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# NAVY VEHICLES: ACOUSTIC EMISSION RELATED TO NONDESTRUCTIVE TESTING

## ABSTRACT

This investigation was aimed at studying acoustic emission for applications to residual stress measurements and for the evaluation of structural integrity of engineering structures. Effects of microstructure, composition and prior cold working on magnetomechanical acoustic emission (MAE) have been studied. Magnetization behavior, magnetostriction and Barkhausen noise are affected by stress as well as other parameters. These responses have been measured simultaneously in order to identify the stress level uniquely. Combinations of advanced signal analysis methods and MAE measurements have been studied to identify the optimum parameters for applications. This work has established mechanisms of MAE signal generation, effects of various parameters that influence the MAE behavior of materials and signal processing techniques that allow materials characterization via MAE. Included are neutron irradiated reactor vessel steels, large size steel plates as well as single crystals of various ferromagnetic metals and alloys.

In the second part of this study, acoustic emission from materials undergoing plastic deformation and fracture have been examined in an attempt to improve detection capability of the impending structural failure. Acoustic emission characteristics of reactor vessel steels, advanced aluminum alloys and metal and ceramic matrix composite materials have been evaluated in detail. Digital signal analysis techniques have been used to investigate further the different types of acoustic emission signals from various sources. This study has clarified acoustic emission signals produced by a number of different mechanisms during plastic deformation and fracture of these materials. These include dislocation related mechanisms, inclusion decohesion and fracture, crack propagation, fiber fracture, delamination and splitting of fibrous composites, among others.

## I. INTRODUCTION

Much progress has been made in recent years in understanding the nature of acoustic emission (AE), and in practical application of AE methods to nondestructive evaluation of components and structures. Clearly, AE signals are related to microscopic sources producing them and their suitable analyses should yield information about the sources. The information, in turn, can provide the basis for an improved nondestructive testing (NDT) method for the prediction of structural failure and/or for the detection of dangerous flaws.

The major goals of this investigation have been (1) research and development of a new method of residual stress measurement and (2) characterization of AE signals and correlation of the characteristics with physical causes. We have contributed significant knowledge in the understanding of AE due to plastic flow, that of AE in structural steels and that of the basic causes of MAE. Other areas in the applications of MAE and fracture related AE in welds and composite materials also received attention in our research efforts.

## II. SUMMARY OF RESULTS

### Residual Stress Measurement and Materials Characterization by MAE Method

This investigation was aimed at studying acoustic emission for applications to residual stress measurements and materials characterization. Stress waves arising from magnetostriction of ferromagnetic materials are called magnetomechanical AE. The basic cause involves magnetostriction during magnetic domain wall movement. Effects of microstructure, composition and prior cold working on magnetomechanical acoustic emission (MAE) have been studied. Magnetization behavior, magnetostriction and Barkhausen noise are affected by stress as well as other parameters. These responses were measured simultaneously in order to identify the stress level uniquely. Combinations of advanced signal analysis methods and MAE measurements provide the most promising NDE methods, and have been studied to identify the optimum parameters for applications.

We have generated the basic knowledge on MAE. From simultaneous measurements of MAE, magnetization (B-H) curve, magnetostriction and Barkhausen noise, much information has been accumulated and the interrelationships of various factors have been clarified. Our study has employed Fe, Ni, Fe-Ni alloys and Fe-Si alloys and test temperature, stress, microstructures and amount of cold work have also been varied. Relying on the results of the basic MAE study, we have continued to explore several different schemes for practical implementation of MAE for residual stress applications. The most promising one relies on the intensity ratio of MAE at different field or frequency ranges. A number of other combinational approaches are also evaluated. By utilizing all the available data on MAE and magnetization for separate identification of residual stress, prior cold work, chemical composition and heat treatment can be made for components of constant geometries.

During the period of this contract, M. Man Kwan, O.Y. Kwon, M. Ohtsu and M. Shibata worked in the area of MAE. Both Kwan and Kwon received Ph. D. based on the work, the latter in March 1988. Published papers are listed at the end of this report and Nos. 1 to 10 are concerned with the topic of MAE. In this area, 19 presentations were made (see the listing that follows). One more is planned for April 1988 (No. 20).

Since the work of Dr. Kwon just completed has not been included in the listing above, the abstract of his thesis will be included as an appendix to this report. Two chapters of the thesis are on MAE and two or more papers will be prepared in the near future. In this work, he obtained MAE and Barkhausen noise (BN) data from large steel samples up to 6 feet long. These tests evaluated effects of sample size and resonant vibration on MAE data. It is shown that rapid decrease of MAE intensity at low stresses in small samples is in fact due to efficient acoustic coupling provided by the applied stresses. In large samples, the slope of MAE intensity vs. stress plots becomes small, but nearly constant. Next, he used pattern recognition analysis including the data of the large samples and a new set of steel samples. Five envelopes were determined for each sample and stored in a microcomputer. These waveform data were then processed using a pattern recognition analysis software and classified according to heat treatment. Nearly perfect classification was achieved. This indicates that we can detect differences in steel heat treatment via MAE and BN signals. The envelope based pattern classification system works well for MAE data for both stress and microstructural characterization. Dr. Kwon extended the MAE characterization and pattern recognition analysis work to neutron irradiated samples. The samples were of nuclear pressure vessel steels and model alloys, irradiated up to  $10^{19}n/cm^2$ . Four different irradiation conditions were evaluated along with control samples. The irradiation was performed at University of Virginia by a group from University of California, Santa Barbara. The results showed that neutron irradiation produces substantial changes in MAE waveforms and intensity. As much as 30 % changes were observed. Since no other method is capable of detecting irradiation effects with this large sensitivities or with nondestructive means, this should be developed further to make MAE a monitoring method for irradiation embrittlement.

#### Structural Monitoring by Acoustic Emission

In the second part of this project, acoustic emission from materials undergoing plastic deformation and fracture has been examined in an attempt to improve detection capability of the impending structural failure. We have established new acoustic emission techniques and applied them in studying the acoustic emission behavior of advanced aluminum alloys, reactor vessel steels and composite materials. Digital signal analysis techniques are used to investigate further the different types of acoustic emission signals from various sources. A major emphasis has been placed on the fracture related AE in high strength aluminum-lithium alloys and fiber-reinforced advanced composites including metal matrix (Al-SiC) and resin matrix (graphite-epoxy) materials.

In this part of the project, we have attempted to establish the basic understanding of AE from structural materials in order to provide a firm foundation on which one can utilize AE as a tool for NDE applications. It is important to identify the origins of different types of acoustic emission. We have studied AE associated with plastic deformation and fracture of structural alloys. In particular, our studies have discovered the dominant role of emissions arising from non-metallic inclusions in steels. In aluminum-lithium alloys, we have found that various precipitates control the slip behavior, which in turn affects acoustic emission characteristics. This work is being continued by Gerry Zamiski as a non-funded Ph. D. thesis research and will be completed in 1988.

Eighteen papers have been published in the area of AE behavior of structural metallic alloys. These are listed as Ref. 11 to 28. AE due to plastic deformation of homogeneous materials was discussed in Ref. 11, 12, 16, 18, 20, 21, and 27. Temperature dependent deformation, microstructural effects and thermal treatment effects have been clarified. AE arising from non-metallic inclusions of steels has also been analyzed. The studies resulted in Refs. 13 - 15, 19, 22 - 24, 26 as well as 28. We have established that main source of AE in structural steels is the decohesion of nonmetallic inclusions, such as MnS. We started to study a new structural Al alloy with Li and the initial report was given as Ref. 27. It showed that coherent precipitates produce quite different AE behavior and additional studies are being conducted as indicated above. Another area of interest from applications approach is the use of pattern recognition analysis. This method can provide real-time discrimination of various detected AE signals. Ref. 25 reports an application of a digital technique to fracture AE analysis.

Another thrust area has been AE from composite materials. Advanced fiber reinforced composites with metal and resin matrices have been used in increasing numbers in a variety of naval aircrafts and weapons systems. Yet, NDE techniques leave much to be desired. AE has been used to locate flaws in numerous missile motorcases. However, the nature of emission processes has not been clarified in many instances. This is especially true in metal matrix composites (MMC), but resin matrix composites are not well understood either.

We have studied MMC plates of SiC whiskers and SiC particulate reinforced Al matrix composites. These composite samples were investigated for their AE behavior during tensile and fracture tests as a function of heat treatment. In conjunction with fractographic studies, it was concluded that fracture in whisker reinforced composites initiates and propagates in the matrix and does not involve whisker fracture. In the particulate reinforced MMC's, interfacial separation was found to be predominant. These studies were reported in Refs. 32 and 33.

The second composite material studied was unidirectional carbon fiber reinforced epoxy. The samples were fabricated in-house using prepregs and included several types of artificial flaws. The flaws promote delamination, splitting and fiber fracture. By evaluating fracture morphologies and AE behavior, AE characteristics of specific types of AE generating mechanisms have been clarified. In addition, pattern recognition analysis techniques were applied to separate AE signals of different origins. Although the analysis procedures are complex at present, different types of AE signals can be successfully classified. These

investigations were reported in Refs. 30, 31, 34 - 36.

Presentations on these topics are listed in the reference section. These include a talk on glass-epoxy composites, residual stresses and general acoustic emission. A list of students and scholars who received financial support is given in the Reference section. Degrees received by some of them are also listed.

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53. Ono, K. "Identification of Damages in Composites via Acoustic Emission and Acousto-Ultrasonic Techniques, 1987 Winter Meeting of ASME, Boston, MA Dec. 13-18, 1987. (Invited)

## Students and Scholars

The following students and postdoctoral scholars received financial support from the contract:

Mr. Albert Avalos, Undergraduate Student (Lab Assistant, Mar. - June, 1986)

Mr. I. Chen, Undergraduate Student (Jan. -June 1985)

Mr. C. Horvath, Undergraduate Student (Jan. -June 1983)

Dr. S.-Y. S. Hsu (Ph.D. completed in Jan. 1981)

Mr. S. Jensen, Undergraduate Student (Lab Assistant, Jan. - June 1985; Mar. 1986 - Sep. 1987)

Mr. Craig Johnson (M.S. completed Dec. 1986)

Mr. E. Kobayashi, unsupported visitor (Sep. 1980 - Aug. 1982).

Dr. M. Man Kwan, (Ph. D. completed in 1983)

Dr. O.Y. Kwon, (Ph.D. completed in March 1988).

Mr. M.Y. Mochiki, unsupported visitor (June 1984 - June 1986)

Mr. D.L. Newell, Graduate Student (Sep. 1982 - Jan. 1983)

Dr. M. Ohtsu, Visiting Assistant Research Engineer (Two months during Oct. - Nov., 1985 and July to August 1986).

Mr. K. Okajima, Graduate Student (M.S. completed Jan. 1981).

Dr. I. Roman, Visiting Research Engineer (July - Aug, 1981; Sep. 1982 - Aug. 1983; Aug. - Oct. 1984; July 1985)

Dr. M. Shibata, Staff Research Engineer (Nov. 1981 - August 1982).

Dr. H.B. Teoh (Ph. D. completed in December 1984).

Mr. Gerry Zamiski (Ph.D. candidate, continuing)

## ABSTRACT OF THE DISSERTATION

Acoustic Emission Characterization of Materials  
by Digital Waveform Processing and Recognition

by

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Doctor of Philosophy in Materials Science and Engineering

University of California, Los Angeles, 1988

Professor Kanji Ono, Chair

Statistical pattern recognition based on the analysis of an individual acoustic emission (AE) signal have been studied for the effective discrimination of AE source mechanisms. An individual AE waveform was analyzed by the use of digital filtering or linear system modeling. It is shown that almost real-time processing and recognition of incoming AE signals can be achieved by utilizing digital computers. With currently limited applicability of fundamental approaches, the present approach can fulfill the need for applications of AE to the characterization of materials and processes.

Two types of digital waveform processing techniques were developed. An envelope-based waveform recognition was for the repetitive magneto-acoustic emission (MAE) and surface Barkhausen (SBN) signals whereas the autoregressive modeling via digital inverse filtering was for transient AE signals. The

inverse filtering with  $z$ -transform provided the spectral estimation of transient AE signals. The parameters in the frequency domain constituted a feature set for pattern recognition.

The microstructural variations of A533B steel and the stress states of AISI 1018 steel bars were successfully determined by the envelope-based pattern recognition of MAE signals. SBN waveforms were also useful for microstructural changes but of no use for stress states. Pattern recognition of MAE waveforms determined the radiation damages of reactor vessel steels as well. This can be a new nondestructive evaluation method for nuclear reactor components.

AE monitoring of multi-pass submerged-arc welding was studied by the system modeling-based waveform recognition of transient AE signals. AE signals due to copper-induced hot cracks were clearly isolated from signals due to phase transformations. The recognition power, however, was insufficient to completely overcome the presence of various noise in this noisy process. Although the inverse filtering required an off-line computer running under UNIX, the present study indicates the potential of discriminating AE signals from different sources in real-time. Further improvements may be necessary for practical applications.