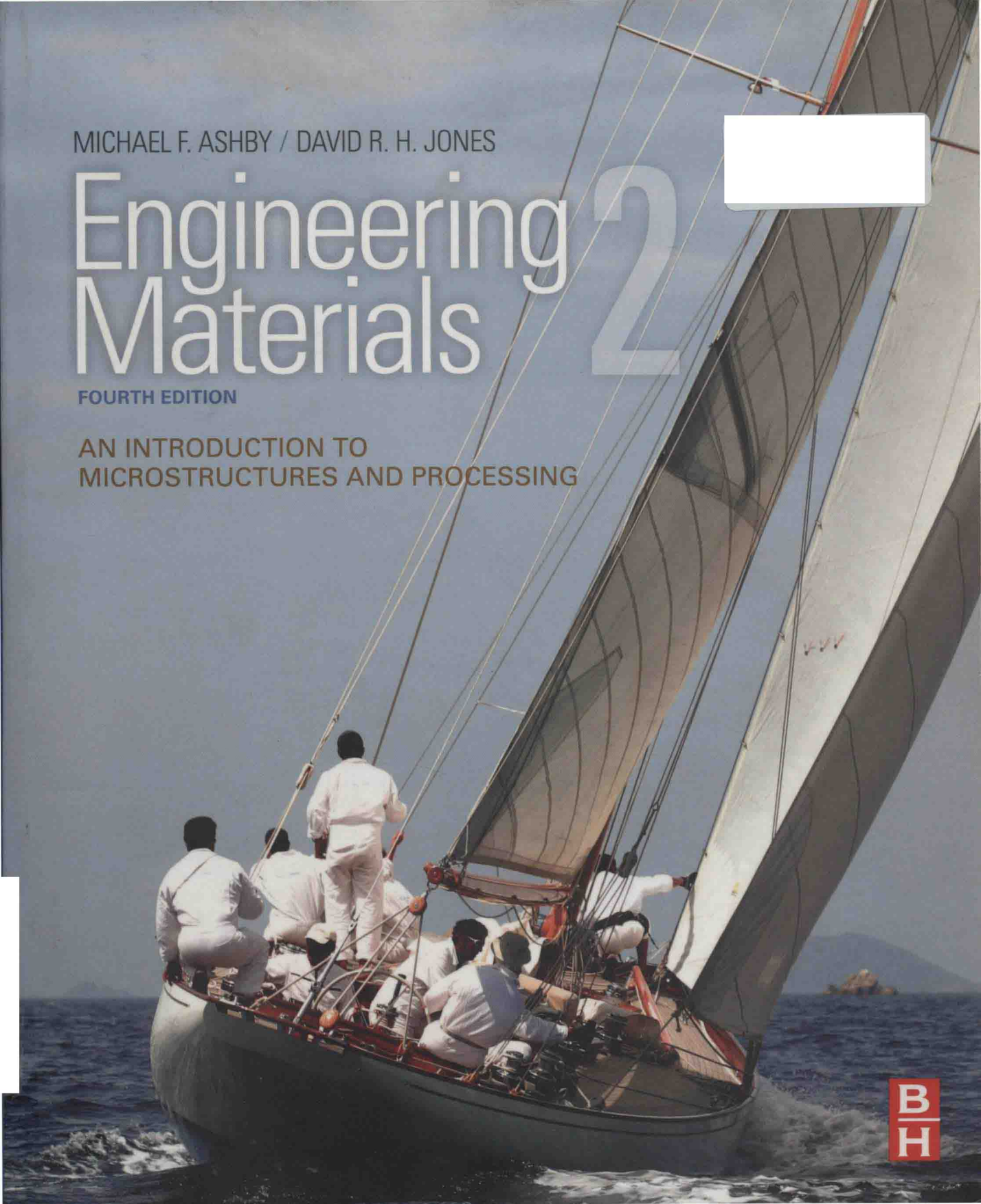


MICHAEL F. ASHBY / DAVID R. H. JONES

Engineering Materials 2

FOURTH EDITION

AN INTRODUCTION TO
MICROSTRUCTURES AND PROCESSING



Engineering Materials 2

An Introduction to Microstructures and Processing

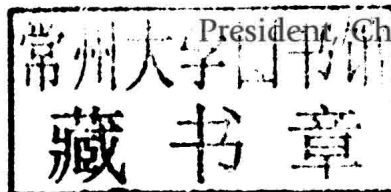
Fourth Edition

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PHYSICAL CONSTANTS (SI UNITS)

Absolute zero of temperature	-273.2°C
Avogadro's number, N_A	$6.022 \times 10^{23} \text{ mol}^{-1}$
Base of natural logarithms, e	2.718
Boltzmann's constant, k	$1.381 \times 10^{-23} \text{ J K}^{-1}$
Charge on electron	$1.602 \times 10^{-19} \text{ C}$
Faraday's constant, F	$9.649 \times 10^4 \text{ C mol}^{-1}$
Gas constant, R	$8.314 \text{ J mol}^{-1} \text{ K}^{-1}$
Magnetic moment of electron	$9.274 \times 10^{-24} \text{ A m}^{-2}$
Permittivity of vacuum, ϵ_0	$8.854 \times 10^{-12} \text{ F m}^{-1}$
Planck's constant, h	$6.626 \times 10^{-34} \text{ J s}$
Rest mass of electron	$9.110 \times 10^{-31} \text{ kg}$
Rest mass of neutron	$1.675 \times 10^{-27} \text{ kg}$
Rest mass of proton	$1.673 \times 10^{-27} \text{ kg}$
Unified atomic mass constant	$1.661 \times 10^{-27} \text{ kg}$
Velocity of light in vacuum	$2.998 \times 10^8 \text{ m s}^{-1}$
Volume of perfect gas at STP (i.e., at 0°C; and under one atmosphere pressure, or $1.013 \times 10^5 \text{ N m}^{-2}$)	$22.4 \times 10^{-3} \text{ m}^3 \text{ mol}^{-1}$ (approximate)

CONVERSION OF UNITS – GENERAL

Angle	1 rad	= 57.30°
Density	1 g cm ⁻³	= 1 Mg m ⁻³
Diffusion Coefficient	1 cm ² s ⁻¹	= 10 ⁻⁴ m ² s ⁻¹
Dynamic Viscosity	1 P	= 0.1 N m ⁻² s
Force	1 kgf 1 lbf 1 dyn	= 9.807 N = 4.448 N = 10 ⁻⁵ N
Length	1 mile 1 foot 1 inch 1 Å	= 1.609 km = 304.8 mm = 25.4 mm = 0.1 nm
Mass	1 ton (long) 1 tonne 1 ton (short) 1 flask (Hg) 1 lb mass 1 troy oz 1 avoirdupois oz 1 carat	= 1.017 Mg = 1.000 Mg = 0.908 Mg = 34.50 kg = 0.454 kg = 31.103 g = 28.35 g = 0.20 g
Stress Intensity	1 ksi $\sqrt{\text{in}}$	= 1.10 MN m ^{-3/2}
Surface Energy	1 erg cm ⁻²	= 1 mJ m ⁻²
Temperature	1°F 32°F corresponds to 0°C	= 0.556 K
Volume	1 UK gallon 1 US gallon 1 liter	= $4.546 \times 10^{-3} \text{ m}^3$ = $3.785 \times 10^{-3} \text{ m}^3$ = 10 ⁻³ m ³

Engineering Materials 2

Preface to the Fourth Edition

In preparing this fourth edition of *Engineering Materials 2*, I have made significant changes, whilst being careful not to alter the essential character of the book. At the most obvious level, I have added many new photographs to illustrate the basic coursework and the case studies—many taken during my travels around the world investigating materials problems. These days, the Internet is an essential tool of knowledge and communication—to the extent that textbooks should be used alongside web-based sources. I have given frequent references in the text to web pages and video clips—ranging from the accident investigation report on the space shuttle Columbia to the low-expansion glass water gauges on a Ffestiniog Railway steam loco. And when a geographical location is involved—like the Sydney Opera House, or the Roman aqueduct in Segovia—I have given the coordinates (latitude and longitude), which can be plugged into the search window in Google Earth to take you right there. Not only does this give you a feel for the truly global reach of materials and engineering, it also leads you straight to the large number of derivative sources and references, such as photographs and web pages, which can help you follow up your own particular interests.

The section on phase diagrams—which had been an appendix in previous editions—is now moved to its logical place early in the book, as two new chapters (Chapters 3 and 4). (The solutions to the examples in these chapters are retained but are placed together at the end of each chapter.) There is more detail on aspects of phase transformations, including interface kinetics, nucleation and growth, and constitutional undercooling. New material has been added on phases in stainless steels (Schaeffler diagram) and modern improvements to stainless steels. The chapter on processing metals has been expanded to two chapters (Chapters 15 and 16), with increased emphasis on secondary processing, including the use of continuous cooling transformation diagrams in steel heat treatment.

The two chapters on mechanical properties of ceramics have been condensed to one (Chapter 19), as a consequence of moving probabilistic fracture of brittle materials to the 4th edition of *Engineering Materials 1*; however, detail has been added on deriving the Weibull parameters from modulus of rupture data. New sections have been added on calculating thermal stress, and reinforcing cement and concrete.

A new section on composites has been added, so each of the four materials classes (metals, ceramics, polymers, composites) now has its own section.

Many new case studies have been added, and many existing case studies have been replaced. In particular, I have added new chapters of case studies in the sections on ceramics (Chapter 22), polymers (Chapter 27), and composites (Chapter 30).

I have added many worked examples to illustrate, develop, or consolidate a topic without interrupting the flow of the text. Most are directly related to real examples of materials processing, microstructures, properties, and applications, and cover a wide range of subjects, ranging from excessive penetration of brazing alloy into electronic device connection pins, through gluing wings and fuselages together in aircraft, to why wood is such a special material.

The number of examples has been doubled, and many contain case studies or practical examples relevant to processing, microstructures, properties, and applications. I have tried to choose case study topics which are informative and connected to the real world. So the worked example on the Columbia space shuttle disaster—caused by polymer foam detaching from the fuel tank and hitting the shuttle's ceramic-composite thermal protection system—indicates how easy it is for a large organization to lose the “folk memory” of past mistakes (the loss of the Challenger shuttle, 17 years earlier).

Materials occupy a central place in engineering for without them, nothing can be made, nothing can be done. The challenge is to know how the ways in which materials are processed directly determines their microstructures, which in turn determine their properties; and to know how these properties can be tailored by processing so they best satisfy the demands of real structures, components, or devices. To the materials engineer who is always curious, aware, and vigilant, the world is a fascinating place.

David Jones
Cambridge, July 2012

ACKNOWLEDGEMENTS

Unless otherwise attributed, all photographs were taken by Dr David R. H. Jones.

Figures 10.6, 10.7, 12.7, 12.8, 14.8 and the photograph for Example 14.10 were commissioned by DRHJ.

The photograph for Example 13.7, and Figures 30.8, 30.9, and 30.10 were taken for DRHJ by Mr Alan Heaver, Department of Engineering, University of Cambridge.

We acknowledge with thanks other photographs and diagrams as follows.

Figures 2.2 and 2.6. Dr D. C. Houghton, Dr D. R. H. Jones and Elsevier (*Acta Metallurgica*, 27, 1979, 1013–1039).

Figure 4.9. Professor G. A. Chadwick and Elsevier (*Metallography of Phase Transformations*, 1972).

Figure 4.16. Mr K. J. Pascoe and van Nostrand Reinhold (*An Introduction to the Properties of Engineering Materials*, 3rd edition, 1978).

Figure 10.8. Dr J. H. Cleland.

Figure 21.14. Professors L. Vehovar, V. Kuhar, A. Vehovar and Elsevier (*Engineering Failure Analysis*, 5, 1998, 21–27).

Diagram for Chapter 21 Worked Example. Professor A. Valiente and Elsevier (*Engineering Failure Analysis*, 8, 2001, 245–261).

Figures 27.1–27.5. Dr D. R. H. Jones and Elsevier (*Engineering Failure Analysis*, 11, 2004, 857–872).

Diagrams for Example 30.12. Dr B. Jakobsen and Elsevier (*Engineering Failure Analysis*, 1, 1994, 193–199).

DRHJ is deeply indebted to his wife Siân for correcting the proofs of this book.

General Introduction

TO THE READER

Materials occupy a central place in engineering for without them, nothing can be made, nothing can be done. They are a key *enabling technology*. The characteristics of individual materials (or groups of related materials) very much dictate how they can be processed; in turn, the processing can strongly influence the final microstructure; and this determines the properties of the processed material, and its ability to perform in the intended application. In many cases, there are choices available to the engineer—of different materials or processing routes. Innovation often takes the form of replacing a part made from one material class (a metal, for example) with another (a fiber composite, for example). Radical changes in the material usually involve redesigning the part so the processing, structure, and properties of the replacement material are taken into account fully. In some cases, however, there is literally only one type of material which will do the job at all: without superalloys, we would have to fly around in piston-engine aircraft; without rubber tires, we would have to travel overland by railroad; without cement and concrete, modern construction would not exist; and we could not do without paper—a wonder composite made from a natural material.

This book gives you a broad introduction to the microstructures of materials, the ways in which materials are processed (altering structure), and how structure determines the final properties. It can be used on its own, or alongside our companion text (M. F. Ashby and D. R. H. Jones, *Engineering Materials 1—An Introduction to Properties, Applications and Design*, 4th edition, Elsevier, 2012; referred to as “EM1Ed4” in the following chapters).

You can see from the Contents that the chapters are arranged into four sections—*metals, ceramics, polymers, and composites*—representing the four distinct *generic classes* of materials. (These classes have very distinct characteristics, which determine the ways in which they are processed, and the properties of the processed structure.) Each section of chapters begins by

introducing the distinct *categories* of materials that go to make up the *generic class*. We then look at the defining features of the microstructures, and see how the materials are processed to get the microstructures (and properties) that we need. Each section of chapters ends with a chapter of *case studies*, which show how the scientific principles of material behavior are relevant to the real engineering world.

At the end of chapters, you will find sets of examples. Each is meant to consolidate, develop, illustrate, or apply a point covered in the text. Try to do the examples from each chapter while it is still fresh in your mind. This way, you will gain confidence that you are on top of the subject. To help you in solving problems, the main definitions and formulae are summarized at the end of the book, together with a list of magnitudes of properties for generic materials classes.

TO THE LECTURER

This book is a concise introduction to the *microstructures and processing* of materials (*metals, ceramics, polymers, and composites*) for students of engineering (and other related subjects). It can be used with our other text (M. F. Ashby and D. R. H. Jones, *Engineering Materials 1—An Introduction to Properties, Applications and Design*, 4th edition, Elsevier, 2012) or on its own.

The text is deliberately concise. Each chapter is designed to cover the content of one 50-minute lecture (30 in all), allowing time for demonstrations and graphics. Six chapters are devoted entirely to *case studies*—these illustrate and develop information presented in the preceding groups of chapters, and place it in the context of real engineering applications. Many chapters also contain shorter *worked examples*. Problems (*examples*) for students to solve are given at chapter ends—again, many contain case studies or practical examples.

We have tried to present the material in an uncomplicated way, while establishing the main physical concepts and showing how processing, microstructures, and properties are interrelated. Given the very large number of engineering materials available, and their diversity of structure and behavior, we found that a good way of doing this was to divide materials up into four main generic classes (each with common unifying characteristics)—*metals, ceramics, polymers, and composites*—and then, within each class, to consider the main *categories* of materials in that *class*.

Finally, it is worth emphasizing that materials data are notoriously variable. The data given here (in tables, and elsewhere) is approximate, and should

never be used for final designs (which require reliable and sufficiently accurate data from either suppliers or specially commissioned tests).

ACCOMPANYING RESOURCES

The following web-based resources are available to teachers and lecturers who adopt or recommend this text for class use. For further details and access to these resources, go to <http://www.textbooks.elsevier.com>

Instructor's manual

A full Solutions Manual with worked answers to the exercises in the main text is available for downloading.

Image bank

An image bank of downloadable figures from the book is available for use in lecture slides and class presentations.

Online materials science tutorials

A series of online materials science tutorials accompanies Engineering Materials 1 and 2. These were developed by Alan Crosky, Mark Hoffman, Paul Munroe, and Belinda Allen at the University of New South Wales (UNSW) in Australia; they are based on earlier editions of the books. The group is particularly interested in the effective and innovative use of technology in teaching. They realized the potential of the material for the teaching of Materials Engineering to their students in an online environment and have developed and then used these very popular tutorials for a number of years at UNSW. The results of this work have also been published and presented extensively.

The tutorials are designed for students of materials science as well as for those studying materials as a related or elective subject—for example, mechanical and/or civil engineering students. They are ideal for use as ancillaries to formal teaching programs and also may be used as the basis for quick refresher courses for more advanced materials science students. In addition, by picking selectively from the range of tutorials available, they will make ideal subject primers for students from related faculties.

The software has been developed as a self-paced learning tool, separated into learning modules based around key materials science concepts.

ABOUT THE AUTHORS OF THE TUTORIALS

Alan Crosky is a professor in the School of Materials Science and Engineering, UNSW. His teaching specialties include metallurgy, composites, and fractography.

Belinda Allen is an educational designer and adjunct lecturer in the Curriculum Research, Evaluation and Development team in the Learning and Teaching Unit, UNSW. She contributes to strategic initiatives and professional development programs for curriculum renewal, with a focus on effective integration of learning technologies.

Mark Hoffman is a professor in the School of Materials Science and Engineering, UNSW. His teaching specialties include fracture, numerical modeling, mechanical behavior of materials, and engineering management.

Paul Munroe has a joint appointment as a professor in the School of Materials Science and Engineering and director of the Electron Microscope Unit, UNSW. His teaching specialties are the deformation and strengthening mechanisms of materials and crystallographic and microstructural characterization.

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