FINAL REPORT

MATERIAL BEHAVIOR IN HIGH SPEED IMPACT

by

George E. Duvall

Washington State University
Physics Department
Pullman, Washington 99163

and

G. Richard Fowles

Washington State University
Physics Department
Pullman, Washington 99163

Sponsored by: Advanced Research Projects Agency ARPA Order No. 985

This research was supported by the Advanced Research Projects Agency of the Department of Defense and was monitored by the Air Force Office of Scientific Research under Contract No. F44620-67-C-0037.

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Department of Physics Washington State University Pullman, Wa. 99163	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE

MATERIAL BEHAVIOR IN HIGH SPEED IMPACT

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Scientific Final

5. AUTHOR(S) (First name, middle initial, last name)

George E. Duvall and G. Richard Fowles

6. REPORT DATE 15 July 1972	7a. TOTAL NO. OF PAGES 8	7b. NO. OF REFS

8a. CONTRACT OR GRANT NO. F44620-67-C-0087 b. PROJECT NO. ARPA Order No. 985 c. 61102F d. 681306	9a. ORIGINATOR'S REPORT NUMBER(S) 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) AFOSR-TR-72-1282

10. DISTRIBUTION STATEMENT

Approved for public release, distribution unlimited.

11. SUPPLEMENTARY NOTES TECH, OTHER	12. SPONSORING MILITARY ACTIVITY AIR FORCE OFFICE OF SCIENTIFIC RESEARCH 1400 Wilson Blvd. (NE) Arlington, Va. 22209

13. ABSTRACT

A gas gun facility was established for the purpose of studying effects of impact in solids. Research was conducted on the dynamic strength of several materials with the goal of relating macroscopic effects to atomic mechanisms. It was discovered that some crystals (lithium fluoride) that are relatively soft and plastic under usual conditions can support extremely large stress differences for short periods of time. Further, the observed strength cannot be explained by usual theories applicable to low strain rate behavior.

I

DD FORM 1 NOV 65 1473

UNCLASSIFIED

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Impact Physics						
Dislocation dynamics						
Compressed Gas Gun						
Non-linear wave propagation						
Dynamic yielding						

ABSTRACT

Technical

An experimental facility for the study of shock effects in solids was constructed and operated for five years. The facility consists mainly of a 4-inch diameter, 44 foot compressed gas gun, ancillary control equipment, high speed electronic recording instruments, and equipment for specimen preparation. The gun was a new design, based partly on existing guns. Research carried out has been primarily in the area of dynamic yielding in crystals with the goal of relating dynamic strength and plastic wave propagation to dislocation dynamics. The yield strength of lithium fluoride was observed to be highly rate dependent; it momentarily supports shear stresses approaching the theoretical strength of the lattice. Moreover, the rate of approach to equilibrium is very sensitive to impurity concentration and to prior heat treatment. Related theoretical research has also been conducted in the areas of wave propagation in discrete lattices, fundamentals of wave propagation in continua, and equations of state of solids.

Non-Technical

A gas gun facility was established for the purpose of studying effects of impact in solids. Research was conducted on the dynamic strength of several materials with the goal of relating macroscopic effects to atomic mechanisms. It was discovered that some crystals (lithium fluoride) that are relatively soft and plastic under usual conditions can support extremely large stress differences for short periods of time. Further, the observed strength cannot be explained by usual theories applicable to low strain rate behavior.

GOALS AND ACCOMPLISHMENTS

The initial goal of this contract was to establish an experimental facility for studying shock waves in solids. This entailed designing and constructing, in collaboration with Utah Research and Development Company, a four-inch diameter, 44 foot long compressed gas gun capable of firing a one-pound projectile to velocities up to 1.5 km/sec. This gun was designed especially for our operation, based on experience with earlier designs. It has proved to be quite satisfactory and many features have since been duplicated in the design of guns for other organizations (e.g. Stanford Research Institute, Air Force Weapons Laboratory, Physics International Co.). This gun is the principal experimental tool of the laboratory. Ancillary equipment consists of controls for the gun, a variety of high speed electronic recording instruments, and specimen preparation equipment.

Active experimental research began with the gun during the second year of the contract. The area chosen for study was that of the dynamic strength of solids with particular emphasis on the role of dislocations in the dynamic yielding process. This work culminated in the Ph.D. theses of Asay, Flinn, Michaels, and Gupta (nearing completion).

Extensive data were taken on the behavior of single crystal lithium fluoride and somewhat less data on single crystal tungsten. The LiF data represents the most extensive study ever performed with shock techniques on a well-controlled material. It was chosen for concentrated study for several reasons: (a) a large amount of information on dislocation dynamics of LiF is available as the result of work by other investigators; (b) it is a relatively simple crystal (cubic) obtainable in high quality samples; (c) it is transparent so that optical recording techniques can be used; (d) its shock impedance is close to that of quartz so that quartz transducers can be readily used; (e) it exhibits pronounced strain-rate effects.

The results shows that the dynamic strength is very sensitive to the concentration of divalent impurities and to prior heat treatment. They also indicate that theoretical explanations for yielding at low strain rates based on multiplication of existing dislocations are not adequate to explain yielding under shock conditions. Study of these data is continuing with the goal of better understanding the relation between macroscopic yielding phenomena and atomic mechanisms.

An interesting theoretical advance was made that has improved methods for analyzing measurements on stress waves to deduce the thermodynamic and kinematic states experienced by a shocked material. This discovery was made independently by Fowles and by Williams of Stanford Research Institute and was published by them jointly. The conservation laws for plane flow are written in a form that explicitly shows the relation between wave speeds and increments in the dependent variables. The resulting equations are applicable to arbitrary plane waves and can be used to reduce data from stress wave measurements in a manner analogous to the use of the Rankine-Hugoniot jump conditions for shocks. The equations are more general, however, than the jump conditions.

Another theoretical study was made, by S. C. Lowell, of wave propagation in a one-dimensional lattice with anharmonic potential. The results are of interest to such aspects of solid behavior as the temperature dependence of the Gruneisen parameter, the thermal expansion coefficient, and the Lindemann criterion for melting.

UNIQUE RESULTS AND FINDINGS

One of the discoveries made under this contract is that lithium fluoride can sustain extremely high shear stresses, up to ten or twenty times the static yield strength, for short periods of time. Moreover, the rate at which the overstress approaches equilibrium is strongly dependent on the impurity concentration and the previous temperature history. Differences in "Hugoniot Elastic Limit" by factors of four or more can therefore be observed in samples that are nominally the same. This result is of importance to wave propagation codes used to predict stress wave attenuation and fracture.

The plastic strain rates inferred from the measurements are not explainable by multiplication of pre-existing dislocations -- a widely accepted mechanism for yielding at low strain rates. Evidently, pronounced nucleation of dislocations occurs within the shock front.

We also discovered that the conservation laws for plane and spherical waves can be written in a general form analogous to the Rankine-Hugoniot conditions for steady shocks. An unexpected result of this formulation is that, in general, a stress wave consists of three separate waves that are not always superimposed. This result is important for the analysis of measurements on stress waves.

One other important result relates to gas gun design. Several features of the gun built under this contract represent improvements over earlier designs in simplicity of manufacture, accuracy, and reliability.

PARTICIPANTS

F -- Faculty

S -- Student

St -- Staff

J. R. Asay (S, Ph.D.)
P. M. Bellamy (St)
G. R. Danker (S, MSc.)
D. P. Dandekar (F)
J. J. Dick (S, Ph.D. nearing completion)
G. E. Duvall (F)
F. Feistmann (S, BSc.)
J. E. Flinn (S, Ph.D.)
J. W. Forbes (S, Ph.D. nearing completion)
G. R. Fowles (F)
D. E. Grady (S, Ph.D.)
Y. M. Gupta (S, Ph.D. nearing completion)
P. Holton (S)
S. C. Lowell (F)
T. E. Michaels (S, Ph.D.)
M. H. Miles (F)
R. H. Mitchell (S, MSc.)
Rama Mohan (S)
V. A. Munden (St)
[illegible] G. Roper (S, Ph.D.)
M. A. Shepherd (St)
D. L. Styris (F)
G. W. Swan (F)
J. Tarr (St)
R. F. Tinder (F)

COUPLING

Organizations

Air Force Materials Laboratory

Air Force Weapons Laboratory

General Motors Corporation

Gordon Conferences on High Pressure

Lawrence Livermore Laboratory

Physics International Company

Sandia Corporation (Albuquerque and Livermore)

Stanford Research Institute

Utah Research and Development Company

Individuals

D. Doran, Battelle Northwest

M. E. Gurtin, Carnegie Mellon University

W. Herrmann, Sandia Corporation

H. G. Hopkins, University of Manchester, England

Q. Johnson, Lawrence Livermore Laboratory

E. H. Lee, Stanford University

E. B. Royce, Lawrence Livermore Laboratory

Various seminars given at Universities and Corporations and various professional meetings attended.

PUBLICATIONS

*"Dynamic Compression of Quartz," G. R. Fowles, J. Geophys. Res. 72, 22, 5729-5742, (November 1967).

"Amplitude Dispersion in Anharmonic Lattices," S. C. Lowell, Bull. Am. Phys. Soc. II, 13, #1, p. 75, (1968).

"Thermodynamic Compatibility of the Specific Heat and Gruneisen's Ratio," G. R. Fowles, J. Appl. Phys. 39, #6, p. 2973, (May 1968).

*"Explosive Acceleration of Projectiles," G. E. Duvall, J. O. Erkman, and C. M. Ablow, The Israel J. of Technology, 7, #6, p. 469, (1969).

"Determination of Constitutive Relations from Plane Wave Experiments," G. R. Fowles, paper presented at Western Applied Mechanics Conference, Albuquerque, N.M., 25-27 August 1969. WSU-SDL 70-01 (April 1970).

"A Constant Current Source for Manganin Gauge Transducers," D. E. Grady, Rev. Sci. Instr. 40, #11, p. 1399, (November 1969).

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

"Elastic Precursor Decay in LiF," J. R. Asay, G. E. Duvall and M. H. Miles, Bull. Am. Phys. Soc. II, 14, #12, p. 1170, (December 1969).

"Plane Stress Wave Propagation in Solids," G. R. Fowles and Roger F. Williams, J. Appl. Phys. 41, #1, p. 360 (1970).

"Dislocation Dynamics and Single-Crystal Constitutive Relations: Shock Wave Propagation and Precursor Decay," J. N. Johnson, O. E. Jones and T. E. Michaels, J. Appl. Phys. 41, #6, p. 2330, (May 1970).

"Gas Gun for Impact Studies," G. R. Fowles, G. E. Duvall, J. R. Asay, P. M. Bellamy, F. Feistmann, D. Grady, T. Michaels and R. H. Mitchell, Rev. Sci. Instr. 41, #7, p. 984 (July 1970), WSU-SDL 69-02.

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

"Shock Induced Metastable States in Potassium Chloride," D. B. Hayes and G. E. Duvall, Bull. Am. Phys. Soc. II, 17, #1, p. 82, (Jan. 1972).

"Determination of Material Relaxation Properties from Measurements on Decaying Elastic Shock Fronts," J. R. Asay, G. R. Fowles and Y. M. Gupta, J. Appl. Phys. 43, #2, p. 744 (February 1972).

"Effect of Impurity Clustering on Elastic Precursor Decay in LiF," J. R. Asay and Y. M. Gupta, J. Appl. Phys. 43, #5, p. 2220 (May 1972).

"Effects of Point Defects on Elastic Precursor Decay in LiF," J. R. Asay, G. R. Fowles, G. E. Duvall, M. H. Miles and R. F. Tinder, J. Appl. Phys. 43, #5, p. 2132 (May 1972).

*Indicates partial support