High-Pressure Shock Compression of Condensed Matter

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Editors

High-Pressure Shock Compression of Solids

With 176 Illustrations

Springer Science+Business Media, LLC

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Library of Congress Cataloging-in-Publication Data
High pressure shock compression of solids / J.R. Asay, M. Shahinpoor, editors.
p. cm. — (High pressure shock compression of materials)
Includes bibliographical references and index.
ISBN 978-1-4612-6943-4 ISBN 978-1-4612-0911-9 (eBook)
DOI 10.1007/978-1-4612-0911-9
1. Materials at high pressures. 2. Shock (Mechanics)
3. Materials—Compression testing. I. Asay, J.R. II. Shahinpoor, Mohsen. III. Series.
TA417.7.C65H54 1992
620.1'1242—dc20 92-3737

Printed on acid-free paper.

Production coordinated by Brian Howe and managed by Christin Ciresi; manufacturing supervised by Vincent Scelta.
Typeset by Asco Trade Typesetting Ltd., Hong Kong.

9 8 7 6 5 4 3 2 1

ISBN 978-1-4612-6943-4

Preface

This book presents a set of basic understandings of the behavior and response of solids to propagating shock waves. The propagation of shock waves in a solid body is accompanied by large compressions, decompression, and shear. Thus, the shear strength of solids and any inelastic response due to shock-wave propagation is of the utmost importance. Furthermore, shock compression of solids is always accompanied by heating, and the rise of local temperature which may be due to both compression and dissipation. For many solids, under a certain range of impact pressures, a two-wave structure arises such that the first wave, called the elastic prescursor, travels with the speed of sound; and the second wave, called a plastic shock wave, travels at a slower speed.

Shock-wave loading of solids is normally accomplished by either projectile impact, such as produced by guns or by explosives. The shock heating and compression of solids covers a wide range of temperatures and densities. For example, the temperature may be as high as a few electron volts (1 eV = 11,500 K) for very strong shocks and the densification may be as high as four times the normal density.

Shock compression of solids, on a macroscopic level, is composed of an orderly sequence of events that evolve over a time period of a few microseconds. The rise time of a shock wave to full amplitude is usually a few nanoseconds or less. The compressive stresses produced during plane shock-wave loading of metals may be as high as a few tens of GPa (1 GP = 10^9 N/m^2 = 10 kbar = 145,038 psi). These stresses clearly exceed the yield strength of metals and force the material into a fluidlike state. Rice, McQueen, and Walsh presented, in 1958, the first comprehensive review of shock compression of solids. However, their work is confined to the measurement of metal compressibility resulting from contact detonation waves. Although their work is the most widely referenced article, it was preceded by other fundamental review articles on shock compression by Lelevier and Ragent in 1954, Walsh and Christian in 1955, Bancroft, Peterson, and Minshall in 1956, and by Goldsmith in 1957. After the appearance of these poineering works the study of condensed matter under shock compression emerged as a scientific discipline in physics (Rice, McQueen, and Walsh's paper, featured in

Solid State Physics, vol. VI, edited by Seitz and Turnbull, Academic Press, New York).

The pioneering work of Rice, McQueen, and Walsh had its origin during World War II when it was realized that the development of nuclear weapons required shock compression of solids by high explosives. In the summer of 1952, Walsh, Rich, and Fowler developed the flash-gap technique that made possible rapid mass production of shock wave assemblies. Their recognition of the potential of impedance-matching techniques enabled them to begin a series of major experiments in shock compression of solids. These included production of megabar shock waves by explosively driven plates by Shreffler and Deal, and the discovery of a 130-kbar phase transition in iron by Bancroft, Peterson, and Minshall in 1956. An article by Taylor summarizes these early activities at the Los Alamos National Laboratories. In the meantime, other important pioneering work was being performed at Stanford Research Institute, by Thomas C. Poulter, Dan MacLachlass, and George E. Duvall in the period 1953–1964, with emphasis on fragmentation and material failure, metal cutting and shaping with explosives, jetting and penetration, wave shaping, explosive welding, twinning and transformation bands, phase transitions in iron and steel, powder compaction, synthesis of diamond by shock waves, cracking of tar sands, and development of explosive devices.

The history of shock compression of solids indicates that the 1950s and 1960s were a time of rebuilding from fundamentals, enthusiasm, innovation, and a strong belief that shock compression constituted an important and as yet untapped discipline of science. Some major developments in shock-wave research during this period involved studies on equations of state using the pin technique, phase transitions using streak cameras, electrical conduction using quartz gauges, charge release–polarization using piezoresistive gauges, shock demagnetization using EMV gauges, shock-induced opacity using laser interferometry, elastic precursor and its decay using high-speed scopes, and the study of residual stress after shock loading.

It may be argued that the first modern paper on shock compression of solids was written by Walsh and Christian. They presented expressions for the equations of state of aluminum, copper, and zinc using Hugoniot data at pressures up to half a megabar. Here, by Hugoniot data, is meant a graph of particle velocity versus shock velocity, which were recorded using argon flash gaps and a rotating mirror streak camera. In the meantime, the measurement of pressure was becoming extremely important. Other concepts, such as elastic precursor and phase transition measurements, were also becoming of ever-increasing importance. Minshall, Bancroft, and Peterson presented a complete account of phase transitions in iron in 1956 and, subsequently, another paper by Duff and Minshall in 1957 addressed phase transitions in bismuth. Another breakthrough was the shock synthesis of inorganic materials from the powdered forms of their elements, in two separate papers by Horiguchi and Nomura on titanium carbide, and by Kimura on zinc ferrite. Shock synthesis of polymers from condensed monomers was reported by Adadurov, Barkalov, Goldanshii, Dremin, Ignatavich, Mikhailov, Tal'roze, and Yampol'skii in 1965. This opened a major new area referred to as shock-induced chemical interaction.

Shock compaction of powders also became another major new area of shock compression, as reported by Rienhart and Pearson in 1963 and by Bergmann and Barrington in 1966. Shock-induced conductivity in dielectrics was first reported by Alder and Christian in 1965. Shock-induced opacity in carbon tetrachloride was reported by Walsh and Rice in 1957. Shock-induced charge release from ferroelectrics was reported in 1957 by Neilson. Shock-induced demagnetization of iron was first reported by Anderson, in 1957. In 1961, Fowles showed that a residual shear stress existed behind the plastic wave. Subsequently, Rice and Taylor reported stress relaxation and decay of an elastic precursor in 1963. Shock-induced polarization and charge release from unpoled dielectrics was first reported by Houver and Eichelberger in 1961. The development of a thick quartz gauge by Neilson greatly enhanced progress in low-pressure research. Fuller and Price and Bernstein and Keough independently reported the development of a manganin piezoresistive gauge in 1964. In the same year, Dremin and Adadurov reported the development of an electromagnetic particle velocity gauge. Another major breakthrough in research on shock compression of solids was the development of VISAR (Velocity Interferometry from the Surface of Any Reflector) in 1965 by Barker and Hollenbach.

Along a different line of research on shock compression of solids, namely, recovery experiments, great progress was also being made. Shock-induced recovery-type chemical reactions in encapsulated samples were first reported by Riabinin in 1956. Shock-induced metallographic transformation and the observation of twin bands in iron were first reported by Smith in 1958. Another major breakthrough was the shock-induced synthesis of diamond in 1961 by DeCarli and Jamieson.

Other important breakthroughs include the discovery of shock-induced electronic transitions, as reported by Royce in 1967 and by Al'tshuler and Bakanova in 1969; the introduction in 1970, by Barker and Hollenbach, of the fused quartz buffer to generate ramp waves; the shock-induced anisotropy in ferromagnetic materials by Grady, Duvall, and Royce in 1972; the measurement of physical properties under shock loading by Graham in 1972 and 1977; the observation of shock-induced insulator-to-metal transitions in iodine in 1977 by McMahan, Hard, and Ross; the acquisition of numerous thermodynamic data for shock-compressed solids in 1977 by Van Thiel, Shaner, and Salina; the introduction of superposed shear waves by Abou-Sayed and Clifton and Gupta in 1976; and the publication of a comprehensive review on shock compression solids by Davison and Graham in 1979.

The literature on shock compression of solids has grown remarkably over the past thirty years. It is extremely difficult to review all pertinent works. However, a number of comprehensive reviews on the subject have been cited.

The present book brings to the reader a state-of-the-art treatment of high-pressure shock compression of solids in a type of tutorial manner. It has been felt by the shock physics and engineering communities that there is a need for such a book to aid the education and training of undergraduate and graduate students of physics and engineering. We hope that the present book will partially fill that vacuum. We certainly welcome any comment or criticism on the content of this book, in the hope that these will be incorporated into later editions of the book.

Albuquerque
New Mexico
April 1993

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CHAPTER 3

Experimental and Diagnostic Techniques

CHAPTER 4

CHAPTER 5

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