Materials in Mechanical Extremes

Fundamentals and Applications

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CAMBRIDGE

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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

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

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1 Natural extremes

1.1 Akrology

1.1.1 Extremes

The dynamic processes operating around us are often treated as transients that are not important when compared with the fixed states they precede. However, an ever-increasing knowledge base has illuminated this view of the operating physics and confirmed that extreme regimes can be accessed for engineering materials and structures. Matter is ever-changing, its form developing in a series of nested processes which complete on the timescales on which mechanisms operate; processes that occur on ever smaller timescales as length scales decrease. This book is concerned with the response that occurs when loads exceed the elastic limit. This affects behaviour in the regime beyond yield which encompasses a range of amplitudes and responses. However, it concerns condensed materials and loading, eventually taking them to a state where they bond in a different manner such that strength is not defined; this limit represents the highest amplitude of loading considered here. Nonetheless the driving forces are vast and awe-inspiring, while the different rates of change observed in operating processes are on scales that span many orders of magnitude. The following pages will highlight prime examples from the physical world and then provide a set of tools that classify mechanisms in order to analyse significant effects of these processes on the materials involved. The wide range of observations and applications create simple but powerful principles that are outlined in what follows.

Materials are central to the technologies required for future needs. Such platforms will place increasing demands on component performance in a range of extremes: stress, strain, temperature, pressure, chemical reactivity, photon or radiation flux, and electric or magnetic fields. For example, future vehicles will demand lighter-weight parts with increased strength and damage tolerance and next-generation fission reactors will require materials capable of withstanding higher temperatures and radiation fluxes. To counter security threats, defence agencies must protect their populations against terrorist attack and design critical facilities and buildings against atmospheric extremes. Finally, exploitation of new deep sea or space environments requires technologies capable of withstanding the range of operational conditions found in these hostile locations. The range of conditions under this umbrella spans high-energy fluxes, severe states and intense electromagnetic loading, but in what follows thermomechanical extremes on condensed matter will be considered. To advance in all of these areas requires a greater understanding of new behaviours and an ability to model the controlling mechanisms.

There is benefit in investing significant effort to map out these nested chronologies, as advances in understanding of materials and processes reveal that dangers and rewards come from embracing new modes of thinking. A key requirement is to consider timescales and length scales that operate outside the regimes in which intuition can operate; regimes in which glass stops an incoming projectile when a metal plate will not, even though the former exists as a pile of dust after the event whilst the latter retains much of its original form. It is the aim of this book to present a simple guide to key methodologies used to define incoming impulses and to track the material response to the extreme loading transmitted. The intention is to build an understanding that may be applied to new, more extreme regimes of loading and response based upon experience gained in the ambient environment.

1.1.2 Extreme material physics

The condensed phase (for most materials) defines a pressure and temperature range of interest which may be approximately fixed at less than 1 TPa and less than 10 000 K respectively. Pressure has one of the largest ranges of all physical parameters in the universe (pressure in a neutron star is *c*. 10^{33} Pa), so that most of the materials in the universe exist under conditions that are very different from the ambient state on the surface of the Earth. Compression induces changes in bonding properties at the atomic scale, synthesising new compounds and causing otherwise inert atoms or molecules to combine. Integrated thermal and mechanical loading creates new structures within matter. These compressions (reducing interatomic spacings by up to a factor of two and increasing densities by over an order of magnitude) result in changes in the electronic structure that begin to shift notions of chemical interaction and atomic bonding. For example, electrons surrounding nuclei or ions become delocalised, changing insulators into metals, and eventually adopting new, correlated electronic states. Instantaneous application of an impulse provides a pump to drive the deformation of materials, and varying its amplitude and duration allows a window into the operative mechanisms that lead to plasticity and damage evolution within them. Under dynamic loading these extreme conditions may be exploited to explore the balance between mechanical ($P\Delta V$) and thermal ($T\Delta S$) energies by examining how this dichotomy governs physical and chemical phenomena in the condensed state. Additionally, shortened loading periods provide a filter to select governing mechanisms according to operating kinetics. The system may then attain a final metastable state that lies beyond equilibrium thermodynamic constraints.

If the fundamental mechanisms can be understood, exciting opportunities to use such extreme thermomechanical conditions to design and manufacture new classes of materials will open up. Such advances may allow limits such as the theoretical strength (the stress needed to shear atomic planes of an ideal crystal across one another) to be attained. In this manner materials may be designed for application and clearly the key property of interest is the strength of a material statically and during flow. Empirical discovery techniques can achieve incremental advances. Steel-making, for example, dates back over 30 centuries, but the strengths of most present-day commercial alloys are less than a factor of two higher than the steel used in swords during the medieval era. The strengths of commercially available steels are of the order of 1 to 5% of the ideal strength limit and this is typical for currently available bulk materials. This is principally linked to the misconception that the properties of materials can be derived on the basis of atomic structure alone, whilst in reality most engineering properties are dominated by defects within the microstructure. Thus a shift in perception and boundary conditions is necessary to bridge the gap between materials today and the theoretically achievable and this requires critical questions to be answered. What are the most important length scales and defect distributions that control deformation and fracture? What are the ultimate strength and temperature performance limits for structural materials and what is their development after yield? Finally, can dynamic processes be harnessed to capture and maintain theoretical limits for some operating period if not permanently?

Materials found across natural environments experience mechanical extremes of pressure, temperature and strain rate or survive electromagnetic loads of great violence. Reaching an understanding of such states and the response of materials subject to them is key in fully describing operating deformation mechanisms. With the knowledge gained it would be possible to contemplate designing not only structures to operate within such environments, but also to adopt strategies to engineer materials with optimised properties to survive there, should physically based models become available. These extreme material states may exist in nature in inaccessible repositories such as at high temperature and pressure at the centre of planets. Alternatively, they may represent the results of one of the two principal dynamic inputs that may reach these states in short times. These two driving stimuli come from forces generated during explosion or impact, and whilst both of these may occur as a result of some natural process, they may also be harnessed to engineer particular effects such as welding or cutting in a controlled manner.

The mechanical response of objects under load is taught to scientists from an early age through Newton's laws. These, in their simplest form, treat a body as a finite mass concentrated at the object's centre and, with the application of conservation of mass, momentum and energy, Newtonian mechanics describes the macroscopic world. A simple illustration of the utility of this treatment is that of the impact of spheres in the once-popular executive toy, the Newton's cradle. Here, equal masses, suspended from a common stationary framework, are allowed to sequentially impact one upon the other (Figure 1.1). When the first impacts a second, momentum is transferred to it and, if it is free, it may travel onward at the same velocity as the impactor. If there are several balls of equal mass, then the force is transferred through the stack to accelerate the last in the sequence to a velocity consistent with its need to match the same momentum to the first. This is a simple and effective illustration of the common experience of impacting bodies, understood using the assumption that the mass acts from a point at the centre of the body.

To move out of the time and length scales that human perception can respond to, requires description of the processes by which momentum is imparted from one sphere to the next. The deceleration of one ball on a face of a central sphere must transmit out a wave front. The contact point is decelerated whilst the first planes of atoms in the

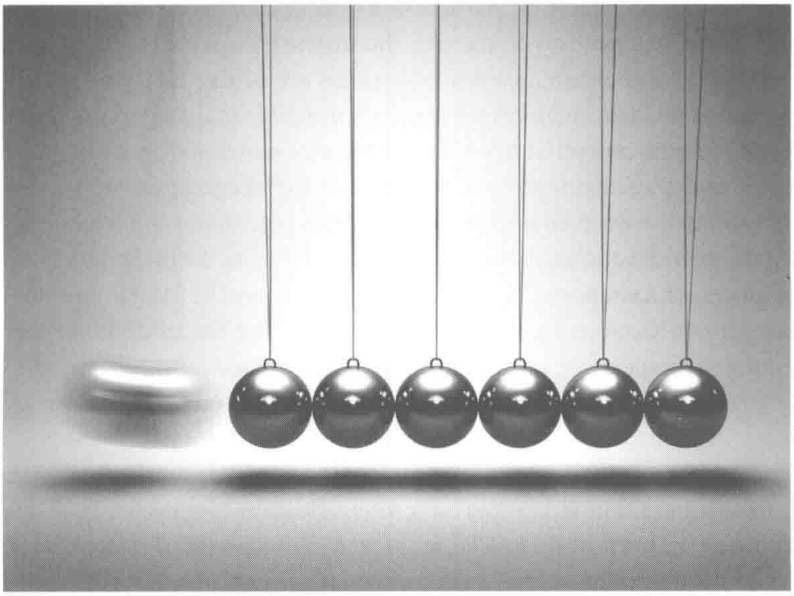

Figure 1.1 Newton's cradle illustrates the effects of waves propagating in a system where all the collisions are elastic. Higher stress impacts can deform materials and produce counter-intuitive physics at the shock front. Source: image copyright shutterstock.com/FreshPaint.

target start to accelerate. Since the two are touching they must travel at the same speed and a wave front travels forward into the target and back into the projectile, accelerating the one and decelerating the other. When the returning wave reflects at the free rear surface it releases stresses in the impactor to zero and accelerates the material ahead of the returning front to the initial impact speed whilst stopping the material behind. Momentum is conserved and Newton mechanics correctly describes the response: forces may act from the centre of mass of the moving objects in the time frame of the office in which the toy sits.

This process has a short high-pressure (or more correctly, high-stress) phase, and after some time, equilibration (a key concept of this book) has occurred; this governs the processes of inelastic flow and chemical reaction described in what follows. The impact state exists until the stress has been relieved within the spheres and the appropriate masses accelerated to their steady speed. In the case of elastic waves the approximate time to reach equilibration, t_{equil}, is given by

$$t_{\mathrm{equil}} = \frac{2d}{c_{\mathrm{L}}}, \tag{1.1}$$

where d is the diameter of the sphere and c_{L} is the wave speed in the metal. Whether the mass is in equilibrium or not depends upon the moment at which an observer chooses to sample the state of the system. If the waves have not released the stresses the state is still equilibrating; if they have, it is in equilibrium and Newtonian mechanics applies. Rheology defines a dimensionless parameter, the Deborah number, to represent the state of fluidity of a material and this is used in glaciology to describe how morphology