Materials in Mechanical Extremes

Fundamentals and Applications

This unified guide brings together the underlying principles, and predictable material responses, that connect metals, polymers, brittle solids and energetic materials as they respond to extreme external stresses.

Previously disparate scientific principles, concepts and terminology are combined within a single theoretical framework, across different materials and scales, to provide the tools necessary to understand, and calculate, the responses of materials and structures to extreme static and dynamic loading. Real-world examples illustrate how material behaviours produce a component response, enabling recognition – and avoidance – of the deformation mechanisms that contribute to mechanical failure. A final synoptic chapter presents a case study of extreme conditions brought about by the infamous Chicxulub impact event.

Bringing together simple concepts from diverse fields into a single, accessible, rigorous text, this is an indispensable reference for all researchers and practitioners in materials science, mechanical engineering, physics, physical chemistry and geophysics.

Neil Bourne has been studying materials under extreme conditions for his entire career. He is a former Chair of the American Physical Society's Topical Group on Shock Compression of Condensed Matter, holds fellowships from the American Physical Society and the Institute of Physics, and obtained his Ph.D. and Sc.D. from the University of Cambridge. He has held appointments at the Universities of Manchester, Cambridge, Cranfield, and Imperial College, London, and as a Distinguished Scientist at the Atomic Weapons Establishment (AWE).

"A critical review of the underlying physics and theoretical framework, experimental platforms, and diagnostics utilized to understand the responses of metals, polymers, brittle solids, and energetics subjected to extreme loading conditions. An in-depth must-have reference for the scientist working in the field and teaching resource for the academic or researcher studying the response of materials to extremes in loading rate, temperature, stress state, and pressure. A cross-cutting multidisciplinary book melding the physics, chemistry, and materials science aspects of the response of condensed matter to mechanical extremes."

George T. (Rusty) Gray III, Los Alamos National Laboratory

"Dr Bourne deserves commendations for his efforts to collect in one volume the mechanical response of a broad range of solids subjected to dynamic loading. This book will serve as a good entry point for those wanting to learn about past and current research activities related to the dynamic response of materials."

Yogendra M. Gupta, Washington State University

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Preface

I cannot explain my curiosity about extreme phenomena in nature; nevertheless I have been drawn to the science that surrounds them – from those occurring on the scale of solar systems to those at work at the smallest regimes within matter. Extreme forces surround us; they govern our weather, the cores of planets, components of engineering structures and the ordering of particles within atoms. At the scales of interest in this book they are either gravitational or electrostatic in origin. Forces drive mechanical routes to impose change and materials are forced to respond to these pressures in non-linear, counter-intuitive and utterly fascinating manners; frequently more quickly than not only the senses, but the recording media that exist today can track. Nothing that changes does so instantaneously; every mechanism takes some time, however small. This mean that the integrated response follows a delicate framework of competing pathways that reorder as the driver for the forces changes. As with many processes, one can only see patterns apparent in retrospect. Furthermore, the difficulties encountered achieving these states mean that there are many untracked routes that matter can take to respond about which we know little. Thus despite the years this book has taken to come to this point, it can only provide a snapshot of behaviour as I see it.

Nevertheless, matter allows the nature of its bonding to be probed by subjecting it to load and the reader will learn to appreciate the variety of materials behaviours and their causes that allow the design of structures or even new materials to withstand the environments considered. The behaviours observed are complex and seemingly counter-intuitive, and quantifying them has frequently filled books in the past with extended solid mechanics. This has made texts rich in analysis and specialised in application and required the reader to be expert in the mathematics of non-linear behaviour. However, it seemed that a reader with an appreciation of the physical sciences and elementary algebra required an open text to emphasise behaviours not analytical subtleties. Thus this book unites principles covering a broad canvas at a level accessible to graduate students. Further, it addresses the regime in which the strength of matter may be described with extensions of solid mechanics at the continuum rather than extrapolation of atomic theory and quantum mechanics at the atomic scale.

It is common in academic life to classify problems and approaches by discipline: physics, chemistry, materials science, engineering, geophysics, cosmology. Each has its own unique history and this development has ensured a rich vocabulary of terminology within each field. However, the cross-cutting themes discussed here have a common root which applies across length scales and amplitudes and describes the consequences

of strength under loading in each of the areas. At some pressure, atoms are forced so closely together that inner electron states become perturbed and the nature of strength itself changes too; this book does not consider this regime. However, below this threshold and from scales within nano-crystals to those of planets within solar systems, a common description, *akrology*, can be applied to the subject.

In 1990 a visitor to the Cavendish laboratory asked me if I knew what a shock wave was. His name was Zvi Rosenberg and I said I did. Over the next 20 years I have tried to justify that statement and attempted to understand and describe what such a front means to a solid material, and to him I owe a debt of gratitude. Within a few years of that time a launcher was fashioned to load materials and a course was developed at the University of Cambridge. There is much exploration and analysis distilled into this volume that has its origins in those times. The field has developed from its roots within national laboratories across the globe and spread over the last decades to infuse university and industry too. This has left gaps in the coverage offered by other texts and the time was thus right for a wider volume encompassing the range of topics covered by this field, focused on the materials themselves not upon the applications that use (or abuse) them.

This book was written as a single discourse working from an introduction in Chapter 1 and ending with a more detailed description of an asteroid impact on Earth in Chapter 9 using the concepts developed in the text. A series of tools are described as the reader works through the book. Chapter 2 gives an analytical framework on which to hang the discussion of what follows. Chapters 3 and 4 describe the platforms and diagnostics typically used to investigate the mechanisms occurring. The meat of the text, in Chapters 5–8, covers the response of metals, brittle solids, polymers and plastics and energetic materials. Finally, Chapter 9 summarises the features of the response of all classes of matter under intense loading in a manner that indicates their possible applications in extreme environments. Since solids and their structure are at the core of this volume, an appendix which summarises materials science, for the benefit of those of us with different backgrounds and training, is included as a reference. It is written from my perspective as a physicist but I hope that the many simplifications I have made will not detract from making it useful to readers from other backgrounds. Although the text contains references to specific work by various authors they and other significant works are collected in the Bibliography at the end of the text to preserve flow.

I am deeply grateful to my colleagues (who are also my friends) who have supported me in the preparation of this book. Rusty Gray, Zvi Rosenberg and Marc Meyers gave constant encouragement from the onset and as always I appreciated sound advice from N. S. Brar, Dennis Grady, Yogi Gupta and Ken Vecchio. Thanks in particular to those who have given me their time reading and commenting on various sections; the work would not be complete without their assistance. These include Jeremy Millett, Rusty Gray, Eric Brown, Marcus Knudsen, Peter Dickson, David Funk, Philip Rae and Rade Vignjevic. I must thank friends across the national laboratories with whom I have worked over the years including Billy Buttler, Kurt Bronkhorst, Carl Cady, Ellen Cerreta, Bob Cauble, Datta Dandekar, Rob Hixson, Neil Holmes, Jim Johnson, Veronica Livescu, Paul Maudlin and Anna Zurek. In the UK, friends and colleagues in universities including David Clary, Bill Clyne, Bill Clegg, John Dear, Lindsay Greer, Stefan Hiermaier,

Ian Jones, Phil Martin, Alec Milne, John Ockenden, Steve Reid and Phil Withers. Also within AWE including Graham Ball, Stephen Goveas, Hugh James, Brian Lambourn, Simon McCleod, Nigel Park, Steve Rothman, Glenn Whiteman, and within DSTL Richard Jones, Bryn James and Ian Pickup. Much interaction and inspiration has come from working with students and staff within my groups in Cambridge, Cranfield and Manchester including Patty Blench, Gary Cooper, Lucy Forde, Simon Galbraith, Robert Havercroft, Dave Johnson, Yann Meziere, Natalie Murray, Gary Stevens, Stephen Walley and finally to John Field who allowed me free rein to start a new area of work all those years ago. Finally, it is inevitable that I have failed to properly acknowledge someone or some organisation within this book that has contributed to its content and I offer my apologies in advance for the omission.

None of this would have been possible without the love and support of my close family; thanks to my parents, to Heather and to my children Freya and Oliver for everything. I dedicate this book to them.

Neil Bourne, 2012

Extreme positions are not succeeded by moderate ones, but by contrary extreme positions.
Friedrich Nietzsche