results, except to note that they agree with the expectation that the anisotropy is of order $\pi d/\lambda$, where d is the source diameter. Thus observation of 20% anisotropy in a 20 μm event requires measurement at frequencies

$$f \sim \frac{c}{5\pi d} \sim 10 \text{ MHz} . \quad (9)$$

Initial results have been obtained in glass at 10 MHz, so ultimate experimental feasibility is very plausible. It is expected that these can be extended to the steel without serious additional complications.

4.0 SUMMARY

Acoustic emission in plate glass and steel has been studied as a function of angle. The low frequency AE in glass (< 1 MHz) was studied in detail, and contributions from P, S and Rayleigh waves identified. These results are isotropic, as expected theoretically. Limited high frequency (5-20 MHz) results have been obtained in glass. This is the first time, to our knowledge, that AE energy has been measured above 3 MHz. The measurement of AE on transgranular crack growth in steel during fatigue crack growth was accomplished by use of a low noise manual hydraulic loading system and an electronic gate to reject grip noise. The signals are complex, and not yet understood in detail. The concept of the wave momentum of an AE, first introduced during the previous year, was elaborated and a measurement technique suggested. The theoretical study of this problem led to the discovery of an infinite, previously unknown, family of elastic surface (Rayleigh-like) waves, and to further cylindrical, radially propagating plate waves. It appears these waves may be useful in other areas of ultrasonics.

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