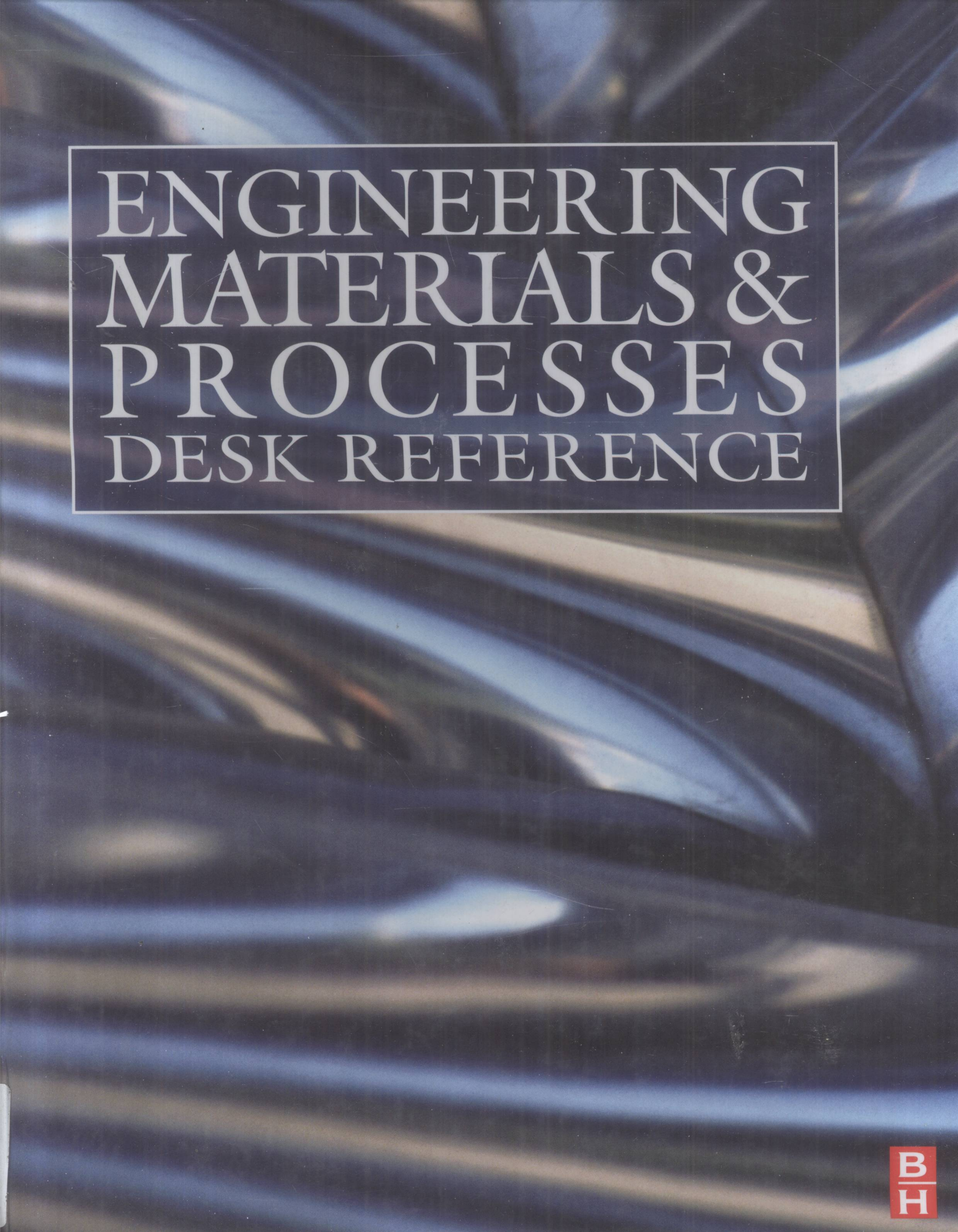
ENGINEERING MATERIALS & PROCESSES DESK REFERENCE



B H

Engineering Materials and Processes Desk Reference

ELSEVIER

Amsterdam · Boston · Heidelberg · London · New York · Oxford
Paris · San Diego · San Francisco · Sydney · Tokyo
Butterworth-Heinemann is an imprint of Elsevier

B
H

Butterworth-Heinemann is an imprint of Elsevier
Linacre House, Jordan Hill, Oxford OX2 8DP, UK
30 Corporate Drive, Suite 400, Burlington, MA 01803, USA

First edition 2009

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is availabe from the Library of Congress

ISBN: 978-1-85-617586-9

Printed and bound in the United States of America

09 10 11 11 10 9 8 7 6 5 4 3 2 1

Engineering Materials and Processes Desk Reference

Note from the Publisher

This book has been compiled using extracts from the following books within the range of Materials and Process Engineering books in the Elsevier collection:

Furlani, E.P. (2001) Permanent Magnet and Electromechanical Devices, 9780122699511
Ashby, M. (2005) Materials Selection in Mechanical Design 9780750661683
Smallman, R. E. and Ngan A.H.W. (2007) Physical Metallurgy and Advanced Materials, 9780750669061
Asthana, R. et al (2006) Materials Processing and Manufacturing Science 9780750677165
Messler R.W. (2004) Joining of Materials and Structures, 9780750677578
Ashby, M. and Jones, D. H. (2005) Engineering Materials 2 9780750663816
Crawford, R.J. (1998) Plastics Engineering, 9780750637640
Mills, N. (2005) Plastics 9780750651486

The extracts have been taken directly from the above source books, with some small editorial changes. These changes have entailed the re-numbering of Sections and Figures. In view of the breadth of content and style of the source books, there is some overlap and repetition of material between chapters and significant differences in style, but these features have been left in order to retain the flavour and readability of the individual chapters.

End of chapter questions
Within the book, several chapters end with a set of questions; please note that these questions are for reference only. Solutions are not always provided for these questions.

Units of measure
Units are provided in either SI or IP units. A conversion table for these units is provided at the front of the book.

Upgrade to an Electronic Version
An electronic version of the Desk reference, the *Engineering Materials and Processes e-Mega Reference*, 9781856175876

- A fully searchable Mega Reference eBook, providing all the essential material needed by Engineering Materials and Processes Engineers on a day-to-day basis.
- Fundamentals, key techniques, engineering best practice and rules-of-thumb at one quick click of a button
- Over 1,500 pages of reference material, including over 1,000 pages not included in the print edition

Go to http://www.elsevierdirect.com/9781856175869 and click on **Ebook Available**

Author Biographies

Professor Michael Ashby is Royal Society Research Professor at Cambridge Engineering Design Centre. He has been associated with the Engineering Design Centre since its inception, as one of the three Principal Investigators. He previously held the post of Professor of Applied Physics in the Division of Engineering and Applied Physics at Harvard University. He is a member of the Royal Society, the Royal Academy of Engineering and the U.S. National Academy of Engineering. He was also the Editor of *Acta Metallurgica* and is now Editor of *Progress in Materials Science.*

Dr. Rajiv Asthana is a Professor of Engineering and Technology at the University of Wisconsin-Stout. He is the author or co-author of three books and 132 refereed journal and conference publications, and book chapters. He has served on several committees of the American Society for Materials and has been a Visiting Scientist at NASA Glenn Research Center, and a scientist with the Council of Scientific & Industrial Research (India), among other institutions. He has received multiple awards, including the ASM-IIM Lectureship of American Society for Materials, and the U.S. National Academy of Sciences/NRC COBASE Research Award.

Professor Roy Crawford is Vice-Chancellor and President of the University of Waikato, New Zealand. His previous positions include Director of the School of Mechanical and Process Engineering and the Polymer Processing Research Centre at Queens University Belfast and Professor of Mechanical Engineering at the University of Auckland. He has given keynote lectures, courses and seminars all over the world and has published eight books and over 350 research papers. He is a Fellow of a number of professional and academic organisations and was elected to the Association of Rotational Moulders Hall of Fame.

Dr. Edward P. Furlani is currently a senior scientist in the research laboratories in the Eastman Kodak Company. He is also Research Professor in the Institute for Lasers, Photonics and Biophotonics at the University at Buffalo. Dr. Furlani has extensive experience in the area of applied magnetics. He has authored over 60 publications in scientific journals and holds over 140 US patents.

Dr Robert Messler, after 16 years in the materials industry, served as Technical Director and Associate Director of the Center for Manufacturing Productivity at Rensselaer. He joined the faculty as Associate Professor and Director of the Materials Joining Laboratory, and served as Associate Dean for Academic & Student Affairs for the School. He has authored four technical books in welding and joining, and over 140 papers in diverse areas of materials engineering. He has received numerous departmental, School, Institute, and national awards.

Dr. Nigel Mills was Reader in Polymer Engineering in the Metallurgy and Materials Department, earning honorary status after retirement, and chairman of the British Standards committee for motorcycle helmets. He previously worked for ICI Petrochemical and Polymer Laboratory in Runcorn. He has published many papers on foam and polymer properties and applications and authored the *Polymer Foams Handbook*.

Professor Ray Smallman, is Emeritus Professor of Metallurgy and Materials Science and honorary senior research fellow at the University of Birmingham. He spent his early career with the Atomic Energy Research Establishment in Harwell, UK. He is now President of the Federation of European Materials Societies and was prominent in its development. He has served on many committees and councils of various associations and received the *Acta Materialia* Gold Medal for his ability and leadership in materials science.

Dr. Ashok V. Kumar is Associate Professor in the Department of Mechanical Engineering at the University of Florida. His main research focus is the broad area of computational methods and design optimization.

Dr. Narendra B. Dahotre is a Professor with joint appointment with Oak Ridge National Laboratory and Department of Materials Science and Engineering of the University of Tennessee-Knoxville. He is also a senior faculty member of the Center for Laser Applications at the University of Tennessee Space Institute-Tullahoma. He is author of two technical books and editor/co-editor of 14 books. He is author of over 125 reviewed technical journal articles.

Dr. D.R.H. Jones is Emeritus Professor in the Mechanics and Materials Division at the University of Cambridge, UK

Professor A.H.W. Ngan is a member of the Mechanical Engineering Department at the University of Hong Kong. In 2007, he was awarded the Rosehain Medal and Prize by the Institute of Materials, Minerals and Mining, UK, and in 2008, he was conferred a higher doctorate (DSc) by the University of Birmingham.

Contents

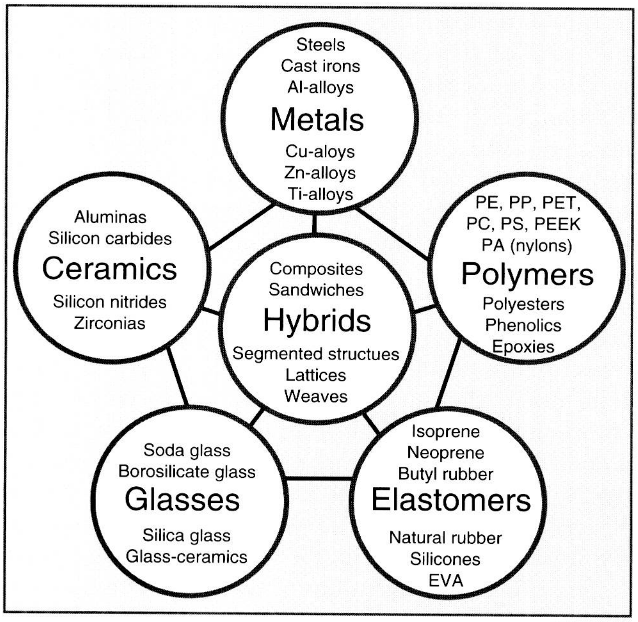
Section One

Introduction

Chapter 1.1

1.1

Introduction to Engineering materials



1.1.1 Introduction and synopsis

Materials, one might say, are the food of design. This chapter presents the menu: the full shopping list of materials. A successful product—one that performs well, is good value for money and gives pleasure to the user—uses the best materials for the job, and fully exploits their potential and characteristics. Brings out their flavor, so to speak.

The families of materials—metals, polymers, ceramics, and so forth—are introduced in Section 1.1.2. But it is not, in the end, a *material* that we seek; it is a certain *profile of properties*—the one that best meets the needs of the design. The properties, important in thermo-mechanical design, are defined briefly in Section 1.1.3. It makes boring reading. The reader confident in the definitions of moduli, strengths, damping capacities, thermal and electrical conductivities and the like, may wish to skip this, using it for reference, when needed, for the precise meaning and units of the data in the Property Charts that come later. Do not, however, skip Sections 1.1.2—it sets up the classification structure that is used throughout the book. The chapter ends, in the usual way, with a summary.

1.1.2 The families of engineering materials

It is helpful to classify the materials of engineering into the six broad families shown in Figure 1.1-1: metals, polymers, elastomers, ceramics, glasses, and hybrids. The members of a family have certain features in common: similar properties, similar processing routes, and, often, similar applications.

Metals have relatively high moduli. Most, when pure, are soft and easily deformed. They can be made strong by alloying and by mechanical and heat treatment, but they remain ductile, allowing them to be formed by deformation processes. Certain high-strength alloys (spring steel, for instance) have ductilities as low as 1 percent, but even this is enough to ensure that the material yields before it fractures and that fracture, when it occurs, is of a tough, ductile type. Partly because of their ductility, metals are prey to fatigue and of all the classes of material, they are the least resistant to corrosion.

Engineering Materials and Processes Desk Reference; ISBN: 9781856175869

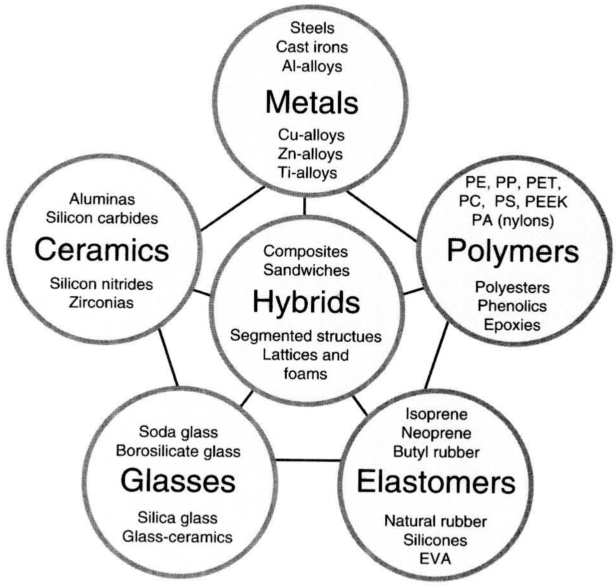


Figure 1.1-1 The menu of engineering materials. The basic families of metals, ceramics, glasses, polymers, and elastomers can be combined in various geometries to create hybrids.

Ceramics too, have high moduli, but, unlike metals, they are brittle. Their "strength" in tension means the brittle fracture strength; in compression it is the brittle crushing strength, which is about 15 times larger. And because ceramics have no ductility, they have a low tolerance for stress concentrations (like holes or cracks) or for high-contact stresses (at clamping points, for instance). Ductile materials accommodate stress concentrations by deforming in a way that redistributes the load more evenly, and because of this, they can be used under static loads within a small margin of their yield strength. Ceramics cannot. Brittle materials always have a wide scatter in strength and the strength itself depends on the volume of material under load and the time for which it is applied. So ceramics are not as easy to design with as metals. Despite this, they have attractive features. They are stiff, hard, and abrasion-resistant (hence their use for bearings and cutting tools); they retain their strength to high temperatures; and they resist corrosion well.

Glasses are non-crystalline ("amorphous") solids. The commonest are the soda-lime and boro-silicate glasses familiar as bottles and ovenware, but there are many more. Metals, too, can be made non-crystalline by cooling them sufficiently quickly. The lack of crystal structure suppresses plasticity, so, like ceramics, glasses are hard, brittle and vulnerable to stress concentrations.

Polymers are at the other end of the spectrum. They have moduli that are low, roughly 50 times less than those of metals, but they can be strong—nearly as strong as metals. A consequence of this is that elastic deflections can be large. They creep, even at room temperature, meaning that a polymer component under load may, with time, acquire a permanent set. And their properties depend on temperature so that a polymer that is tough and flexible at 20°C may be brittle at the 4°C of a household refrigerator, yet creep rapidly at the 100°C of boiling water. Few have useful strength above 200°C. If these aspects are allowed for in the design, the advantages of polymers can be exploited. And there are many. When combinations of properties, such as strength-per-unit-weight, are important, polymers are as good as metals. They are easy to shape: complicated parts performing several functions can be molded from a polymer in a single operation. The large elastic deflections allow the design of polymer components that snap together, making assembly fast and cheap. And by accurately sizing the mold and pre-coloring the polymer, no finishing operations are needed. Polymers are corrosion resistant and have low coefficients of friction. Good design exploits these properties.

Elastomers are long-chain polymers above their glass-transition temperature, T_g. The covalent bonds that link the units of the polymer chain remain intact, but the weaker Van der Waals and hydrogen bonds that, below T_g, bind the chains to each other, have melted. This gives elastomers unique property profiles: Young's moduli as low as 10^{-3} GPa (10^5 time less than that typical of metals) that increase with temperature (all other solids show a decrease), and enormous elastic extension. Their properties differ so much from those of other solids that special tests have evolved to characterize them. This creates a problem: if we wish to select materials by prescribing a desired attribute profile (as we do later in this book), then a prerequisite is a set of attributes common to all materials. To overcome this, we settle on a common set for use in the first stage of design, estimating approximate values for anomalies like elastomers. Specialized attributes, representative of one family only, are stored separately; they are for use in the later stages.

Hybrids are combinations of two or more materials in a pre-determined configuration and scale. They combine the attractive properties of the other families of materials while avoiding some of their drawbacks. Their design is the subject of Chapters 13 and 14. The family of hybrids includes fiber and particulate composites, sandwich structures, lattice structures, foams, cables, and laminates. And almost all the materials of nature—wood, bone, skin, leaf—are hybrids. Fiber-reinforced composites are, of course, the most familiar. Most of those at present available to the engineer have a polymer matrix reinforced by fibers of glass, carbon or Kevlar (an aramid). They are light, stiff and strong, and they can be tough. They, and other hybrids using a polymer as one component, cannot be used above 250°C because the polymer softens, but at room temperature their performance can be outstanding. Hybrid components are

Table 1.1-1 Basic design-limiting material properties and their usual SI units*

Class	Property	Symbol and units	
General	Density	ρ	(kg/m^3 or Mg/m^3)
	Price	C_m	($/kg)
Mechanical	Elastic moduli (Young's, shear, bulk)	E, G, K	(GPa)
	Yield strength	σ_Y	(MPa)
	Ultimate strength	σ_u	(MPa)
	Compressive strength	σ_c	(MPa)
	Failure strength	σ_f	(MPa)
	Hardness	H	(Vickers)
	Elongation	ε	(–)
	Fatigue endurance limit	σ_e	(MPa)
	Fracture toughness	K_{1C}	($MPa.m^{1/2}$)
	Toughness	G_{1C}	(kJ/m^2)
	Loss coefficient (damping capacity)	η	(–)
Thermal	Melting point	T_m	(C or K)
	Glass temperature	T_g	(C or K)
	Maximum service temperature	T_{max}	(C or K)
	Minimum service temperature	T_{max}	(C or K)
	Thermal conductivity	λ	(W/m.K)
	Specific heat	C_p	(J/kg.K)
	Thermal expansion coefficient	α	(K^{-1})
	Thermal shock resistance	ΔT_s	(C or K)
Electrical	Electrical resistivity	ρ_e	(Ω.m or $\mu\Omega$.cm)
	Dielectric constant	ε_d	(–)
	Breakdown potential	V_b	(10^6 V/m)
	Power factor	P	(–)
Optical	Optical, transparent, translucent, opaque	Yes/No	
	Refractive index	n	(–)
Eco-properties	Energy/kg to extract material	E_f	(MJ/kg)
	CO_2/kg to extract material	CO_2	(kg/kg)
Environmental resistance	Oxidation rates	Very low, low, average, high, very high	
	Corrosion rates		
	Wear rate constant	K_A	MPa^{-1}

* Conversion factors to imperial and cgs units appear inside the back and front covers of this book.

expensive and they are relatively difficult to form and join. So despite their attractive properties the designer will use them only when the added performance justifies the added cost. Today's growing emphasis on high performance and fuel efficiency provides increasing drivers for their use.

1.1.3 The definitions of material properties

Each material can be thought of as having a set of attributes: its properties. It is not a material, *per se*, that the designer seeks; it is a specific combination of these attributes: a *property-profile*. The material name is the identifier for a particular property-profile.

The properties themselves are standard: density, modulus, strength, toughness, thermal and electrical conductivities, and so on (Tables 1.1-1). For completeness and precision, they are defined, with their limits, in this section. If you think you know how properties are defined, you might jump to Section 1.1.5, returning to this section only if need arises.

General properties

The *density* (units: kg/m^3) is the mass per unit volume. We measure it today as Archimedes did: by weighing in air and in a fluid of known density.

The *price*, C_m (units: $/kg), of materials spans a wide range. Some cost as little as $0.2/kg, others as much as $1000/kg. Prices, of course, fluctuate, and they depend on the quantity you want and on your status as a "preferred customer" or otherwise. Despite this uncertainty, it is useful to have an approximate price, useful in the early stages of selection.

Mechanical properties

The *elastic modulus* (units: GPa or GN/m^2) is defined as the slope of the linear-elastic part of the stress–strain curve (Figure 1.1-2). Young's modulus, E, describes response to tensile or compressive loading, the shear modulus, G, describes shear loading and the bulk modulus, K, hydrostatic pressure. Poisson's ratio, ν, is dimensionless: it is the negative of the ratio of the lateral strain, ε_2, to the axial strain, ε_1, in axial loading:

$$\nu = -\frac{\varepsilon_2}{\varepsilon_1}$$

In reality, moduli measured as slopes of stress–strain curves are inaccurate, often low by a factor of 2 or more, because of contributions to the strain from anelasticity, creep and other factors. Accurate moduli are measured dynamically: by exciting the natural vibrations of a beam or wire, or by measuring the velocity of sound waves in the material.

In an isotropic material, the moduli are related in the following ways:

$$E = \frac{3G}{1 + G/3K}; \quad G = \frac{E}{2(1+\nu)}; \quad K = \frac{E}{3(1-2\nu)} \tag{1.1.1}$$

Commonly $\nu \approx 1/3$ when

$$G \approx \frac{3}{8}E \text{ and } K \approx E \tag{1.1.2a}$$

Elastomers are exceptional. For these $\nu \approx 1/2$ when

$$G \approx \frac{1}{3}E \text{ and } K \gg E \tag{1.1.2b}$$

Data sources like those described in Chapter 15 list values for all four moduli. In this book we examine data for E; approximate values for the others can be derived from equation (1.1.2) when needed.

The *strength* σ_f, of a solid (units: MPa or MN/m^2) requires careful definition. For metals, we identify σ_f with the 0.2 percent offset yield strength σ_y (Figure 1.1-2), that is, the stress at which the stress–strain curve for axial loading deviates by a strain of 0.2 percent from the linear-elastic line. It is the same in tension and compression. For polymers, σ_f is identified as the stress at which the stress–strain curve becomes markedly non-linear: typically, a strain of 1 percent (Figure 1.1-3). This may be caused by shear-yielding: the irreversible slipping of molecular chains; or it may be caused by crazing: the formation of low density, crack-like volumes that scatter light, making the polymer look white. Polymers are a little stronger ($\approx$20 percent) in compression than in tension. Strength, for ceramics and glasses, depends strongly on the mode of loading (Figure 1.1-4). In tension, "strength" means the fracture strength, σ_t. In compression it means the crushing strength σ_c, which is much larger; typically

$$\sigma_c = 10 \text{ to } 15\ \sigma_t \tag{1.1.3}$$

When the material is difficult to grip (as is a ceramic), its strength can be measured in bending. The *modulus of rupture* or MoR (units: MPa) is the maximum surface stress in a bent beam at the instant of failure (Figure 1.1-5).

One might expect this to be the same as the strength measured in tension, but for ceramics it is larger (by

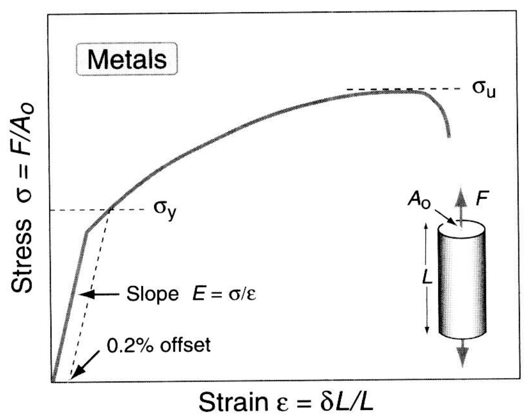


Figure 1.1-2 The stress–strain curve for a metal, showing the modulus, E, the 0.2 percent yield strength, σ_Y, and the ultimate strength, σ_u.

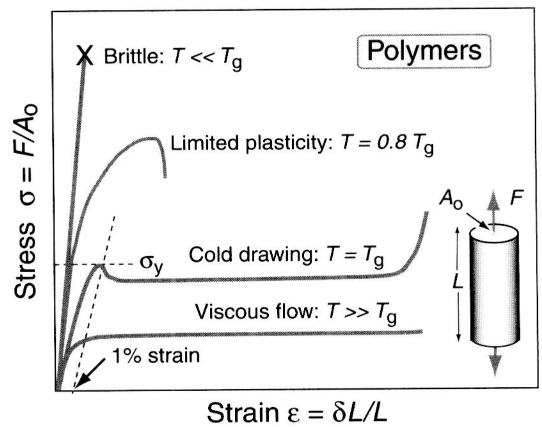


Figure 1.1-3 Stress–strain curves for a polymer, below, at and above its glass transition temperature, T_g.

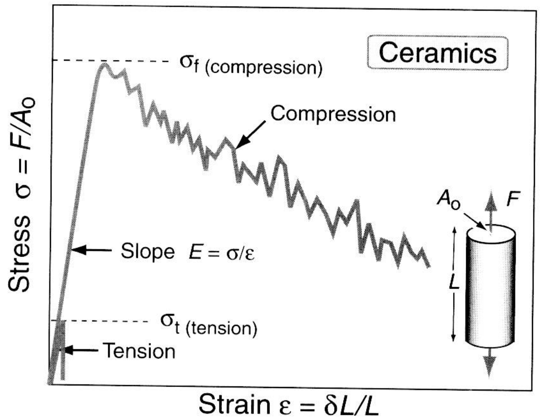


Figure 1.1-4 Stress– strain curves for a ceramic in tension and in compression. The compressive strength σ_c is 10 to 15 times greater than the tensile strength σ_t.

a factor of about 1.3) because the volume subjected to this maximum stress is small and the probability of a large flaw lying in it is small also; in simple tension all flaws see the maximum stress.

The strength of a composite is best defined by a set deviation from linear-elastic behavior: 0.5 percent is sometimes taken. Composites that contain fibers (and this includes natural composites like wood) are a little weaker (up to 30 percent) in compression than tension because fibers buckle. In subsequent chapters, σ_f for composites means the tensile strength.

Strength, then, depends on material class and on mode of loading. Other modes of loading are possible: shear, for instance. Yield under multi-axial loads is related to that in simple tension by a yield function. For metals, the Von Mises' yield function is a good description:

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2\sigma_f^2 \quad (1.1.4)$$

where σ_1, σ_2, and σ_3 are the principal stresses, positive when tensile; σ_1, by convention, is the largest or most positive, σ_3 the smallest or least. For polymers the yield function is modified to include the effect of pressure:

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2\sigma_f^2\left(1 + \frac{\beta p}{K}\right)^2 \quad (1.1.5)$$

where K is the bulk modulus of the polymer, $\beta \approx 2$ is a numerical coefficient that characterizes the pressure dependence of the flow strength and the pressure p is defined by

$$p = -\frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3)$$

For ceramics, a Coulomb flow law is used:

$$\sigma_1 - B\sigma_2 = C \quad (1.1.6)$$

where B and C are constants.

The *ultimate (tensile) strength*, σ_u (units: MPa), is the nominal stress at which a round bar of the material, loaded in tension, separates (see Figure 1.1-2). For brittle solids—ceramics, glasses, and brittle polymers—it is the same as the failure strength in tension. For metals, ductile polymers and most composites, it is larger than the strength, σ_f, by a factor of between 1.1 and 3 because of work hardening or (in the case of composites) load transfer to the reinforcement.

Cyclic loading not only dissipates energy; it can also cause a crack to nucleate and grow, culminating in fatigue failure. For many materials there exists a fatigue or *endurance limit*, σ_e (units: MPa), illustrated by the $\Delta\sigma - N_f$ curve of Figure 1.1-6. It is the stress amplitude

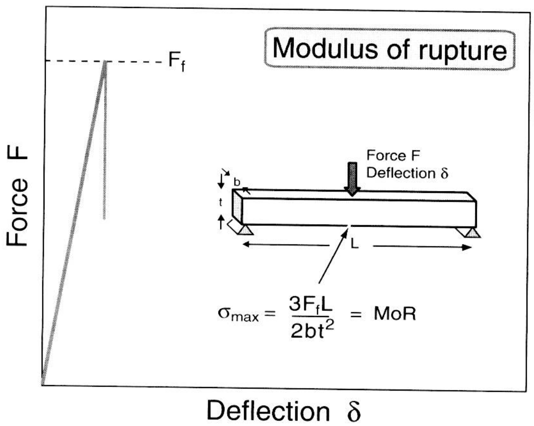


Figure 1.1-5 The MoR is the surface stress at failure in bending. It is equal to, or slightly larger than the failure stress in tension.

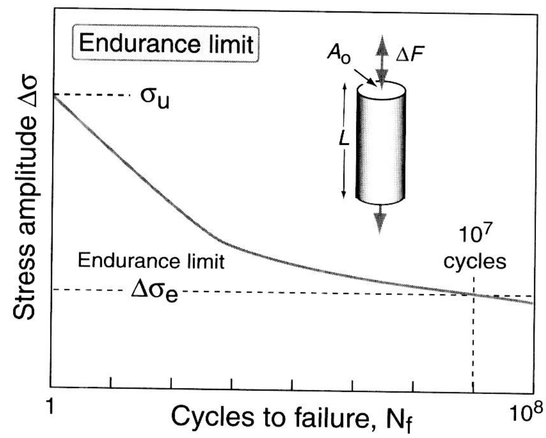


Figure 1.1-6 The endurance limit, $\Delta\sigma_e$, is the cyclic stress that causes failure in $N_f = 10^7$ cycles.

$\Delta\sigma$ below which fracture does not occur, or occurs only after a very large number ($N_f > 10^7$) of cycles.

The *hardness*, H, of a material is a crude measure of its strength. It is measured by pressing a pointed diamond or hardened steel ball into the surface of the material (Figure 1.1-7). The hardness is defined as the indenter force divided by the projected area of the indent. It is related to the quantity we have defined as σ_f by

$$H \approx 3\sigma_f \tag{1.1.7}$$

and this, in the SI system, has units of MPa. Hardness is most usually reported in other units, the commonest of which is the Vickers H_v scale with units of kg/mm^2. It is related to H in the units used here by

$$H_v = \frac{H}{10}$$

The *toughness*, G_{IC}, (units: kJ/m^2), and the *fracture toughness*, K_{IC}, (units: MPa.m$^{1/2}$ or MN/m$^{1/2}$), measure the resistance of a material to the propagation of a crack. The fracture toughness is measured by loading a sample containing a deliberately-introduced crack of length $2c$ (Figure 1.1-8), recording the tensile stress σ_c at which the crack propagates. The quantity K_{IC} is then calculated from

$$K_{1C} = Y\sigma_c\sqrt{\pi c} \tag{1.1.8}$$

and the toughness from

$$G_{1C} = \frac{K_{1C}^2}{E(1+\nu)} \tag{1.1.9}$$

where Y is a geometric factor, near unity, that depends on details of the sample geometry, E is Young's modulus and ν is Poisson's ratio. Measured in this way K_{1C} and G_{1C} have well-defined values for brittle materials (ceramics, glasses, and many polymers). In ductile materials a plastic zone develops at the crack tip, introducing new features into the way in which cracks propagate that necessitate more involved characterization. Values for K_{1C} and G_{1C} are, nonetheless, cited, and are useful as a way of ranking materials.

The *loss-coefficient*, η (a dimensionless quantity), measures the degree to which a material dissipates vibrational energy (Figure 1.1-9). If a material is loaded elastically to a stress, σ_{max}, it stores an elastic energy

$$U = \int_0^{\sigma_{max}} \sigma d\varepsilon \approx \frac{1}{2}\frac{\sigma_{max}^2}{E}$$

per unit volume. If it is loaded and then unloaded, it dissipates an energy

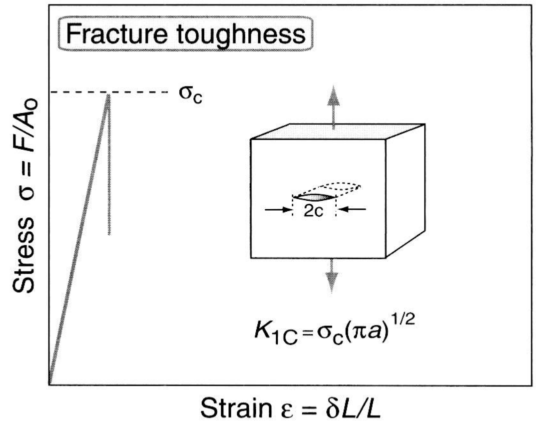


Figure 1.1-8 The fracture toughness, K_{1C}, measures the resistance to the propagation of a crack. The failure strength of a brittle solid containing a crack of length $2c$ is $K_{1C} = Y(\sigma_c/\sqrt{\pi c})$ where Y is a constant near unity.

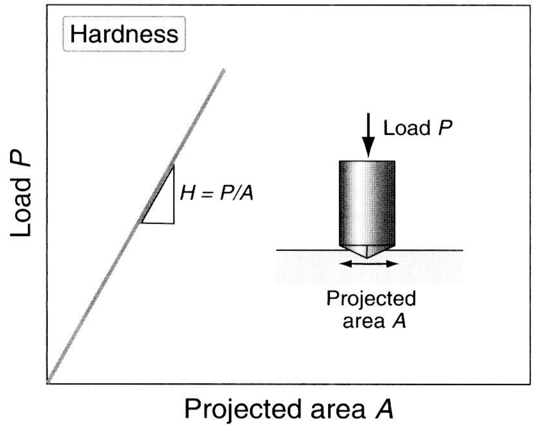


Figure 1.1-7 Hardness is measured as the load P divided by the projected area of contact, A, when a diamond-shaped indenter is forced into the surface.

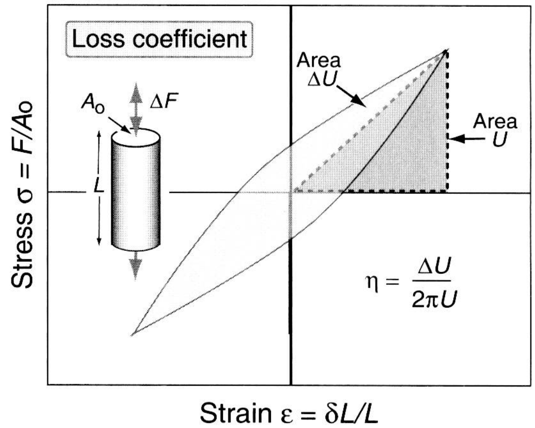


Figure 1.1-9 The loss coefficient η measures the fractional energy dissipated in a stress–strain cycle.

$$\Delta U = \oint \sigma d\varepsilon$$

The loss coefficient is

$$\eta = \frac{\Delta U}{2\pi U} \tag{1.1.10}$$

The value of η usually depends on the time-scale or frequency of cycling.

Other measures of damping include the *specific damping capacity*, $D = \Delta U/U$, the *log decrement*, Δ (the log of the ratio of successive amplitudes of natural vibrations), the *phase-lag*, δ, between stress and strain, and the "Q"-*factor* or *resonance factor*, Q. When damping is small ($\eta < 0.01$) these measures are related by

$$\eta = \frac{D}{2\pi} = \frac{\Delta}{\pi} = \tan\delta = \frac{1}{Q} \tag{1.1.11}$$

but when damping is large, they are no longer equivalent.

Thermal properties

Two temperatures, the *melting temperature*, T_m, and the *glass temperature*, T_g (units for both: K or C) are fundamental because they relate directly to the strength of the bonds in the solid. Crystalline solids have a sharp melting point, T_m. Non-crystalline solids do not; the temperature T_g characterizes the transition from true solid to very viscous liquid. It is helpful, in engineering design, to define two further temperatures: the *maximum* and *minimum service temperatures* T_{max} and T_{min} (both: K or C). The first tells us the highest temperature at which the material can reasonably be used without oxidation, chemical change, or excessive creep becoming a problem. The second is the temperature below which the material becomes brittle or otherwise unsafe to use.

The rate at which heat is conducted through a solid at steady state (meaning that the temperature profile does not change with time) is measured by the *thermal conductivity*, λ (units: W/m.K). Figure 1.1-10 shows how it is measured: by recording the heat flux q (W/m^2) flowing through the material from a surface at higher temperature T_1 to a lower one at T_2 separated by a distance X. The conductivity is calculated from Fourier's law:

$$q = -\lambda\frac{dT}{dX} = \lambda\frac{(T_1 - T_2)}{X} \tag{1.1.12}$$

The measurement is not, in practice, easy (particularly for materials with low conductivities), but reliable data are now generally available.

When heat flow is transient, the flux depends instead on the *thermal diffusivity*, a (units: m^2/s), defined by

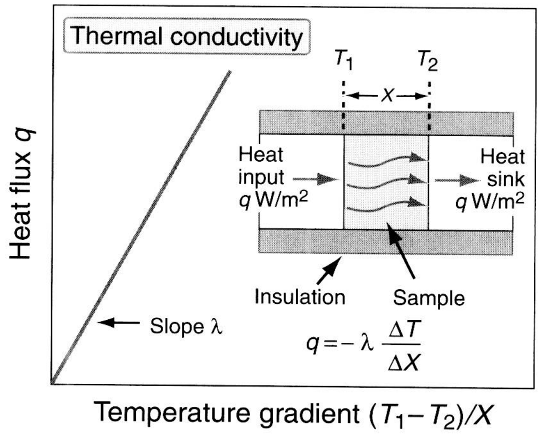


Figure 1.1-10 The thermal conductivity λ measures the flux of heat driven by a temperature gradient *dT/dX*.

$$a = \frac{\lambda}{\rho C_p} \tag{1.1.13}$$

where ρ is the density and C_p is the *specific heat at constant pressure* (units: J/kg.K). The thermal diffusivity can be measured directly by measuring the decay of a temperature pulse when a heat source, applied to the material, is switched off; or it can be calculated from λ, via equation (1.1.13). This requires values for C_p. It is measured by the technique of calorimetry, which is also the standard way of measuring the glass temperature T_g.

Most materials expand when they are heated (Figure 1.1-11). The thermal strain per degree of temperature change is measured by the *linear thermal-expansion coefficient*, α (units: K^{-1} or, more conveniently, as "microstrain/C" or $10^{-6}C^{-1}$). If the material is thermally isotropic, the volume expansion, per degree, is 3α. If it is anisotropic, two or more coefficients are required, and the volume expansion becomes the sum of the principal thermal strains.

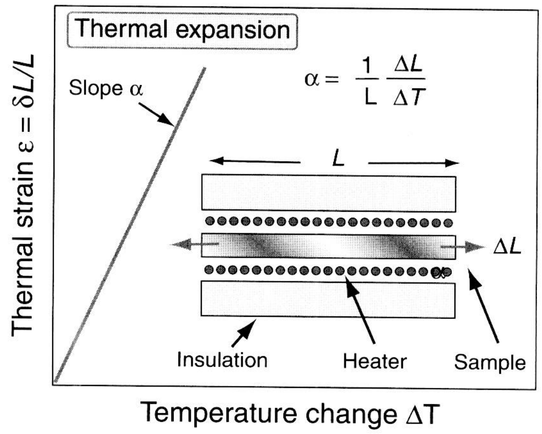


Figure 1.1-11 The linear-thermal expansion coefficient α measures the change in length, per unit length, when the sample is heated.