AD-A035 578 JOHNS HOPKINS UNIV BALTIMORE MD DEPT OF MECHANICS AN--ETC F/G 11/6

AN ULTRASONIC TECHNIQUF FOR (ETECTION OF THE ONSET OF FATIGUE D--ETC(U)

APR 76 R E GREEN, R B POND F44620-71-C-0062

UNCLASSIFIED AFOSR-TR-76-0811 NL

1 OF 1

AD A035578

END

DATE FILMED 3-77

AFOSR - TR - 76 - 081
AFOSR Scientific Report

THE JOHNS HOPKINS UNIVERSITY

Department of Mechanics
and Materials Science

AN ULTRASONIC TECHNIQUE FOR DETECTION OF THE ONSET OF FATIGUE DAMAGE

by

Robert E. Green, Jr.
Robert B. Pond, Sr.

Air Force Office of
Scientific Research

Contract No. F44620-71-C-0062

April 1976

Baltimore, Maryland 21218

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFOSR-TR-76-0811
2. GOVT ACCESSION NO.:
3. RECIPIENT'S CATALOG NUMBER:

4. TITLE (and Subtitle): AN ULTRASONIC TECHNIQUE FOR DETECTION OF THE ONSET OF FATIGUE DAMAGE.

5. TYPE OF REPORT & PERIOD COVERED: FINAL rept. 1 MAR [redacted]71- FEB [redacted]76,

6. PERFORMING ORG. REPORT NUMBER:

7. AUTHOR(s): ROBERT E. GREEN, Jr.; ROBERT B. POND, Sr

8. CONTRACT OR GRANT NUMBER(s): F44620-71-C-0062

9. PERFORMING ORGANIZATION NAME AND ADDRESS: JOHNS HOPKINS UNIVERSITY, DEPARTMENT OF MECHANICS AND MATERIALS SCIENCE, BALTIMORE, MARYLAND 21218

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 681307; 9782-01; 61102F

11. CONTROLLING OFFICE NAME AND ADDRESS: AIR FORCE OFFICE OF SCIENTIFIC RESEARCH/NA, BUILDING 410, BOLLING AIR FORCE BASE, WASHINGTON, D.C. 20332

12. REPORT DATE: Apr[redacted] 1976

13. NUMBER OF PAGES: 22

14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office): 24p. 9782 01

15. SECURITY CLASS. (of this report): UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

ULTRASONIC ATTENUATION
ACOUSTIC EMISSION
NONDESTRUCTIVE TESTING
FATIGUE

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report is a summary of research activities performed under Air Force Office of Scientific Research Contract No. F44620-71-0062 for the period March 1, 1971 through February 28, 1976. The primary purpose of the research was to develop an optimum ultrasonic technique for the early detection of fatigue damage. As a result of the research conducted it is concluded that the optimum ultrasonic technique for early detection of fatigue damage is a technique which permits simultaneous measurements of acoustic emission activity and ultrasonic attenuation changes.

DD FORM 1473, 1 JAN 73 — EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED 407515 LB

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

An Ultrasonic Technique for Detection of The Onset of Fatigue Damage

FINAL SCIENTIFIC REPORT

(March 1, 1971 - February 28, 1976)

Air Force Office of Scientific Research

Contract No. F44620-71-0062

April 1976

Prepared by: Robert E. Green, Jr., and
Robert B. Pond, Sr.
Department of Mechanics and Materials Science
The Johns Hopkins University
Baltimore, Maryland 21218

Submitted to: Air Force Office of Scientific Research/NA
Building 410
Bolling Air Force Base
Washington, D. C. 20332

An Ultrasonic Technique for Detection of The Onset of Fatigue Damage

Robert E. Green, Jr., and Robert B. Pond, Sr.

Mechanics and Materials Science Department

The Johns Hopkins University

Baltimore, Maryland 21218

ABSTRACT

This report is a summary of research activities performed under Air Force Office of Scientific Research Contract No. F44620-71-0062 for the period March 1, 1971 through February 28, 1976. The primary purpose of the research was to develop an optimum ultrasonic technique for the early detection of fatigue damage. As a result of the research conducted it is concluded that the optimum ultrasonic technique for early detection of fatigue damage is a technique which permits simultaneous measurements of acoustic emission activity and ultrasonic attenuation changes.

Summary of Research Accomplishments

During the past several years, under the sponsorship of the Air Force Office of Scientific Research Contract No. F44620-71-C-0062, the current investigators have studied various methods of detecting the onset of fatigue damage in metals by use of ultrasonic techniques. A systematic comparison between body wave reflection, surface wave reflection, ultrasonic attenuation, and acoustic emission showed that body wave reflection and surface wave reflection techniques are inferior to ultrasonic attenuation and acoustic emission techniques for the early detection of fatigue damage. This is because both reflection techniques require that an appreciable fraction of the available ultrasonic energy be reflected from a crack of sufficient size and correct orientation in order to be detected. To the contrary, both ultrasonic attenuation and acoustic emission can detect movement of dislocations prior to microcrack formation.

Both ultrasonic attenuation and acoustic emission techniques for the detection of fatigue damage employ fixed sensors and permit continuous remote monitoring. Acoustic emission can detect crack formation and movement which is not directly in the normal sound field of the sensor. Ultrasonic attenuation measurements can only detect defects created within the sound field of the transducer. Acoustic emission can only detect creation or growth of flaws in a material, while ultrasonic attenuation can detect static flaws as well as dynamic flaws. For this reason, acoustic emission must be monitored continuously in order not to miss any defect creation or motion. Intermittent ultrasonic attenuation measurements permit detection of defect creation or rearrangement between measurements. Acoustic emission is capable of detecting dislocation breakaway from pinning points. Ultrasonic attenuation can detect vibration of dislocation loops between pinning points as well as breakaway. Acoustic emission flaw detection systems of current design normally operate in the frequency range from 20 kHz to 1 MHz and in this range background noise is intense. Filtering and special transducer arrangements coupled with logic circuits and computers have circumvented this problem in some cases, but the noise problem remains a major one. Ultrasonic attenuation systems normally operate in the frequency range above 1 MHz where background noise is usually negligible. The general waveform of an acoustic emission signal cannot be specified and is extremely difficult to separate from noise sources having the same frequency distribution since both occur in a near random fashion. The waveform of an ultrasonic pulse is easily determined and it is a simple matter to electrically separate the signal from noise in the ultrasonic attenuation technique even if the noise is of the same frequency since the ultrasonic signals occur at regular known intervals in time and noise signals arrive at irregular intervals.

Ultrasonic attenuation measurements made simultaneously with fatigue tests on aluminum specimens gave warning of crack initiation and eminent fracture much earlier than conventional ultrasonic methods. This was found to be true for metal bars which were initially defect free and for metal bars which initially contained induced latent defects. The remarkable success of the ultrasonic attenuation method of detecting fatigue damage as developed in this program is clearly evident in the previous publications (1-5).

Although the ultrasonic attenuation technique is superior to the acoustic emission technique in many respects, one important advantage of the acoustic emission technique is the remote sensing capability it provides. Due to the potential offered by the acoustic emission technique in this regard, work was initiated to determine if acoustic emission could be successfully exploited as a fatigue monitoring technique. A detailed survey of the acoustic emission literature revealed that although several previous investigators had monitored acoustic emission during fatigue testing (6-18), considerable additional work was required before acoustic emission can be reliably used as a continuous monitor during fatigue cycling to predict crack formation and fracture. The main problem associated with fatigue failure prediction by acoustic emission monitoring is the difficulty of separating the acoustic emission signals associated with defect creation and movement from background noise. Since the amplitude, frequency content, and propagational characteristics associated with elastic waves emitted from various structural defects are unknown, it is evidently clear that acoustic emission monitoring will not be optimally suited for in-service fatigue damage detection until much more work is done to elucidate the basic causes of the emissions themselves as well as the particular features of the emissions directly attributable to the underlying defects.

The current practice for evaluating structural damage by acoustic emission monitoring is to count the signals emitted during deformation of the material and to plot the results as total counts or count rate as a function of some measure of the deformation such as stress, strain, or the number of fatigue cycles. A number of problems are associated with this simplistic approach including a lack of knowledge of the influence of test specimen geometry on the received signals, of the effect of the medium coupling the acoustic emission transducer to the workpiece, and the amplitude and frequency response of the transducer itself. Moreover, the signals are normally passed through a filter, discriminator, and gate circuit wherein an incoming signal above a set threshold voltage will produce a shaped output signal which is fed into a count rate or count totalizer circuit. In order to make reliable assessment of such data, it is normally assumed that all events producing acoustic emissions of sufficient amplitude to be counted are equally damaging to the structure, that all damaging events will produce acoustic emissions of sufficient amplitude to be counted, and that each event will cause an acoustic emission which will be counted only once and not overlap with other signals. To make such assumptions is improper since there is more than one type of event which can generate acoustic emission, some of which are damaging and some not, and there is very little documentation in the literature which permits discrimination between different events by acoustic emission techniques. A given high amplitude acoustic emission signal may be produced by a single event which causes damage to the structure or by the simultaneous occurrence of a number of small events which cause no structural damage but whose net effect is to produce the large acoustic emission signal. A structurally damaging event may occur but the emissions associated with it may be too weak, propagate away from the detecting transducer, or be of the wrong frequency to be detected. A single event may take place with several emissions of sufficient amplitude that the detector records several counts for one event or a single event may be such that the direct signal and multiply reflected signals arrive at the detecting transducer at different times thus resulting again in multiple counts from a single event.

Slip, twinning, crack initiation, crack growth, and fracture are all events which produce structural changes in various metals and alloys including aluminum, titanium, and steel which are of primary importance in aircraft construction. All of these events produce acoustic emissions, and quite probably different acoustic emissions, since they have been well documented to produce different structural alterations. Moreover, in many alloys subject to fatigue cycling, several of these deformation mechanisms occur simultaneously and hence several sources of acoustic emission are simultaneously active. Therefore, it is extremely difficult if not impossible to assess the state of structural damage during fatigue testing from acoustic emission data unless the specific emission characteristics associated with each deformation-emission mechanism is individually determined beforehand.

With this purpose in mind, a detailed study has been initiated to determine the characteristics associated with various deformation mechanisms in metal single crystals and polycrystalline aggregates. Experiments on twinning (19,20) showed that a correspondence exists between the duration of the acoustic emission signal and the volume of twinned material as determined by cinematographic observation of the generation and growth of twin bands. It was also found that the direction of the stress, tensile or compressive, induced in the body of the crystal due to twinning can be determined from the polarity of the elastic wave emitted by the twin as detected by the transducer. This last result points out an important problem associated with acoustic emission testing not noted by prior investigators. Since elastic waves emitted by various defects can have different polarities depending on the type of internal stress which generates the waves, it is possible for signal cancellation to occur at the detecting transducer. Thus, if two relatively large sources of acoustic emission generate waves of opposite polarity which arrive at the detecting transducer simultaneously, the destructive superposition of these two signals would yield no net signal at the transducer, while the initiating events themselves could conceivably play an important role in destroying the structural integrity of the test piece. Admittedly, it is highly improbable that complete signal cancellation would occur in actual practice, but partial cancellation and signal modification due to mutual interference of simultaneously arriving acoustic emission signals is highly probable.

Acoustic emission measurements made on a series of lead-tin binary alloys of different compositions during constant-strain-rate tensile tests (20,21) showed that different alloy compositions possessed different microstructures which, in turn, caused different structure sensitive acoustic emission signals. Immediate reloading of a number of the test specimens which had been previously loaded and unloaded showed that although the acoustic emission activity was reduced on the second loading, emissions commenced at the beginning of reloading at load levels much lower than the maximum level reached on the first loading. These results give direct experimental evidence against the often quoted "Kaiser Effect." This work showed that for the alloys tested, chemical composition, microstructure, degree of deformation, and prior mechanical history all affect the acoustic emission to a marked degree. Therefore, the deformation mechanisms active in these alloys cannot be simply characterized by analysis of the acoustic emission counts alone.

While the phenomenon of mechanical twinning is usually sufficiently gross with most materials that simple macroscopic inspection reveals the twins, in other cases such as slip and microcrack formation a more sophisticated observation is necessary in order to reveal the surface displacements associated with the deformation process. Moreover, since the amplitude of the acoustic emission signal associated with slip is much lower than that associated with twinning or cracking, much greater amplification is required in order to detect the acoustic emission signals in the slip generated case. This increase in amplification necessitates a corresponding decrease in the extraneous noise sources associated with the various components of the test system. Work is currently in progress in which acoustic emission associated with slip in polycrystalline aluminum alloys as used in aircraft construction is correlated with simultaneous measurements of ultrasonic attenuation.

During the course of the acoustic emission tests, it became evident that the sensitivity and spectral response characteristics of acoustic emission transducers are quite variable and often do not agree with the specifications quoted by the commercial manufacturers. It has been determined that the origin of these difficulties can be traced back to improper transducer design and lack of adequate transducer test facilities by the manufacturers. Therefore, a system to independently calibrate the spectral response characteristics of acoustic emission transducers has been constructed and is currently being used to calibrate all transducers. This system is similar in design to that recently developed at the National Bureau of Standards (22) and appears to be far superior to any system reported previously.

A detailed survey of previous theoretical analyses of acoustic emission has been completed. Although a number of theoretical studies have been carried out, none of these has succeeded in predicting the amplitude or spectral characteristics associated with acoustic emissions from selected defects.

It has been well documented in the scientific literature that the two non-destructive testing techniques, acoustic emission and ultrasonic attenuation, are extremely sensitive to the microstructural alterations associated with the mechanical deformation of materials. Both techniques have been extensively exploited in basic research experiments concerned with obtaining information about the fundamental mechanisms causing plastic deformation, microcrack formation, crack growth, and fracture and in applied technical investigations concerned with detection of defects causing failure in structural materials. Theoretical treatments have also appeared in which the observed experimental results for both acoustic emission and ultrasonic attenuation are attributed to similar deformation mechanisms. Yet, despite the extensive investigation and similarity in description of the fundamental mechanisms acting, only one brief study has previously employed the two techniques simultaneously(23). Since these two techniques offer the best practical possibility of early detection of fatigue damage, considerable effort has been devoted to careful simultaneous measurements of acoustic emission and ultrasonic attenuation on a single test specimen subject to uniaxial tensile elongation (24,25).

One inch diameter rod stock of various aluminum alloys (1100 H, 6061 T6, 2024 T3, 7075 T651) was machined to have a reduced gauge section in a "dog bone" configuration. Gauge sections of 5.08 and 10.16 cm in length and diameters 1.27 and 1.02 cm were used. The end faces were machined flat and parallel. In general, the specimens were given no further preparation since the examination of commercial products was the primary interest.

All of the specimens were subjected to uniaxial tensile loading by an Instron testing machine. In these studies crosshead rates of 0.05 and 0.02 cm/min were used. In order to couple the grips to the load cell different couplers were employed to assure that no flexure of the specimen occurred during deformation, since this would cause spurious ultrasonics results. The grips, which were specifically designed for this study, provided easy access to either end of the specimen for transducer placement, uniform uniaxial application of the load, and reasonable acoustic isolation from the loading machine. No influence of the mechanical or electrical operation of the Instron on either the ultrasonic attenuation or acoustic emission monitoring was encountered.

Continuous ultrasonic attenuation measurements were made using a Matec Model 6600 Pulse Modulator and Receiver coupled with a Matec Model 2407A Attenuation Recorder. By subtracting the initial attenuation value and dividing by the instantaneous specimen length, the change in attenuation per unit length (dB/cm) was obtained. In conjunction with this monitoring system a 0.5 in (1.27 cm) diameter Aerotech 10 MHz Gamma transducer was operated in the pulse-echo mode at a repetition rate of 200 per second. The transducer was directly coupled to the upper specimen face with nonaqueous stopcock grease. A 3 Kg weight was used to supply a constant load to the transducer, while a specially designed spacing ring was used to assure central positioning, avoiding excessive reflections of the pulse from the lateral surfaces. Care was taken to insure that the amplitude of the ultrasonic driving pulse was well below that necessary to excite the acoustic emission sensor. The acoustic emission system used in the present study consisted of a one inch diameter 100 kHz Panametrics Model 5070 resonant sensor coupled directly to the lower end of the specimen with nonaqueous stopcock grease and held in place by a spring. The signal from the transducer was amplified and band pass filtered from 10 kHz to 300 kHz by a Tektronix 1A7A High Gain Amplifier. Further filtering by a Kronhite Model 3202 Filter from 80 kHz to 120 kHz occurred before the signal was counted by a Monsanto Model 112A Counter. In these studies threshold counting and rate counting were both employed in order to best discern the acoustic emission behavior.

Load, ultrasonic attenuation, and acoustic emission were monitored as a function of extension for the four aluminum alloys. For all alloys tested it was found that the acoustic emissions occurred predominantly during the pre-yield region of the deformation. In fact, in most cases, almost no acoustic emission was detected after yield. The ultrasonic attenuation, however, was found to exhibit an opposite behavior, in that the change in attenuation per unit length prior to yield was essentially imperceptible. Upon yielding the change in attenuation increased in some tests and decreased in others. In addition, a local perturbation in attenuation change as a function of elongation was observed, which was most predominant in the alloys with high yield strengths, 2024 T3 and 7075 T651. In order to study these perturbations more fully, and to discern whether or not there was any corresponding activity associated with the acoustic emission a series of tests was performed on 7075 T651 specimens. During these tests a major part of the effort was devoted to making certain that the perturbations were only the result of the mechanical deformation of the test material and not some artifact introduced by the testing system. In this series of tests the specimen size and heat treatment were varied as well as the gripping arrangement and elongation rate. In every test the local perturbations were observed, with the most significant changes in behavior occurring in those specimens which had been heat treated. Two particularly significant findings arose out of this series of experiments. First, during the testing of a specimen which had received a T6 heat treatment at a gain increased to 85 dB lower level emissions, of about the same amplitude level as that associated with the background, were detected. The rate of emission exhibited a maximum around 3% strain, although the previously pronounced emissions observed before yield were indistinguishable from the other emissions at this gain setting. The second significant finding was observed with another 7075 T651 specimen which was subjected to repeated loading and unloading to 393 MPa; emission was again monitored at 80 dB gain. During the first loading the characteristic pre-yield emission occurred but on immediate reloading and upon reloading after 72 hours no emission was observed. However, on loading after allowing the specimen to recover for 80 hours at 130°F, acoustic emission activity similar to that observed during the first loading was observed.

The results of these tests indicate that for the aluminum alloys investigated the deformation mechanisms causing acoustic emission activity and ultrasonic attenuation changes are different and, therefore, simultaneous monitoring by both techniques constitute a complimentary test method which yields more information about the deformation mechanisms than either technique alone.

Conclusions

The following conclusions have resulted from the research supported under this contract:

1. Conventional body wave and surface wave ultrasonic methods are inferior to ultrasonic attenuation and acoustic emission techniques for the early detection of fatigue damage.
2. Acoustic emission has the advantage of remote source location, while ultrasonic attenuation has the advantage of easily yielding reliable data in the presence of background noise.
3. Acoustic emission monitoring will not be optimally suited for in-service fatigue damage detection until much more work is done to elucidate the basic causes and physical characteristics of the emissions directly attributable to structural defects. This in turn will permit optimum design of an acoustic emission monitoring system which can operate in the presence of background noise.
4. Several observed features of acoustic emission testing deserve special note.
   (a) Partial cancellation and signal modification due to mutual interference of simultaneously arriving acoustic emission signals is highly probable.

(b) Acoustic emission signals are influenced by chemical composition, microstructure, degree of deformation, and prior mechanical and thermal history.

(c) Acoustic emission signals are strongest for fracture and crack propagation, fairly strong for twinning, and very weak for slip processes.

5. The sensitivity and spectral response characteristics of commercial piezoelectric transducers are quite variable and often do not agree with the specifications quoted by the manufacturers, because of improper transducer design and lack of adequate test facilities on the part of the manufacturers.

6. No theoretical treatment currently exists which can predict the amplitude and spectral characteristics associated with acoustic emissions from selected defects.

7. Simultaneous monitoring of acoustic emission activity and ultrasonic attenuation changes constitute a complimentary test method which yields more information about the deformation mechanisms than either technique alone.

8. Optimization of an acoustic emission technique to permit reliable measurements in the presence of background noise is a necessity for fatigue test monitoring.

9. The optimum ultrasonic technique for early detection of fatigue damage is a technique which permits simultaneous measurements of acoustic emission activity and ultrasonic attenuation changes.

References

1. Green, Robert E., Jr., and Pond, Robert B., Sr., "An Ultrasonic Technique for Detection of the Onset of Fatigue Damage," Annual Report (1971-72), Air Force Office of Scientific Research AFOSR-TR-72-1199 (1972).

2. Joshi, Narayan R., and Green, Robert E., Jr., "Ultrasonic Detection of Fatigue Damage," Proceedings of the Symposium on Fracture and Fatigue, George Washington University, May 1972, J. Engr. Fract. Mech. 4, 577 (1972).

3. Green, Robert E., Jr., "Ultrasonic Attenuation Detection of Fatigue Damage," Proceedings of the Ultrasonics International 1973 Conference, Imperial College, London, England, March 1973, p. 187, IPC Science and Technology Press, Ltd., Guildford, England (1973).

4. Green, Robert E., Jr., and Pond, Robert B., Sr., "An Ultrasonic Technique for Detection of the Onset of Fatigue Damage," Annual Report (1972-73) Air Force Office of Scientific Research AFOSR-TR-73-0901 (1973).

5. Panowicz, Walter V., Jr., Pond, Robert B., Sr., and Green, Robert E., Jr., "Ultrasonic Detection of Fatigue Damage in Aluminum Specimens Containing Induced Latent Defects (submitted for publication).

6. Gerberich, W. W. and Hartbower, C. E., "Some Observations on Stress Wave Emission as a Measure of Crack Growth," Internat. J. Fract. Mech. 3, 185 (1968).

7. Hartbower, C. E., Gerberich, W. W., and Liebowitz, H., "Investigation of Crack-Growth Stress-Wave Relationships," J. Engr. Fract. Mech. 1, 291 (1968).

8. Hartbower, C. E., Gerberich, W. W., and Crimmins, P. P., "Monitoring Subcritical Crack Growth by Detection of Elastic Stress Waves," The Welding Journal WEJUA 47 1s (1968).

9. Hutton, P. H., "Use of Acoustic Emission to Study Failure Mechanics in Metals," ASME Paper No. 69-Met-8.

10. Hutton, P. H., "Acoustic Emission - A New Tool for Evaluating Structural Soundness," Battelle Northwest Report BNWL-SA-2449 (1969).

11. Hutton, P. H., "Acoustic Emission Applied to Determination of Structural Integrity," Automotive Engineering 79, 33 (1971).

12. Dunegan, H. L., Harris, D. O., and Tetelman, A. S., "Detection of Fatigue Crack Growth by Acoustic Emission Techniques," Materials Evaluation 28, 221 (1970).

13. Harris, D. O., Dunegan, H. L., and Tetelman, A. S., "Prediction of Fatigue Lifetime by Combined Fracture Mechanics and Acoustic Emission Techniques," Proceedings of the Air Force Conference on Fatigue and Fracture of Aircraft Structures and Materials, Air Force Flight Dynamics Laboratory Report, AFFDL TR 70-144, p. 459 (1970).

14. Harris, D. O. and Dunegan, H. L., "Verification of Structural Integrity of Pressure Vessels by Acoustic Emission and Periodic Proof Testing," Dunegan Research Corporation, Livermore, California Technical Report DRC-71-2 (May 1971).

15. Nakamura, Y., "Acoustic Emission Monitoring System for Detection of Cracks in a Complex Structure," Materials Evaluation 29, 8 (1971).

16. Rollins, F. R., Jr., "Acoustic Emission from Boron-Aluminum Composites During Tensile Fracture and Fatigue," Midwest Research Institute, Kansas City, Missouri, Technical Report No. 6 to Office of Naval Research (1971).

17. Egle, D. M., Mitchell, J. R., Bergey, K. H., and Appl, F. J., "Acoustic Emission for Monitoring Fatigue Crack Growth," Proceedings 27th Annual Conference Instrument Society of America, Paper 72-638, New York (1972).

18. Egle, D. M., "Detecting High Cycle Fatigue Crack Growth Using Acoustic Emission," Presented at the Fracture and Flaws Symposium, Albuquerque, New Mexico (1973).

19. Van Doren, Stephen L., Pond, Robert B., Sr., and Green, Robert E., Jr., "Acoustic Characteristics of Twinning in Indium," Air Force Office of Scientific Research Technical Report AFOSR-TR-75-0607 (1975).

20. Pond, Robert B., Sr., "Acoustic Emission Study of Twinning in Indium Crystals and Lead-Tin Alloys" Proceedings of the Interdisciplinary Workshop for Quantitative Flaw Definition," Science Center, Rockwell International, Thousand Oaks, California AFML-TR-74-238 (1974).

21. Jan, Chang-Shu, Pond, Robert B., Sr., and Green, Robert E., Jr., "Acoustic Emission During Deformation of Lead-Tin Alloys," Air Force Office of Scientific Research Technical Report AFOSR-TR-75-1066 (1975).

22. Breckenridge, Franklin R., Tschiegg, Carl E., and Greenspan, Martin, "Acoustic Emission: Some Applications of Lamb's Problem," J. Acoust. Soc. Amer. 57, 626 (1975).

23. Imanako, T., Sano, K., and Shimizu, M., "Dislocation Attenuation and Acoustic Emission During Deformation in Copper Single Crystal," Crystal Lattice Defects, 4, 57 (1973).

24. Duke, John C., Jr., "Simultaneous Acoustic Emission and Ultrasonic Attenuation Monitoring of the Mechanical Deformation of Aluminum," Master's Thesis, Department of Mechanics and Materials Science, The Johns Hopkins University, Baltimore, Maryland (1976).

25. Duke, John C., Jr., and Green, Robert E., Jr., "Simultaneous Acoustic Emission and Ultrasonic Attenuation Monitoring of the Mechanical Deformation of Aluminum," Accepted for presentation and publication in the Proceedings of the Second International Conference on Mechanical Behavior of Materials to be held in Boston, Massachusetts (August 1976).

Publications Resulting from Contract Work

1. Green, Robert E., Jr., and Pond, Robert B., Sr., "An Ultrasonic Technique for Detection of the Onset of Fatigue Damage," Annual Report (1971-72), Air Force Office of Scientific Research AFOSR-TR-72-1199 (1972).

2. Joshi, Narayan R., and Green, Robert E., Jr., "Ultrasonic Detection of Fatigue Damage," Proceedings of the Symposium on Fracture and Fatigue, George Washington University, May 1972, J. Engr. Fract. Mech. 4, 577 (1972).

3. Green, Robert E., Jr., "Ultrasonic Attenuation Detection of Fatigue Damage," Proceedings of the Ultrasonics International 1973 Conference, Imperial College, London, England, March 1973, p. 187, IPC Science and Technology Press, Ltd., Guildford, England (1973).

4. Green, Robert E., Jr., and Pond, Robert B., Sr., "An Ultrasonic Technique for Detection of the Onset of Fatigue Damage," Annual Report (1972-73) Air Force Office of Scientific Research AFOSR-TR-73-0901 (1973).

5. Panowicz, Walter V., Jr., Pond, Robert B., Sr., and Green, Robert E., Jr., "Ultrasonic Detection of Fatigue Damage in Aluminum Specimens Containing Induced Latent Defects." Submitted for publication in Metallurgical Transactions A.

6. Van Doren, Stephen L., Pond, Robert B., Sr., and Green, Robert E., Jr., "Acoustic Characteristics of Twinning in Indium," Air Force Office of Scientific Research Technical Report AFOSR-TR-75-0607 (1975).

7. Pond, Robert B., Sr., "Acoustic Emission Study of Twinning in Indium Crystals and Lead-Tin Alloys," Proceedings of the Interdisciplinary Workshop for Quantitative Flaw Definition AFML-TR-74-238 (June 1974).

8. Jan, Chang-Shu, Pond, Robert B., Sr., and Green, Robert E., Jr. "Acoustic Emission During Deformation of Lead-Tin Alloys," Air Force Office of Scientific Research Technical Report AFOSR-TR-75-1066 (1975).

9. Green, Robert E., Jr., "Ultrasonic Investigation of Mechanical Properties," Volume III, Treatise on Materials Science and Technology, Academic Press, New York (1973).

10. Green, Robert E., Jr., "Non-Linear Effects Associated with High-Power Ultrasonics," Proceedings of the Eighth International Congress on Acoustics,' Imperial College, London, England (1974).

11. Green, Robert E., Jr., "Non-Linear Effects of High-Power Ultrasonics in Crystalline Solids," Ultrasonics, pp. 117-127 (1975).

12. Green, Robert E., Jr., "Emerging Field NDT Methods: Ultrasonics-General" Proceedings of the U. S. Department of Transportation and the American Society for Nondestructive Testing Joint Meeting on Opportunities for NDT in Transportation (August 1974). Materials Evaluation 33, 187 (1975).

13. Van Doren, Stephen L., Pond, Robert B., Sr., and Green, Robert E., Jr., "Acoustic Characteristics of Twinning in Indium," submitted for publication in J. Appl. Phys.

14. Duke, John C., Jr., and Green, Robert E., Jr., "Simultaneous Acoustic Emission and Ultrasonic Attenuation Monitoring of the Mechanical Deformation of Aluminum," Accepted for presentation and publication in the Proceedings of the Second International Conference on Mechanical Behavior of Materials to be held in Boston, Massachusetts (August 1976).

15. Green, Robert E., Jr., "Acoustic Emission: A Critical Comparison Between Theory and Experiment," submitted for presentation and publication in the Proceedings of the Ultrasonics International 1977 Conference to be held at Imperial College, London (June, July 1977).