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13. ABSTRACT

A procedure was developed for synthesizing a complete, solid equation of state and applied to iron. An experimental technique was developed for measuring shock induced magnetic anisotropy in YIG. An improved procedure was developed for averaging magnetic moment in polycrystalline material. A theory of the asymptotic behavior of magnetization with field was developed for ferromagnetic materials. A code was written for 2-D elastic-plastic wave propagation in a bar. Analytic solutions for finite amplitude waves in lattices were developed.

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FINAL REPORT

SHOCK WAVES IN SOLIDS

by

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AFOSR 69-1758

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ABSTRACT

This grant was established to assist in development of shock wave techniques for application to problems in solid state and materials science. Particular problems to be studied were: equation of state at high pressure, dynamic failure of solids, electronic phenomena induced by shock, theory of wave propagation and kinetics of solid-solid phase transitions. In the course of the work it has been possible to (i) develop a procedure for synthesizing a logically complete, semi-empirical equation of state, using all available experimental data, and apply it to solid iron; (ii) develop a framework of dislocation and continuum mechanics for interpretation of shock experiments in dynamic failure; (iii) develop an experimental technique for measuring shock-induced magnetic anisotropy and remove some long-standing anomalies in magneto-elastic theory; (iv) develop a numerical procedure for elastic wave propagation in a cylindrical bar with a discontinuity in cross-section or material properties; (v) develop some analytic solutions for finite amplitude waves in lattices; (vi) initiate an experimental program to study the kinetics of solid-solid phase transitions in KCl. Attempts were made to measure the thermoelectric power of platinum under shock conditions, without success.

The overall goal of this research was to study and develop means by which propagation of shock waves can be used to determine material properties not accessible to static measurements, particularly in areas of equations of state of solids, kinetics of solid-solid phase transitions, dynamic failure of solids, and electrical phenomena. Efforts along these various lines have been largely successful; though the problems tend to be open ended, substantial progress has been made along several lines.

Equation of State of Solids: Various problems in wave propagation, nuclear effects, impact phenomena, etc., require complete equations of state of materials, including both volume and temperature or entropy dependence. Construction of such equations has been a frequently practiced but rather mysterious art in the recent past, and most efforts have been deficient in as much as they ignored a good deal of available data and relied heavily on theory, intuition, and a few data points. Dr. D. J. Andrews has succeeded in synthesizing an equation of state for iron which includes as input specific heat from 0°K to the melting point, thermal expansion coefficients over the same range, ultrasonic measurements of pressure vs volume at constant temperature, and shock Hugoniot measurements. These are incorporated in a consistent thermodynamic framework and the results can be used to calculate any thermodynamic parameters for the solid state. The results are very impressive and accuracy appears to be limited only by experimental uncertainties in the input data. The procedure is being published and will be available to others in the future. If followed it will substantially reduce confusion in this area.

Strain-Induced Magnetic Anisotropy: A problem of long standing in the theory of magnetism has been the influence of arbitrary elastic strain on the magnetic state of a solid body. During the period 1965-1968 some new light had been shed on this problem by shock wave experiments at Sandia Laboratories and Lawrence Radiation Laboratory, but these experiments contained some inconsistencies which cast doubt on their validity. Dr. Dennis E. Grady has managed to resolve these problems in a brilliant combined theoretical and experimental attack on the problems which has produced a definitive model of the entire process. In the course of this work he has also resolved a long-standing anomaly concerning field dependence of the magnetization in ferromagnetic materials. Besides the basic scientific significance, this work provides a principle which may be useful in the development of pressure gages for underground nuclear explosions and another which may help in classifying natural ferrites.

Dynamic Failure of Solids: A long standing question in mechanics of solids has been whether or not the failure of a material through yield or fracture under dynamic conditions, say impact, involves different mechanisms from those which operate under static or quasistatic conditions. This grant provided support for development of the theoretical framework of wave propagation and dislocation theory for design and interpretation of a long series of experiments on another contract by Dr. J. R. Asay. The answer to this question seems to be "yes," and this work may provide a rationale for incorporating dynamic tests when characterizing materials to be used under impact conditions.

Mechanics of Wave Propagation: If stress waves are to be used as tools for probing the behavior of matter, their propagation characteristics must be thoroughly understood under conditions in which they will be used. One set of conditions is supplied by the cylindrical elastic bar. This has been treated as a one-dimensional problem in most experimental work for the better part of the last century. In recent years there has accumulated evidence that finite diameter effects are often dominant in such experiments as the Hopkinson Bar. The problem is intractable analytically, and Dr. J. L. Habberstad has developed a two dimensional program for propagation in a bar which can be used for calculating reflection at a discontinuity in cross-section or material properties. This program provides a tool for analysis of such experiments.

Professor S. C. Lowell has been studying analytical methods for calculating finite amplitude wave propagation in non-linear lattices. Such calculations provide solutions against which numerical solutions can be checked. It also turns out that they provide useful relations among lattice interaction potentials and equation of state parameters. This work and that by Dr. Habberstad have been partially supported on this grant.

Kinetics of Solid-Solid Phase Transitions: Some experiments to measure transition rates have been performed by Mr. Y. Gupta and Mr. Rama Mohan. The intent of these was to study the effect of shear stresses on transition rates in CdS and BaF_2. The results were inconclusive but lead to design of a new series of experiments with KCl which are being carried out successfully by Mr. D. B. Hayes. Results are not yet in a state for discussion.

Thermo-electric Power in Metals: The EMF produced by a thermocouple subjected to strong mechanical shock has been reported by several observers to be five to ten times that expected on the basis of calculated temperatures and statically determined thermo-electric coefficients. This led Dr. D. L. Styris, assisted by Mr. J. L. Dick, to attempt to measure thermo-electric power of single metals under shock for comparison with Bridgman's measurements made at static high pressure. These experiments have been unsuccessful to date and the problem is being reconsidered. It is a very important one because it may shed new light on electron-phonon interactions in solids, but to this date there is no reportable progress.

Overall Significance: The work carried out under this grant has been a substantial part of the total national effort to bring theoretical and experimental techniques of shock wave propagation together with selected problems of solid state physics to the benefit of both. The success of the effort is evidenced by the expanding acceptance of shock wave techniques and results by the physics community and by the appearance of wave propagation papers based on new physical phenomena in the literature of continuum mechanics.

Publications and Talks

*"Elastic Precursor Decay in Single Crystal Tungsten," T. E. Michaels and G. E. Duvall, Bull. Am. Phys. Soc. Series II, 14, #12, p. 1170 (Dec. 1969)

"Axisymmetrical Elastic-Plastic Wave Propagation in 6061-T6 Aluminum Bars of Finite Length," G. E. Duvall, ASME Trans. J. Appl. Mech. Jan. 1970 (Discussion)

*"Wave Propagation in Monatomic Lattices with Anharmonic Potential," S. C. Lowell, Proc. Roy. Soc. London, A, 318, p. 93 (1970)

"Concepts and Applications of Shock Waves," paper presented by G. E. Duvall at Gordon Conference, Issaquah, Wa. 7/27-31/70

*"Effect of Point Defects on Precursor Decay in LiF," J. R. Asay, G. E. Duvall, and G. R. Fowles, Bull. Am. Phys. Soc. Series II, 15, #12, p. 1606, (Dec. 1970)

"Theory of Pressure-Induced Demagnetization of Porous Polycrystalline Cubic Ferrites," D. E. Grady, and G. E. Duvall, Bull. Am. Phys. Soc. Series II, 15, #12, p. 1603 (Dec. 1970)

*"A Two-Dimensional Numerical Solution for Elastic Waves in Variously Configured Rods," J. L. Habberstad, J. Appl. Mech. Series E, 38, #1, p. 62 (March 1971)

*"Calculation of Mixed Phases in Continuum Mechanics," D. J. Andrews, J. Comp. Phys. 7, #2, April 1971.

"Electrical Conductivity of Materials under Shock Compression," D. L. Styris and G. E. Duvall, High Temperatures-High Pressures, 2, #5, 1971.

"Approach to Saturation in Ferromagnetic Materials," D. E. Grady, accepted for publication in Physical Review.

"Shock Induced Anisotropy in Ferromagnetic Materials: I. Domain Theory Analysis of Single Crystal Behavior," D. E. Grady, submitted to J. Appl. Phys.

"Shock Induced Anisotropy in Ferromagnetic Materials: II. Polycrystalline Behavior and Experimental Results for YIG," D. E. Grady, E. B. Royce and G. E. Duvall, submitted to J. Appl. Phys.

*"Equation of State of the Alpha and Epsilon Phases of Iron," D. J. Andrews, submitted to Physical Review

"Experimental Technique for Measuring Shock Induced Anisotropy in Ferromagnetic Materials," D. E. Grady, to be submitted to Rev. Sci. Instr.

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1. E. B. Royce, Lawrence Radiation Laboratory
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   Mark Percival, Sandia Laboratories
   W. Hoover, Lawrence Radiation Laboratory
   M. E. Backman, Naval Weapons Center
   H. G. Hopkins, University of Manchester, England

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   G. E. Duvall: Sandia Laboratories, Lawrence Radiation Laboratory, Stanford Research Institute, TRW, Inc.

   G. R. Fowles: Physics International, General Motors, Stanford Research Institute

3. Scientific exchange: (in additi-r to listed papers)

   G. E. Duvall: Chairman of 1970 Gordon Conference on High Pressure

   Seminar "Equation of State and Shock Application" given at the Air Force Materials Laboratory, Wright-Patterson Air Force Base, April 13, 1971

   Seminar "Fundamental Problems in Shock Wave Propagation," University of Kentucky, Lexington, Nov. 1970

   Participation in Symposium on Wave Propagation, ASME Meeting, Los Angeles, November 1969

   Seminar "Plane Shock Waves in Solids," Drexel Institute of Technology, October 1969

   Applied Mechanics Meeting, Albuquerque, Aug. 1969

   G. R. Fowles Seminar at Air Force Institute of Technology, Wright-Patterson Air Force Base, Feb. 1971

   M. E. Gurtin Lectures on Wave Propagation at Washington State University March 1970

Personnel Involved in this Grant

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Research Assistants & Students:

D. J. Andrews - now a postdoctoral student at Division of Earth & Planetary Science, Massachusetts Institute of Technology
D. E. Grady - now staff physicist at Stanford Research Institute
*J. L. Habberstad - now at Bureau of Mines, Spokane, Wa.
*J. R. Asay - now with Sandia Laboratories, Albuquerque
*J. E. Flinn - now at Argonne, Idaho Falls, Idaho
*D. B. Hayes
*Y. Gupta
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*R. White - now at U.S. Naval Undersea Res. & Dev. Warfare Center
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