1992

QUANTITATIVE NON-DESTRUCTIVE EVALUATION OF

HIGH-TEMPERATURE SUPERCONDUCTING MATERIALS

Grant No. DE-FG02-86ER13484, A007
Progress Report for the period Sept. 1, 1990 - Aug. 31, 1991

prepared by

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Submitted to

Office of Basic Energy Science
U.S. Department of Energy
Washington, D.C. 20545

June 14, 1991

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1. Summary of Current Project

Even though the currently intensive research efforts on high-temperature superconducting materials have not yet converged on a well specified practical material, the indications are that such a material may be quite brittle, anisotropic, and may contain many flaws such as microcracks and voids at grain boundaries. Consequently, practical applications of high temperature superconducting materials will require a very careful strength analysis based on fracture mechanics considerations. Because of the high sensitivity of the strength of such materials to the presence of defects, methods of quantitative non-destructive evaluation may be expected to play an important role in strength determinations.

This proposal is concerned with the use of ultrasonic methods to detect and characterize isolated cracks, clusters of microcracks and microcracks distributed throughout the material. Particular attention has been, and will continue to be devoted to relating ultrasonic results to fracture mechanics considerations.

2. Summary of Results since September 1, 1989

Considerable progress has been achieved in the general area of ultrasonic waves in cracked solids (Section 2.1.1.C of the Proposal for the period Sept. 1, 1989 - August 31, 1992). Recent results obtained in the course of research sponsored by this project, are concerned with ultrasound in solids that are permeated by cracks. The purpose of these studies is to relate the density of cracks and their geometrical parameters to wave speed and attenuation, in order that measured data of the latter quantities can be used to estimate the extent of crack permeation.

Work that has recently been completed, and has been submitted for publication may be summarized as follows:

2.1 Propagation of Ultrasound in a Cracked Solid

In a linearly elastic solid containing a distribution of obstacles (such as inclusions, cavities, or cracks) a propagating wave is subjected to multiple scattering. Each obstacle removes from the direction of propagation a part of the energy, and the coherent wave appears to be attenuated (even though there are no dissipation mechanisms present). The attenuation depends on frequency and on the distance traveled through the solid. The speed of the coherent wave depends also on frequency.

In work that was recently completed we have considered the propagation of antiplane waves in an unbounded linearly elastic solid that contains a distribution of flat cracks. The cracks are parallel to each other, the distribution is dilute, and the incident wave is normal to the plane of the cracks. The speed of the coherent wave in the cracked solid is obtained as a function of dimensionless frequency and of crack density.

In order to obtain the speed of the coherent wave it was assumed first that the coherent wave in the cracked solid propagates with a complex-valued wavenumber. The real part of the wavenumber is the ratio of the frequency and of the speed and the imaginary part is the attenuation coefficient. Second an expression was derived for the attenuation coefficient. Finally the wave speed was determined by using the Kramer-Kronig relations.

The existence of a complex-valued wavenumber can be motivated by appealing to the work of Waterman and Truell. In this work, the multiple scattering of waves caused by a random array of obstacles is discussed in detail. A probability distribution is assigned to the ensemble of configurations of obstacles, and an averaging procedure is used to obtain the displacement of the coherent wave. By making some special assumptions,

Waterman and Truell succeed in obtaining an explicit expression for the complex-valued wavenumber of the coherent wave.

The work of these authors is important, because it establishes that multiple scattering of waves produces coherent waves that propagate with complex-valued wavenumbers, and also it provides a physical interpretation of this phenomenon. However, the explicit expression of Waterman and Truell applies only when the obstacles are statistically independent points; in particular, the results do not apply when the obstacles are cracks.

It is possible in principle to reproduce for cracks the analysis of Waterman and Truell; one would have to use the linear scattering operator that relates the exciting field to the scattered field for a single crack, and great difficulties would have to be anticipated. Thus, we use an alternative approach by appealing to the Kramers-Kronig relations. This approach, which is illustrated here for the simple case of antiplane scattering, is of general validity and can be applied without difficulty. When the attenuation coefficient is known, one can determine the speed of the coherent wave; conversely, when the speed is known, one can determine the attenuation coefficient.

The derivation of the Kramers-Kronig relations and the underlying assumptions have been discussed in detail by several authors. A comparison between theoretical and experimental results for random composites and polycrystals can be found in the literature. These references reveal that the Kramers-Kronig relations have been used to solve important problems in various fields of physics and of engineering. In engineering, they have been used mostly to determine the speed or attenuation of elastic waves in composite materials. To our knowledge, they have not been used to determine for all frequencies the speed and attenuation of elastic waves in cracked

materials--except in a paper by Zhang and Achenbach, and in the recently completed work discussed above.

2.2 Reflection and Transmission of Surface Waves by an Edge

The reflection and transmission of a plane time-harmonic surface wave which is obliquely incident on the edge of a specimen has been investigated theoretically, numerically and experimentally. The theoretical formulation of the problem, which takes advantage of the translational invariance along the edge of the specimen, has been reduced to a system of singular integral equations for the diffracted displacement components along the faces of the quarterspace axes normal to the edge. The truncation of these equations leads to the definition of reflection and transmission coefficients, R and T . The equations have been solved for R, T and the diffracted displacements by the use of the boundary element method. A self-calibrating experimental technique has been proposed which deploys four surface wave transducers, and which removes the effects of variable coupling between the transducers and the faces of the quarterspace as the positions of the transducers are varied. The technique is particularly suited for the measurement of $|R/T|$ as a function of the angle of incidence. Excellent agreement has been observed between numerically and experimentally obtained values.

2.3 Effect of Surface Discontinuities on $V(z)$ and $V(z_0)$ for the Line-Focus

Acoustic Microscope

A refined calculation of $V(z)$ and $V(z, x_0)$ curves has been presented for a line-focus acoustic microscope and for a specimen which contains a discontinuity normal to its free surface. In the context of a Fourier integral approach, more accurate expressions have been employed for (1) the angular spectrum of the field produced by the lens, (2) the voltage response of the transducer and (3) the reflection coefficient of the object. In

addition, the usual "thin" lens theory has been extended to "thick" lens theory. For $V(z, x_0)$, details have been given for the case of a surface-breaking crack, and the inverse problem of determining the Rayleigh-wave reflection coefficient of a crack has been solved in an approximate manner. Comparisons between theoretical and experimental results have been presented for the case that the discontinuity is the edge of the specimen. The reflection coefficient calculated from experimental results agrees well with the theoretical value.

2.4 Numerical Analysis of the Acoustic Signature of a Surface-Breaking Crack

The boundary element method has been used to calculate the acoustic signature, produced by a line focus acoustic microscope, of an elastic object containing a surface-breaking crack. The acoustic signature has a vertical (z) and horizontal (x) dependence. A model of the microscope developed in an earlier paper has been used here and extended to take account of the crack. The mathematical formulation of the scattering problem for the cracked object leads to hypersingular integral equations. A suitable technique has been employed to solve such equations by the boundary element method. An electromechanical reciprocity identity has been used to relate the received voltage to the acoustic wavefields collected by the lens. The acoustic wavefield scattered from the cracked object have been investigated and curves have been presented which display the acoustic signature, as functions of (x, z) , for cracks of various depths and orientations. A method has been suggested to measure the depth of a surface-breaking crack using the acoustic signature.

2.5 BIE/BEM Approach to Scattering of Ultrasound by Cracks

The boundary element method has become a well established technique for the numerical solution of the boundary integral equations that govern the displacements of the crack faces in a cracked body. Once the relative separations of corresponding points on the crack faces (i.e., the crack-opening displacements) have been calculated by the boundary element method, other quantities of interest can be obtained by the use of appropriate integral representations.

The general category of problems that have been discussed in this work is of interest when a body containing a crack is subjected to rapid excitation. When the excitation is generated by a service load, the quantities of interest are ones related to the mechanics of fracture, such as elastodynamic stress intensity factors. A second application, which requires essentially the same mathematical formalisms, is in the field of quantitative non-destructive evaluation.

Formulations of boundary integral equations and their numerical solutions by the boundary element method have been discussed for elastodynamic fields in bodies containing interior cracks. Special attention has been devoted to the "crack-opening displacement" (COD) approach. Techniques to deal with the higher-order singularities that occur in the COD approach have been discussed in some detail.

3. Work in Progress

3.1 Characterization of Interphase Behavior by Ultrasonics Methods

A juncture between adjoining materials of different mechanical properties should often be considered as an interphase, i.e., as a very thin layer of mechanical properties that are different from those of the adjoining materials. The actual mechanical properties of a thin interphase

are generally difficult to determine. A technique that has, however, been employed with some success is quantitative ultrasonics. By the use of this technique, reflection and transmission coefficients can be obtained, which when interpreted in the light of a suitable mechanical model for the interphase, yield parameters describing the interphase properties. For the case that the wavelength of the incident wave is sufficiently larger than the thickness of the interphase, it has been found that the interphase can be modeled by a distribution of spring elements. It has, however, been pointed out that even for a thin interphase a spring layer whose constants are expressed in terms of the elastic constants of the interphase generally may not be entirely adequate, since the inertia effect of the interphase cannot always be ignored. From some simple calculations the present authors have, however, concluded that if the ratio of the thickness of the interphase to the wavelength is less than 0.2, the interphase can in fact be modeled by a spring layer, but one whose spring constants depend not only on the elastic properties of the interphase, but also on its mass density, as well as on the angle of incidence. Alternatively, the model can be slightly modified to include inertia effects explicitly. It has also been proposed that an interface containing a distribution of cracks can be represented by the spring-layer model. For a periodic planar array of cracks, the validity of this model over a specified range of frequencies was verified and explicit expressions for the spring constants in terms of the crack widths and the crack spacings have been presented. Hence the use of a spring layer can be justified, certainly for an interface containing defects, but also for a thin-interface layer provided that in the latter case the spring constants are appropriately selected.

The mechanical properties of interphases tend to be particularly critical at the intersection of an interphase with a free surface. The use of surface waves presents, however, a convenient method to measure the properties near a free surface. In recent work the reflection and transmission of surface waves by an interphase has been investigated for normal incidence. By the use of the spring-layer model the mathematical statement of the problem can then be reduced to a system of singular integral equations for the displacements on the free surface and for the tractions and displacements across the interface. Numerical solutions of this system have been computed, by the use of the usual 2 dimensional boundary element method.

In current work, the spring layer model has been further modified to include oblique incidence, and to include viscoelasticity to account for the effect of energy dissipation which often exists in the interphase.

The specific configuration that has been considered consists of a half space composed of two elastic quarter spaces. The quarter spaces are joined by an interphase which has been modeled by a visco-elastic spring layer. Oblique incidence of a plane Rayleigh wave under an angle θ with the normal to the interphase has been considered. Let the x_3 axis denote the intersection of the interphase and the free surface. Since the geometrical configuration is independent of the coordinate direction along the x_3 axis, and since the incident wave is a plane wave, the wave system will be translationally invariant with respect to x_3 . Hence all wavefields will have the terms $\exp(ik_R x_3 \sin\theta)$ in common. By taking advantage of the translational invariance and by the use of an appropriate elastodynamic Green's function, which was obtained recently, the formulation of the

problem has been reduced to a system of singular integral equations which are independent on the variable x_3 . This system is being solved numerically by the boundary element method to yield the desired reflection and transmission coefficients, R and T, as functions of the angle of incidence and the visco-elastic constants of the interphase.

3.2 A Measurement Model for the Line-Focus Acoustic Microscope

Over the last decade a significant development in nondestructive evaluation has been its evolution to a well defined field of interdisciplinary science and engineering. In the course of this development it has become well recognized that a fundamental approach to NDE must be based on quantitative models of the measurement processes of the various inspection techniques. A model's principal purpose is to predict, from first principles, the measurement system's response to specific anomalies in a given material or structure, (e.g. cracks, voids, distributed damage, corrosion, deviations in material properties from specifications, and others). Thus, a measurement model includes the configuration of probe and component being inspected as well as a description of the generation, propagation, and reception of the interrogating energy. In the ultrasonic case, this description requires computations of the transducer radiation pattern, refraction of the beam at the parts' surface, the beam profile and the propagation characteristics in the host material including effects of material anisotropy, attenuation, diffraction losses, etc. Detailed modeling of the field-flaw interactions which generate the measurement system's response function are also included, as well as information of material and other conditions that produce noise and add an uncertainty to the measurement results. A well constructed measurement model should be able to predict specific instrumental responses to anomalies in complex materials

and structures as well as to "standard" flaws placed in various calibration blocks.

A number of measurement models have been formulated in the past several years for different inspection techniques. For practical applications, the challenge lies in making approximations that permit the computations to be tractable while retaining sufficient accuracy so that the engineering applications are not compromised.

The availability of a measurement model has many benefits. Numerical results based on a reliable model are very helpful in the design and optimization of efficient testing configurations. A good model is also indispensable in the interpretation of experimental data and the recognition of characteristic signal features. The relative ease of parametrical studies based on a measurement model facilitates an assessment of the probability of detection of anomalies. A measurement model is a virtual requirement for the development of an inverse technique based on quantitative data. Last but not least a measurement model whose accuracy has been tested by comparison with experimental data provides a practical way of generating a training set for a neural network or a knowledge base for an expert system.

A versatile and reliable measurement model is essential to acoustic microscopy. As part of our current work we are developing a measurement model for a line-focus acoustic microscope in conjunction with a specimen containing various defects. The development is based on earlier work by Achenbach et al. for the corresponding case of a defect-free specimen.

For the present purpose a two-dimensional focused acoustic beam is modeled to scan an object both in the horizontal and vertical directions. The focused beam excites leaky Rayleigh waves as well as geometrically

reflected waves, which both may interact with the defects to generate a scattered field which propagates back through the lens to the transducer. The scanning in the vertical direction produces the so-called $V(z)$ curves, while horizontal scanning yields $V(x,z)$ curves. These curves are affected by the presence of a defects.

The configuration consists of transducer, buffer rod, lens, coupling fluid and specimen. The transducer radiates a tone-burst, so that the delay introduced by the buffer rod allows the separation of the various signals. The first returning signal is caused by the reflection of the incident wavefield from the surface of the lens, the second returning set of signals is scattered from the specimen and the subsequent returning signals arise from multiple reflections. The second set of signals is of interest here. Methods are being developed to accurately calculate the second reflections.

4. Personnel

Principal Investigator: J. D. Achenbach

Research Assistant: Yung-Chun Lee

The following Post-Doctoral Associates and Visiting Scholars have participated or are participating in this work:

V. S. Ahn

Y. C. Angel

J. G. Harris

J. O. Kim

Z.-L. Li

5. Oral Presentations of Project Work since Sept. 1, 1990.

Invited Lectures related to this Project

Oct. 17, 1990, "Detection and Characterization of Cracks by Ultrasonic Methods," The Johns Hopkins University

- Nov. 1, 1990, "Quantitative Non-Destructive Evaluation," Center for Mechanics of Composites, Texas A & M University
- Nov. 27, 1990, "Ultrasonic Surface Wave Technique to Determine Fatigue Damage," Symposium on Damage Mechanics in Engineering Materials, ASME Winter Annual Meeting, Dallas, Texas
- April 26, 1991, "The BEM/COD Approach to Wave Scattering by Interior and Near-Surface Cracks," First Int. Conference on Mathematical and Numerical Aspects of Wave Propagation Phenomena, Strasbourg, France
- May 1, 1991, "Numerical and Experimental Results for Scattering of Ultrasound by Surface-Breaking Cracks," 121 Meeting Acoustical Society of America, Baltimore, MD.
- May 29, 1991, "Mathematical Modeling for Quantitative Ultrasonics," 5th International Symposium on Nondestructive Characterization of Materials, Karuizawa, Japan.
- July 22, 1991, "Scattering of Ultrasound by Whisker-Like Inclusions," 1st US National Congress on Computational Mechanics, Chicago, Illinois.

6. Publications since Sept. 1990

(with Ch. Zhang) "Effective Wave Velocity and Attenuation in a Material with Distributed Penny-Shaped Cracks," Int. J. Solids and Structures, **27**, pp. 751-767, 1990.

(with Ch. Zhang) "Dispersion and Attenuation of Surface Waves due to Distributed Surface-Breaking Cracks," J. Acoust. Soc. Am., **88**, pp. 1986-1992, 1990.

"Effects of Distributed Microcracking on Effective Wave Speed and Attenuation of Ultrasound," Proc. Eighth Symposium on Energy Engineering Sciences, Argonne Nat. Lab., May 9-11, 1990, Argonne Nat. Lab.

(with Z.L. Li) "BIE/BEM Approach to Scattering of Ultrasound by Cracks," in Mathematical and Numerical Aspects of Wave Propagation Phenomena, eds.

G. Cohen, L. Halpern and P. Joly, SIAM, Philadelphia, 1991.

(with V.S. Ahn and J.G. Harris), "Numerical Analysis of the Acoustic Signature of a Surface-Breaking Crack," IEEE Transactions on Ultrasonics Ferroelectrics and Frequency Control, accepted for publication.

(with Y.C. Angel), "Attenuation and Speed of Antiplane Waves in a Cracked Solid using Kramers-Kronig Relations, J. Acoust. Soc. Am., accepted for publication.

(with I. Komsky and Ch. Zhang), "Ultrasonic Surface Wave Technique to Determine Fatigue Damage," in Damage Mechanics in Engineering Materials, AMD-Vol. 109/MD-Vol. 24, American Society of Mechanical Engineers, 1990.

(with Z.L. Li and J.O. Kim), "Effect of Surface Discontinuities on $V(z)$ and $V(z, x_0)$ for the Line-Focus Acoustic Microscope, WAVE MOTION, in press.

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5/18/92**