Shock Wave and High Pressure Phenomena

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Material Properties under Intensive Dynamic Loading

In Collaboration with
W.W. Anderson
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With 311 Figures

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Preface

This book is the result of collaboration between the Russian Federal Nuclear Center – All Russian Scientific Research Institute of Experimental Physics (RFNC-VNIIEF) located in Sarov, Russia and the University of California – Los Alamos National Laboratory (UC-LANL). The genesis of this project was the compilation of a set of lecture notes used by a number of leading VNIIEF researchers in courses taught to students of the Sarov Physical and Technical Institute (SarFTI) specializing in "Theoretical and Experimental Mechanics." A revised and significantly supplemented version of those lecture notes was ultimately published as a monograph (in Russian) by VNIIEF Press, and is used today as a textbook in courses on shock mechanics being taught at SarFTI. Recognizing the potential benefit of the manuscript to students and researchers in the field of shock mechanics in the English-speaking world, a VNIIEF/LANL collaboration was established to revise/translate/update the manuscript. This book is the result of that effort.

Understanding the physical and thermomechanical response of materials subjected to intensive dynamic loading is a challenge of great significance in engineering today. When intensive dynamic loads, such as those that result from the detonation of high explosives (HE), high-velocity impact, or rapid localized heating (such as might develop under the effects of incident laser light or relativistic electron beam), are applied to condensed matter, the result is a complex pattern of material flow involving waves of discontinuous (shock) as well as continuous (expansion) nature.

Shock compression (followed by expansion) precipitates both reversible and irreversible physical, physicochemical and mechanical processes in the material. These processes include (but are not limited to), strong compression of solids, extremely high heating rates, phase transformations, electronic structure change, work hardening, thermal softening, and the initiation and evolution of damage (such as spall). The process of detonation, manifest in the rapid release of energy that occurs as a result of the chemical transformation that takes place when a shock wave (of sufficient strength) propagates through HE occupies a special niche in the shock mechanics discipline.

Accurate diagnosis of the response of materials to intensive dynamic loading, an understanding of the fundamental mechanisms that are responsible for the observed material behavior, and the development of predictive mathematical models that are capable of faithfully forecasting material response under a variety of loading scenarios, are a necessity for the successful solution of a variety of engineering problems. Moreover, shock waves (and an understanding of shock mechanics) play a significant role in scientific studies aimed at gaining a better understanding of the behavior of materials under intensive loading. Material thermodynamic properties under high and ultrahigh pressures, and the rheological properties of materials (primarily metals) subjected to high strain rate loading, are but two examples wherein shock mechanics is the scientists fundamental tool of exploration. The many challenges in science and engineering, such as those alluded to above, serve as strong motivation for the study of shock and detonation waves in condensed media.

Purposeful studies of material dynamics in extreme states (under conditions of intensive dynamic loading) took on elevated importance both in Russia and abroad in the 1940s, and became the focus of intense research efforts in places like Los Alamos and Sarov (at the time known as Arzamas-16). Results from these studies demonstrated both the uniqueness and variety of material behavior under intensive dynamic loading. Through the intervening years, a wealth of experimental data on this problem has been acquired, made possible by significant progress in the development and use of equipment for producing very intense loads and the development of a number of discrete and continuous diagnostic methods for recording the very fast processes that are important in studies of the behavior of materials under the conditions of shock loading.

Some of the early studies in shock mechanics focused on the compressibility of materials. Notable are systematic efforts beginning in the early 1960s at VNIIEF (Arzamas-16) investigating shock wave structure, material resistance to short duration tensile stresses, plastic deformation of shock-compressed bodies, and expansion isentropes (similar efforts were taking place in research centers outside of Russia). Recently, much attention has been given to a study of structural variations brought about by intense mechanical and thermal loading, and to determining the relationships between the field variables (essential for the development of accurate predictive models).

The quantity of information being published in scientific technical journals and in conference proceedings pertaining to the behavior of materials subjected to the conditions of shock wave loading is continuously increasing. This testifies to the present-day importance of this topic in science and engineering. Several well-known books are presently available, which provide analysis of some of the issues related to the challenge of studying material behavior under the conditions of shock wave loading [1–5]. While these books provide an excellent treatment of many of the theoretical aspects of shock mechanics, and in many cases of the behavior of materials under intense dynamic loading, it is our view that insufficient attention is paid to the experimental methods and diagnostics. This book is an attempt to supplement these excellent works by focusing on just these areas: experimental and diagnostic methods.

It is our view that insignificant attention has been given to a formal presentation of the methods and diagnostics that are important in obtaining an accurate understanding of the processes that take place under shock loading. In many cases, methods have been handed down from practitioner to practitioner, with little dissemination of knowledge. This volume is an attempt to rectify this. Herein we attempt to elucidate a variety of techniques that have been used or are being used today in studies of shock mechanics. We include discussions of some methods that were used in the past but are no longer used today because we believe that the reader will be well served by placing the current state-of-the art in historical context.

The authors expect that this book will be of interest to scientists, engineers, students, and postgraduates who specialize in areas of physics/engineering wherein an understanding of the behavior of materials in conditions involving intensive dynamic loading is important. A partial, but by no means exclusive list, would include those working in the areas of high pressure and high temperature physics, shock wave physics and the phenomena of fast processes, constitutive behavior (equations of state and deviator), damage mechanics, and the optical properties of compressed materials. We believe that this volume could be adopted as a textbook or could be used as supplementary reading material for courses dealing with shock physics. We believe that practitioners who are already working in the field will find this volume to be a useful source of reference material.

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Nomenclature

For the most part, industrial nations around the world use essentially the same engineering materials. Despite this fact, the same material may be known by several different names around the world. Since this book originated in Russia, materials in the text are referred to by their common Russian name or abbreviation. These names may not be familiar to readers from other countries. Therefore we provide as an aid to the reader this table of the abbreviations used in this text with a precise description and composition of the material.

Table. List of materials.

Abbreviation used	*Composition (analogue if available)*
	Steels
Steel 12Kh18N10T	69.3% Fe + 18% Cr + 10%Ni + 2.7% others (*stainless steel*)
Steel KhS38	95.3% Fe + 0.42% C + 1.4% Si + 0.6% Mn + 1.6%Cr + 0.67% others
Steel St.3	(*Armco-iron*)
Steel St.20 (low-carbon steel)	98.63% Fe + 0.17% C + 0.17% Si + 0.35% Mn + 0.68% others
Steel 45 (medium-carbon steel)	98.54% Fe + 0.48% C + 0.33% Si + 0.65% Mn
Steel 30KhGSA	93.44% Fe + 0.28% C + 0.9% Si + 0.8% Mn + 0.8% Cr + 0.35% others
Steel 40Kh	97.77% Fe + 0.4% C + 0.19% Si + 0.74% Mn + 0.9% Cr

Steels (continued)	
Steel EP712	93.44% Fe + 0.16% C + 2.4% Cr + 1.2%Ni + 1.4% W + 1.4% others
Steel 36NKhTYu	Fe + 0.36% C + (Ni+Cr+Ti+Al)
Aluminum and its alloys	
Aluminum D1	91.55% Al + 4.8% Cu + 0.8% Mg + 2.85% others (*Al 2017*)
Aluminum AD1	Pure aluminum (Al no less than 99.3%) (*Al 1230*)
Aluminum alloy V95	86% Al + 7.0% Zn + 2.8% Mg + 2.0% Cu + 2.2% others (*Al 7075*)
Aluminum D16	93.25% Al + 3.8% Cu + 1.8% Mg + 1.15% others (*Al 2024*)
Aluminum AMg6	92% Al + 6.8% Mg + 1.2% others
Other metals and alloys	
Titanium alloy VT-14	86.6% Ti + 6.3% Al + 3.8% Mo + 1.9% V + 1.4% others
Titanium alloy PT-3V	99% Ti + 0.1% C + 0.25% Fe + 0.12% Si + 0.3% Zr + 0.23% others
Brass LS59-1	60% Cu + 1.4% Pb + 38.07% Zn + 0.53% others (*C*3800)
Mg95	Pure magnesium (Mg no less than 95%)
Ceramics	
KVPT	97% Al_2O_3 + 1% TiO_2 + 0.2% Fe_2O_3 +1.8% others (High density corundum with titanium)
Chylumin	93% Al_2O_3 + 4.9% SiO_2 + 0.25% TiO_2 + 0.85% Fe_2O_3 +1% CaO
Polymers	
Plexiglas	PMMA (polymethylmethacrylate)
Polytetrafluorethylene	Fluorine plastic $[-CF_2-CF_2-]_n$ (*Teflon*)
Caprolon	$[-NH(CH_2)_5CO-]_n$