Materials：Engineering，Science，Processing and Design

材　料

——工程、科学、加工和设计

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导　读

M F Ashby 先生是英国剑桥大学工程系的 Division C（Mechanics, Materials and Design）的教授，他还是英国皇家学会的会员、皇家工程院院士、美国国家工程院院士。他早年毕业于剑桥大学，后曾在德国哥廷根大学的金属物理研究所和美国哈佛大学工程和应用物理系工作了12年。1973年他到剑桥大学工程系后，任英国皇家学会研究教授之职。他还是剑桥工程设计中心的首席研究员。

Ashby 教授主要从事工程设计方面的研究工作。从1990年起，他更是主要进行工程设计中材料性能和选用方面的研究工作。关于 Ashby 教授，2002年我在剑桥工作时曾有幸见过几次面，并聆听过他的报告，记得是关于材料轧制变形方面的，详细内容已经记不清了，但实验方案设计之周全、工作之细致，给我留下了深刻印象。另外还有一件事情也使我印象深刻：我刚到剑桥时，浏览系里的网页，看到了他写的一篇文章，标题是“How to write a paper”，这是他为年轻人，特别是高年级大学生和研究生写的一篇论文写作指导报告。从论文规划、概念、内容，直到写作的风格、语法和标点符号等，洋洋38页，极为详尽。虽从未正式出版发表，但一直公开挂在网上，供大家下载。他不断修改，仅正式版就出了5个。读后受益很大，回国后一直作为我的研究生必读的文献。像他这样的大家，对这样一个看起来不大，但实则功德无量的小事，做来如此认真，足见其工作之细致、治学之严谨、提携后进之热情负责。后来陆续看了一些他的文章，听了他的报告，更增加敬佩。

Ashby 教授的主要学术贡献是其关于工程材料的性能图表、材料及其加工方法的选择方面的成果。可以说是 Ashby 教授开拓了这一研究领域的工作。从20世纪90年代初开始，他们进行了系统而卓有成效的研究，包括各种材料和各类设备应用领域的相关研究工作，最终形成了工程化的计算辅助材料选择系统。本书及其配套软件可以说是这一工作的系统理论总结和成果表现。

关于本书的思想是我2002年读到 Ashby 教授的另一本著作第一次接触到的（Materials selection in mechanical design, Butterworth-Heinemann, 1999。2005年出了第三版），印象非常深刻，也很感新鲜；不是书中内容高深，而是其思想、其讲述材料科学的方式上的创新。正如在本书序言中所讲，这是为机械设计所写，追求的不是完整的系统理论，而是其实用性。

一般的材料学方面的著作大多是从材料学基础开始，再到材料的性能和应用。前者主要介绍原子结构、晶体结构和缺陷、相变等，后者主要介绍各种工程材料，如金属材料、高分子材料、陶瓷材料、复合材料及功能材料等的性能和应用。内容当然是系统完整，对材料的研究开发者而言不可或缺，对使用者也很有价值。但对后者，也就大多数设计者（材料选用者）总显得过于专业，而实用数据及相关选择工艺又讲的太少。现就是各种材料学和材料手册上的材料性能数据比较分散，更是缺乏不同材料性能上的比较，不易于设计使用者整体上的把握。而本书则是以机械设计为导向，详细介绍了机械装备设计和使

用过程中遇到的不同类型问题的材料相关性性能及其选用和加工工艺等。

本书共分为20章，按内容可分为4个部分：

第一部分，绪论部分——材料及其加工（第1～2章）。简单介绍了材料及其加工工艺的发展历史和分类。作为后面的介绍的铺垫，这部分是本书的基础。

第二部分，材料和设计的匹配（第3章）。主要介绍了设计时所需要的材料及其加工工艺信息、材料的选用策略和技术路线。这部分是本书的要点。

第三部分，不同类型工程问题设计时的材料性和选择（第4～17章）。根据工程中问题的重要程度和普遍性，由高到低分章介绍，主要包括弹性问题、塑性问题、断裂问题、疲劳问题、摩擦磨损问题、热力学问题、高温疲劳问题、电磁和光学问题及腐蚀问题等，对重要问题分为两章。这部分是本书的重点内容。

第四部分，加工制造工艺问题（第18～20章）。主要介绍了加工工艺的特点和选择，加工工艺对材料性能的影响，材料、加工和环境问题等。

正如前所述，和一般的材料类著作相比，本书主要在以下方面具有特色：

第一，如本书前言所述，这是一本以设计为主导的材料学著作，其终极目标是设计，其读者群是工程设计人员或从事设计研究的理论工作者。这就注定不能，也没有必要全面完整地介绍材料学的理论体系。本书重点介绍的是工程设计中所涉及的材料的宏观性能参数、材料的选择和加工工艺，当然也包含一些基本的材料学理论。这一体系对其设定的读者群而言是非常适用的。这不能不归功于Ashby教授工程方面的学习和工作背景。

第二，本书配有大量的图表，实用而精美，这也是本书的一大特色。这些图表将不同种类的各种性能参数，如重量、强度、成本等形象而系统地表现出来，为读者对不同材料性能的整体把握提供便利，为材料及其加工工艺的选择提供了依据。其中的实用数据的丰富翔实细致，非有几十年的积累不可。

第三，本书文字表述通俗、轻松，除非必要，较少有难懂的专业术语，这也是面向非材料学专业读者所应有。

第四，本书在正文内配有案例研究，每章末尾配有练习和上机实践，这里的练习和上机内容经过了很好的设计，均是为加深正文内容的理解而设。其中的上机练习是和作者的计算机辅助材料选择软件包配套的。当然没有配套软件包也并不影响本书内容的完整性。

总而言之，世界大师的作者、广泛的内容、全新的思路、丰富直观的图表，简洁轻松的文字，使本书成为既有顶级学术水平的著作又是通俗易懂的实用图书。在我国加快创新体系建设和创新能力培养的今天，在从制造大国向制造强国迈进的过程中，本书的引进必将有很大的效益。

本书适合从事工程材料、机械制造、机械设计及相关专业的高年级大学生和研究生阅读，也可供从事工程设计研究和实践的读者阅读。

臧勇

北京科技大学机械工程学院

前　言

以学科为主导还是以设计为主导？材料教学的两种方式。

大多数的事情可以通过多种方式做到。在教学领域更是如此。例如，外语的教学方式取决于学生希望用外语来做什么——比如说是阅读文学作品，或是寻找住处、订饭和买啤酒。这门学科的教学也是这样。

它的传统方式是从基本原理开始：电子、原子、原子的结合和堆积、晶体学和晶粒缺陷。基于此建立了合金理论，包括相变动力学及电子和光学显微镜下可见尺度上的微观结构的演变。这些为在常规度量所用的毫米、厘米尺度上对材料性能的理解和控制提供了条件。但这种方式并不重视结构的行为、材料的选择方法以及设计。

另一种方式是以设计为主导。其起点就是需求：在给定的设计中材料正常工作所必须满足的要求。要使材料和设计相匹配，就要求了解材料所能提供的性能以及能够成功选择材料所需要的其他信息。一旦建立起了性能重要的概念，就应该“深入研究”下去，也就是说，去研究隐藏在其背后的科学——这是很有价值的，因为对这些基本原理的理解本身就可为材料的选择和利用提供有用信息。

两种方式均有意义。这取决于学生所期望的使用知识的方式。如果其目的是科学研究，第一种方法是自然合理的。如果是为了工程设计，第二种方法会更好。本书就是按第二种方式编写的。

这本书有什么不同？

有许多关于工程材料科学的书籍，关于设计的更多。这本书有什么不同呢？

第一，是专门用于指导材料选择和控制、以设计为主导的方法。这种方法是系统的，从设计要求到优化材料的选择。书中用大量的案例研究来说明这种方法，作业也提供了应用练习。

第二，是以可视化交流为重点及其独有的图形化的材料性能表现方式——材料性能图表。这些作为该方法的核心特征，既有助于对理解材料性能的本质、性能的控制及其基本极限等，同时，也为材料的选择及了解材料的使用方式提供了工具。

第三，是它的广度。在这里我们以展示材料的性能、本质及它们在工程设计中出现的方式为目标。浏览目录就会看到本书章节涉及以下内容：

- 物理性能
- 力学特性
- 热行为
- 电学、磁学和光学反应
- 耐用性
- 加工过程及其对性能的影响方式
- 环境问题

整本书我们都以简单而直接陈述为目的，尽可能地使材料科学有助于指导工程设计，而避开那些对这一最终目标没有用处的细节。

第四，就是与 Cambridge Engineering Selector（CES）[1] 的完美配合——这是一个功能强大、使用广泛的基于 PC 的软件包，其既是一种包含材料及加工资料的资源，又是一种实践本书方法的工具。这本书也是独立的：应用上述软件并不是使用本书的前提条件。CES EduPack 软件包的使用有助于加强学习的体验。它能实现真实地涉及多重关于材料和加工特性的限制选择研究，也能让使用者研究材料性能的调控方式。

CES EduPack 包含一个附加工具，它能让人在更深的层次上探索材料科学。CES Element 数据库储存了所有 111 种元素关于物理学、结晶学、力学、热学、电学、磁学和光学性能的基础数据。它通过文字描述，在更深层次上研究各种性能之间的关系。

另外两本教科书将本书的方法发展到更高层次，第一本是关于机械设计的[2]，第二本是关于工业设计的[3]。

1. The CES EduPack 2007, Granta Design Ltd., Rustat House, 62 Clifton Court, Cambridge CB1 7EG, UK, www.grantadesign.com.
2. Ashby, M.F.(2005) Materials Selection in Mechanical Design, 3rd edition, Butterworth-Heinemenn, Oxford, UK, Chapter 4. ISBN 0-7506-6168-6(一段更详细的文字将此处提出的观点做了更深入的展开)
3. Ashby, M.F. and Johnson, K, (2002) Materials and Design-The Art and Science of Materials Selection in Product Design, Butterworth-Heinemenn, Oxford, UK, ISBN0-7506-5554-2(从美学观点看材料和加工，重点在产品设计)

致　　谢

没有其他人的建议、建设性的批评和想法不可能有这类书。许多同事慷慨地贡献出他们的时间和思想。我们要特别感谢剑桥大学的 Mick Brown 教授、Archie Campbell 教授、Dave Cardwell 教授、Ken Wallace 教授和 HenJohnson 教授给予的建议，感谢他们由衷的帮助。同样感谢剑桥 Granta Design 公司的工作组，是他们负责了 CES 软件的开发，使用这一软件绘制的材料性能图表已成为本书的一大特色。

随书资源

练习

每章末尾配有3种不同类型的练习。第一种练习只是基于本书自身所包含的资料、图表和数据；第二种是使用本书提出的方法应用CES软件；第三种是使用CES系统的一部分——CES Element数据库，以更为深入地探索理论知识。

教师手册

本书自身包含了一套理解练习。练习的答案可以免费提供给使用本书的教师。要在线获取这些资料请访问http://textbooks.elsevier.com，并按照屏幕上的说明操作。

图片库

图片库可为使用本书的教师提供本书jpeg和gif格式的图片，其可用于上课用的幻灯片及资料。要获取这些资料请访问http://texbooks.elsevier.com，并按照屏幕上的说明操作。

CES教学版（CES EduPack）

CES EduPack是由Michael Ashby和Granta Design开发的、与本书配套的基础软件包。材料：工程、科学、加工和设计及CES EduPack的配套使用，将提供完整的材料、制造和设计的教程。更进一步的信息请查看本书的最后一页或访问www.grantadesign.com。

目　　录

（臧勇　译）

Contents

Preface

Science-led or Design-led? Two approaches to materials teaching

Most things can be approached in more than one way. In teaching this is especially true. The way to teach a foreign language, for example, depends on the way the student wishes to use it—to read the literature, say, or to find accommodation, order meals and buy beer. So it is with the teaching of this subject.

The traditional approach to it starts with fundamentals: the electron, the atom, atomic bonding, and packing, crystallography and crystal defects. Onto this is built alloy theory, the kinetics of phase transformation and the development of microstructure on scales made visible by electron and optical microscopes. This sets the stage for the understanding and control of properties at the millimeter or centimeter scale at which they are usually measured. The approach gives little emphasis to the behavior of structures, methods for material selection, and design.

The other approach is design-led. The starting point is the need: the requirements that materials must meet if they are to perform properly in a given design. To match materials to designs requires a perspective of the range of properties they offer and the other information that will be needed about them to enable successful selection. Once the importance of a property is established there is good reason to 'drill down', so to speak, to examine the science that lies behind it—valuable because an understanding of the fundamentals itself informs material choice and usage.

There is sense in both approaches. It depends on the way the student wishes to use the information. If the intent is scientific research, the first is the logical way to go. If it is engineering design, the second makes better sense. This book follows the second.

What is different about this book?

There are many books about the science of engineering materials and many more about design. What is different about this one?

First, a *design-led approach* specifically developed to guide material selection and manipulation. The approach is systematic, leading from design requirements to a prescription for optimized material choice. The approach is illustrated by numerous case studies. Practice in using it is provided by Exercises.

Second, an emphasis on *visual communication* and a unique graphical presentation of material properties as *material property charts*. These are a central feature of the approach, helpful both in understanding the origins of properties, their manipulation and their fundamental limits, as well as providing a tool for selection and for understanding the ways in which materials are used.

Third, its *breadth*. We aim here to present the properties of materials, their origins and the way they enter engineering design. A glance at the Contents pages will show sections dealing with:

- Physical properties
- Mechanical characteristics
- Thermal behavior

- Electrical, magnetic and optical response
- Durability
- Processing and the way it influences properties
- Environmental issues

Throughout we aim for a simple, straightforward presentation, developing the materials science as far as is it helpful in guiding engineering design, avoiding detail where this does not contribute to this end.

And fourth, *synergy* with the Cambridge Engineering Selector (CES)[1]—a powerful and widely used PC-based software package that is both a source of material and process information and a tool that implements the methods developed in this book. The book is self-contained: access to the software is not a prerequisite for its use. Availability of the CES EduPack software suite enhances the learning experience. It allows realistic selection studies that properly combine multiple constraints on material and processes attributes, and it enables the user to explore the ways in which properties are manipulated.

The CES EduPack contains an additional tool to allow the science of materials to be explored in more depth. The CES Elements database stores fundamental data for the physical, crystallographic, mechanical, thermal, electrical, magnetic and optical properties of all 111 elements. It allows interrelationships between properties, developed in the text, to be explored in depth.

The approach is developed to a higher level in two further textbooks, the first relating to mechanical design[2], the second to industrial design[3].

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[1] The CES EduPack 2007, Granta Design Ltd., Rustat House, 62 Clifton Court, Cambridge CB1 7EG, UK, www.grantadesign.com.

[2] Ashby, M.F. (2005), *Materials Selection in Mechanical Design*, 3rd edition, Butterworth-Heinemann, Oxford, UK, Chapter 4. ISBN 0-7506-6168-2. (*A more advanced text that develops the ideas presented here in greater depth.*)

[3] Ashby, M.F. and Johnson, K. (2002) *Materials and Design—The Art and Science of Material Selection in Product Design*, Butterworth-Heinemann, Oxford, UK. ISBN 0-7506-5554-2. (*Materials and processes from an aesthetic point of view, emphasizing product design.*)

Acknowledgements

No book of this sort is possible without advice, constructive criticism and ideas from others. Numerous colleagues have been generous with their time and thoughts. We would particularly like to recognize suggestions made by Professors Mick Brown, Archie Campbell, Dave Cardwell, Ken Wallace and Ken Johnson, all of Cambridge University, and acknowledge their willingness to help. Equally valuable has been the contribution of the team at Granta Design, Cambridge, responsible for the development of the CES software that has been used to make the material property charts that are a feature of this book.

Resources that accompany this book

Exercises

Each chapter ends with exercises of three types: the first rely only on information, diagrams and data contained in the book itself; the second makes use of the CES software in ways that use the methods developed here, and the third explores the science more deeply using the CES Elements database that is part of the CES system.

Instructor's manual

The book itself contains a comprehensive set of exercises. Worked-out solutions to the exercises are freely available to teachers and lecturers who adopt this book. To access this material online please visit http://textbooks.elsevier.com and follow the instructions on screen.

Image Bank

The Image Bank provides adopting tutors and lecturers with jpegs and gifs of the figures from the book that may be used in lecture slides and class presentations. To access this material please visit http://textbooks.elsevier.com and follow the instructions on screen.

The CES EduPack

CES EduPack is the software-based package to accompany this book, developed by Michael Ashby and Granta Design. Used together, *Materials: Engineering, Science, Processing and Design* and CES EduPack provide a complete materials, manufacturing and design course. For further information please see the last page of this book, or visit www.grantadesign.com.

Chapter 1

Introduction: materials—history and character

Professor James Stuart, the first Professor of Engineering at Cambridge.

Chapter contents

1.1 Materials, processes and choice

Engineers *make* things. They make them out of *materials*. The materials have to support loads, to insulate or conduct heat and electricity, to accept or reject magnetic flux, to transmit or reflect light, to survive in often-hostile surroundings, and to do all this without damage to the environment or costing too much.

And there is the partner in all this. To *make* something out of a material you also need a process. Not just any process—the one you choose has to be compatible with the material you plan to use. Sometimes it is the process that is the dominant partner and a material-mate must be found that is compatible with it. It is a marriage. Compatibility is not easily found—many marriages fail—and material failure can be catastrophic, with issues of liability and compensation. This sounds like food for lawyers, and sometimes it is: some specialists make their living as expert witnesses in court cases involving failed materials. But our aim here is not contention; rather, it is to give you a vision of the materials universe (since, even on the remotest planets you will find the same elements) and of the universe of processes, and to provide methods and tools for choosing them to ensure a happy, durable union.

But, you may say, engineers have been making things out of materials for centuries, and successfully so—think of Isambard Kingdom Brunel, Thomas Telford, Gustave Eiffel, Henry Ford, Karl Benz and Gottlieb Daimler, the Wright brothers. Why do we need new ways to choose them? A little history helps here. Glance at the portrait with which this chapter starts: it shows James Stuart, the first Professor of Engineering at Cambridge University from 1875 to 1890 (note the cigar). In his day the number of materials available to engineers was small—a few hundred at most. There were no synthetic polymers—there are now over 45 000 of them. There were no light alloys (aluminum was first established as an engineering material only in the 20th century)—now there are thousands. There were no high-performance composites—now there are hundreds of them. The history is developed further in Figure 1.1, the time-axis of which spans 10 000 years. It shows roughly when each of the main classes of materials first evolved. The time-scale is nonlinear—almost all the materials we use today were developed in the last 100 years. And this number is enormous: over 160 000 materials are available to today's engineer, presenting us with a problem that Professor Stuart did not have: that of optimally selecting from this huge menu. With the ever-increasing drive for performance, economy and efficiency, and the imperative to avoid damage to the environment, making the right choice becomes very important. Innovative design means the imaginative exploitation of the properties offered by materials.

These properties, today, are largely known and documented in handbooks; one such—the *ASM Materials Handbook*—runs to 22 fat volumes, and it is one of many. How are we to deal with this vast body of information? Fortunately another thing has changed since Prof. Stuart's day: we now have digital information storage and manipulation. Computer-aided design is now a standard part

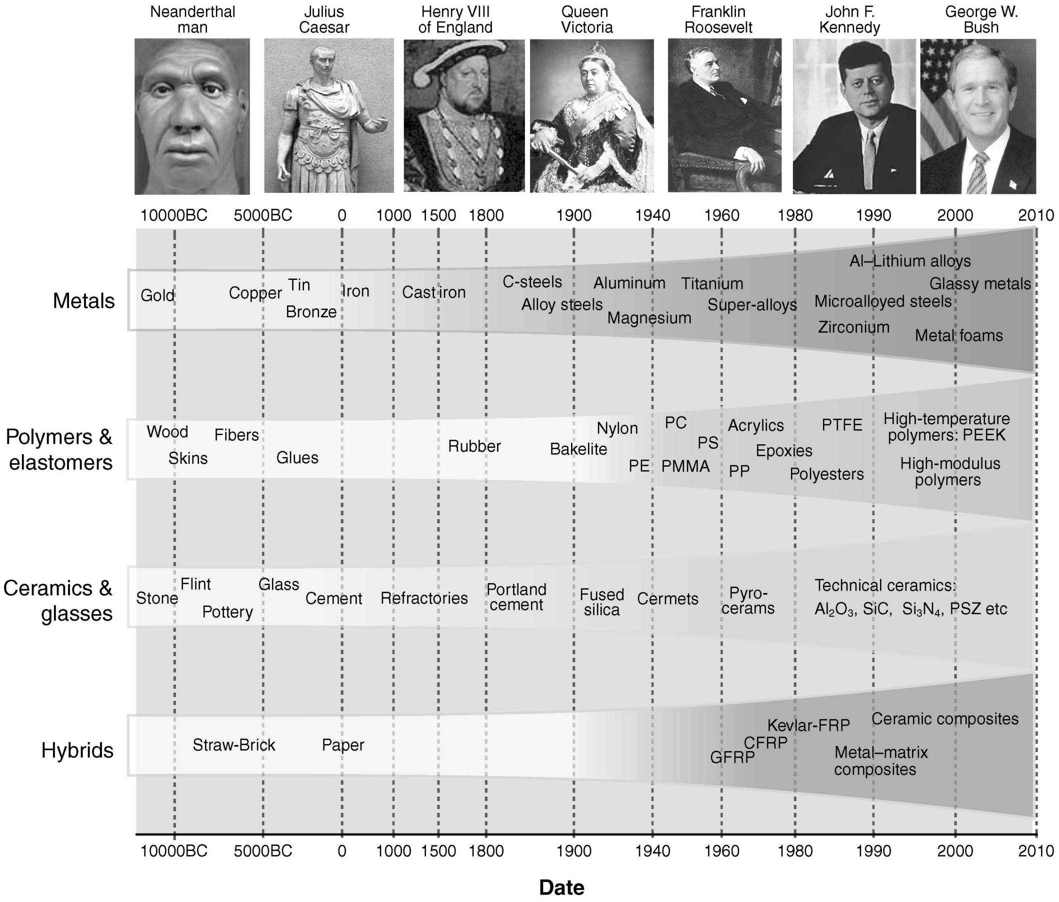

Figure 1.1 The development of materials over time. The materials of pre-history, on the left, all occur naturally; the challenge for the engineers of that era was one of shaping them. The development of thermochemistry and (later) of polymer chemistry enabled man-made materials, shown in the colored zones. Three—stone, bronze and iron—were of such importance that the era of their dominance is named after them.

of an engineer's training, and it is backed up by widely available packages for solid modeling, finite-element analysis, optimization, and for material and process selection. Software for the last of these—the selection of materials and processes—draws on databases of the attributes of materials and processes, documenting their mutual compatibility, and allows them to be searched and displayed in ways that enable selections that best meet the requirements of a design.

If you travel by foot, bicycle or car, you take a map. The materials landscape, like the terrestrial one, can be complex and confusing; maps, here, are also a good idea. This text presents a design-led approach to materials and manufacturing processes that makes use of maps: novel graphics to display the world of materials and processes in easily accessible ways. They present the properties of materials in ways that give a global view, that reveal relationships between properties and that enable selection.

1.2 Material properties

So what are these properties? Some, like density (mass per unit volume) and price (the cost per unit volume or weight) are familiar enough, but others are not, and getting them straight is essential. Think first of those that have to do with carrying load safely—the *mechanical properties*.

Mechanical properties

A steel ruler is easy to bend *elastically*—'elastic' means that it springs back when released. Its elastic stiffness (here, resistance to bending) is set partly by its shape—thin strips are easy to bend—and partly by a property of the steel itself: its *elastic modulus*, E. Materials with high E, like steel, are intrinsically stiff; those with low E, like polyethylene, are not. Figure 1.2(b) illustrates the consequences of inadequate stiffness.

The steel ruler bends elastically, but if it is a good one, it is hard to give it a permanent bend. Permanent deformation has to do with *strength*, not stiffness. The ease with which a ruler can be permanently bent depends, again, on its shape and on a different property of the steel—its *yield strength*, σ_y. Materials with large σ_y, like titanium alloys, are hard to deform permanently even though their stiffness, coming from E, may not be high; those with low σ_y, like lead, can be deformed with ease. When metals deform, they generally get stronger (this is called 'work hardening'), but there is an ultimate limit, called the *tensile strength*, σ_{ts}, beyond which the material fails (the amount it stretches before it breaks is called the *ductility*). Figure 1.2(c) gives an idea of the consequences of inadequate strength.

So far so good. One more. If the ruler were made not of steel but of glass or of PMMA (Plexiglas, Perspex), as transparent rulers are, it is not possible to bend it permanently at all. The ruler will fracture suddenly, without warning, before it acquires a permanent bend. We think of materials that break in this way as brittle, and materials that do not as tough. There is no permanent deformation here, so σ_y is not the right property. The resistance of materials to cracking and fracture is measured instead by the *fracture toughness*, K_{1c}. Steels are tough—well, most are (steels *can* be made brittle)—they have a high K_{1c}. Glass epitomizes brittleness; it has a very low K_{1c}. Figure 1.2(d) suggests consequences of inadequate fracture and toughness.

We started with the material property *density*, mass per unit volume, symbol ρ. Density, in a ruler, is irrelevant. But for almost anything that moves, weight carries a fuel penalty, modest for automobiles, greater for trucks and trains, greater still for aircraft, and enormous in space vehicles. Minimizing weight has

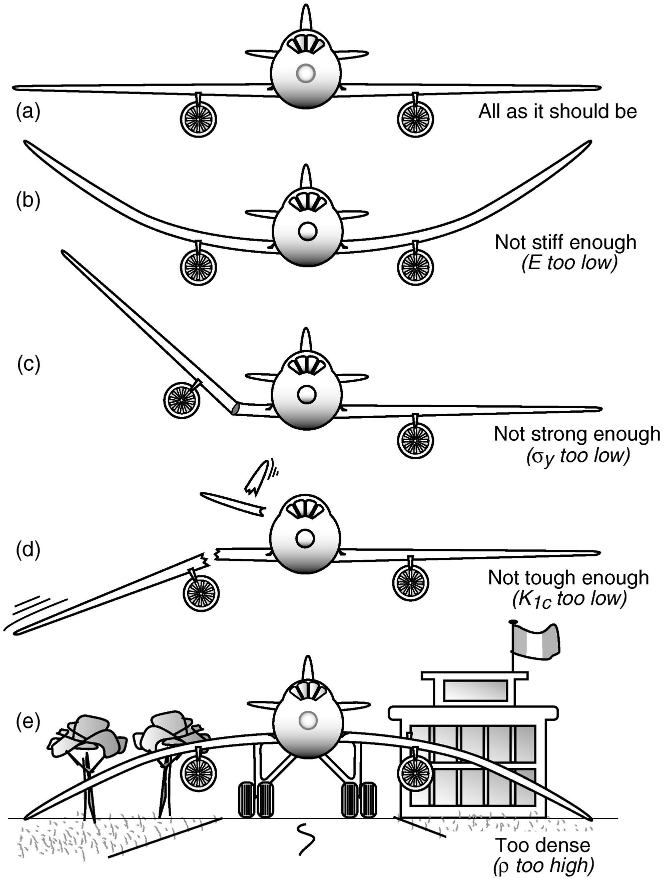

Figure 1.2 Mechanical properties.

much to do with clever design—we will get to that later—but equally to choice of material. Aluminum has a low density, lead a high one. If our little aircraft were made of lead, it would never get off the ground at all (Figure 1.2(e)).

These are not the only mechanical properties, but they are the most important ones. We will meet them, and the others, in Chapters 4–11.

Thermal properties

The properties of a material change with temperature, usually for the worse. Its strength falls, it starts to 'creep' (to sag slowly over time), it may oxidize, degrade or decompose (Figure 1.3(a)). This means that there is a limiting temperature called the *maximum service temperature*, $T_{\max}$, above which its use is impractical. Stainless steel has a high $T_{\max}$—it can be used up to 800°C; most polymers have a low $T_{\max}$ and are seldom used above 150°C.