

MATERIALS SELECTION

IN

MECHANICAL DESIGN

SECOND EDITION

MICHAEL F. ASHBY

Department of Engineering, Cambridge University, England

BUTTERWORTH
HEINEMANN

OXFORD AUCKLAND BOSTON JOHANNESBURG MELBOURNE NEW DELHI

Butterworth-Heinemann
Linacre House, Jordan Hill, Oxford OX2 8DP
225 Wildwood Avenue, Woburn, MA 01801-2041
A division of Reed Educational and Professional Publishing Ltd

 A member of the Reed Elsevier plc group

First published by Pergamon Press Ltd 1992
Reprinted with corrections 1993
Reprinted 1995, 1996, 1997
Second edition 1999
Reprinted 2000 (twice)

© Michael F. Ashby 1999

All rights reserved. No part of this publication may be reproduced in any material form (including photocopying or storing in any medium by electronic means and whether or not transiently or incidentally to some other use of this publication) without the written permission of the copyright holder except in accordance with the provisions of the Copyright Designs and Patents Act 1988 or under the terms of a licence issued by the Copyright Licensing Agency Ltd, 90 Tottenham Court Road, London, England W1P 0LP. Applications for the copyright holder's written permission to reproduce any part of this publication should be addressed to the publishers

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

Library of Congress Cataloguing in Publication Data

A catalogue record for this book is available from the Library of Congress

ISBN 0 7506 4357 9

Typeset by Laser Words, Madras, India
Printed in Great Britain



FOR EVERY TITLE THAT WE PUBLISH BUTTERWORTH-HEINEMANN
WILL PAY FOR BPCU TO PLANT AND CARE FOR A TREE

Preface

‘Materials, of themselves, affect us little; it is the way we use them which influences our lives’. Epictetus, AD 50–100, *Discourses* Book 2, Chapter 5.

New materials advanced engineering design in Epictetus’ time. Today, with more materials than ever before, the opportunities for innovation are immense. But advance is possible only if a procedure exists for making a rational choice. This book develops a systematic procedure for selecting materials and processes, leading to the subset which best matches the requirements of a design. It is unique in the way the information it contains has been structured; the structure gives rapid access to data and it gives the user great freedom in exploring the potential of choice. The method is available as software* which allows even greater flexibility.

The approach emphasizes design with materials rather than materials ‘science’, although the underlying science is used, whenever possible, to help with the structuring of criteria for selection. The first six chapters require little prior knowledge: a first-year engineering knowledge of materials and mechanics is enough. The chapters dealing with shape and multi-objective selection are a little more advanced but can be omitted on a first reading. As far as possible the book integrates materials selection with other aspects of design; the relationship with the stages of design and optimization, and with the mechanics of materials, are developed throughout. At the teaching level, the book is intended as the text for 3rd and 4th year engineering courses on Materials for Design: a 6 to 10 lecture unit can be based on Chapters 1 to 6; a full 20+ lecture course, with associated project work with the associated software, uses the entire book.

Beyond this, the book is intended as a reference text of lasting value. The method, the charts and tables of performance indices have application in real problems of materials and process selection; and the catalogue of ‘useful solutions’ is particularly helpful in modelling — an essential ingredient of optimal design. The reader can use the book at increasing levels of sophistication as his or her experience grows, starting with the material indices developed in the case studies of the text, and graduating to the modelling of new design problems, leading to new material indices and value functions, and new — and perhaps novel — choices of material. This continuing education aspect is helped by a list of further reading at the end of each chapter, and by a set of problems covering all aspects of the text. Useful reference material is assembled in Appendices at the end of the book.

Like any other book, the contents of this one are protected by copyright. Generally, it is an infringement to copy and distribute material from a copyrighted source. But the best way to use the charts which are a feature of the book is to have a clean copy on which you can draw, try out alternative selection criteria, write comments, and so forth; and presenting the conclusion

* The Cambridge Materials Selector (*CMS*), available from Granta Design, Trumpington Mews, 40B High Street, Trumpington, Cambridge CB2 2LS, UK.

of a selection exercise is, often, most easily done in the same way. Although the book itself is copyrighted, the reader is authorized to make copies of the charts, and to reproduce these, with proper reference to their source, as he or she wishes.

M.F. Ashby
Cambridge, August 1998

Contents

PREFACE	xi
ACKNOWLEDGEMENTS	xiii
1 Introduction	1
1.1 Introduction and synopsis	1
1.2 Materials in design	1
1.3 The evolution of engineering materials	3
1.4 The evolution of materials in vacuum cleaners	4
1.5 Summary and conclusions	6
1.6 Further reading	7
2 The design process	8
2.1 Introduction and synopsis	8
2.2 The design process	8
2.3 Types of design	10
2.4 Design tools and materials data	11
2.5 Function, material, shape and process	13
2.6 Devices to open corked bottles	14
2.7 Summary and conclusions	18
2.8 Further reading	19
3 Engineering materials and their properties	20
3.1 Introduction and synopsis	20
3.2 The classes of engineering material	20
3.3 The definitions of material properties	22
3.4 Summary and conclusions	31
3.5 Further reading	31
4 Materials selection charts	32
4.1 Introduction and synopsis	32
4.2 Displaying material properties	32
4.3 The material property charts	36
4.4 Summary and conclusions	63
4.5 Further reading	64

5	Materials selection — the basics	65
5.1	Introduction and synopsis	65
5.2	The selection strategy	65
5.3	Deriving property limits and material indices	69
5.4	The selection procedure	77
5.5	The structural index	82
5.6	Summary and conclusions	83
5.7	Further reading	83
6	Materials selection — case studies	85
6.1	Introduction and synopsis	85
6.2	Materials for oars	85
6.3	Mirrors for large telescopes	89
6.4	Materials for table legs	93
6.5	Cost — structural materials for buildings	97
6.6	Materials for flywheels	100
6.7	Materials for high-flow fans	105
6.8	Golf-ball print heads	108
6.9	Materials for springs	111
6.10	Elastic hinges	116
6.11	Materials for seals	119
6.12	Diaphragms for pressure actuators	122
6.13	Knife edges and pivots	125
6.14	Deflection-limited design with brittle polymers	129
6.15	Safe pressure vessels	133
6.16	Stiff, high damping materials for shaker tables	137
6.17	Insulation for short-term isothermal containers	140
6.18	Energy-efficient kiln walls	143
6.19	Materials for passive solar heating	147
6.20	Materials to minimize thermal distortion in precision devices	151
6.21	Ceramic valves for taps	154
6.22	Nylon bearings for ships' rudders	157
6.23	Summary and conclusions	160
6.24	Further reading	161
7	Selection of material and shape	162
7.1	Introduction and synopsis	162
7.2	Shape factors	162
7.3	The efficiency of standard sections	172
7.4	Material limits for shape factors	175
7.5	Material indices which include shape	180
7.6	The microscopic or micro-structural shape factor	182
7.7	Co-selecting material and shape	186
7.8	Summary and conclusions	188
7.9	Further reading	190
	Appendix: geometric constraints and associated shape factors	190

8	Shape — case studies	194
8.1	Introduction and synopsis	194
8.2	Spars for man-powered planes	194
8.3	Forks for a racing bicycle	198
8.4	Floor joists: wood or steel?	200
8.5	Increasing the stiffness of steel sheet	204
8.6	Ultra-efficient springs	206
8.7	Summary and conclusions	209
9	Multiple constraints and compound objectives	210
9.1	Introduction and synopsis	210
9.2	Selection by successive application of property limits and indices	210
9.3	The method of weight-factors	212
9.4	Methods employing fuzzy logic	214
9.5	Systematic methods for multiple constraints	215
9.6	Compound objectives, exchange constants and value-functions	218
9.7	Summary and conclusions	226
9.8	Further reading	227
10	Case studies: multiple constraints and compound objectives	228
10.1	Introduction and synopsis	228
10.2	Multiple constraints — con-rods for high-performance engines	228
10.3	Multiple constraints — windings for high field magnets	232
10.4	Compound objectives — materials for insulation	237
10.5	Compound objectives — disposable coffee cups	241
10.6	Summary and conclusions	245
11	Materials processing and design	246
11.1	Introduction and synopsis	246
11.2	Processes and their influence on design	246
11.3	Process attributes	261
11.4	Systematic process selection	262
11.5	Screening: process selection diagrams	264
11.6	Ranking: process cost	274
11.7	Supporting information	279
11.8	Summary and conclusions	279
11.9	Further reading	280
12	Case studies: process selection	281
12.1	Introduction and synopsis	281
12.2	Forming a fan	281
12.3	Fabricating a pressure vessel	284
12.4	Forming a silicon nitride micro-beam	289
12.5	Forming ceramic tap valves	290
12.6	Economical casting	292
12.7	Computer-based selection — a manifold jacket	293

12.8	Computer-based selection — a spark plug insulator	298
12.9	Summary and conclusions	301
12.10	Further reading	301
13	Data sources	303
13.1	Introduction and synopsis	303
13.2	Data needs for design	303
13.3	Screening: data structure and sources	305
13.4	Further information: data structure and sources	307
13.5	Ways of checking and estimating data	309
13.6	Summary and conclusions	312
13.7	Further reading	313
	Appendix: data sources for material and process attributes	313
14	Case studies: use of data sources	334
14.1	Introduction and synopsis	334
14.2	Data for a ferrous alloy — type 302 stainless steel	334
14.3	Data for a non-ferrous alloy — Al–Si die-casting alloys	335
14.4	Data for a polymer — polyethylene	338
14.5	Data for a ceramic — zirconia	340
14.6	Data for a glass-filled polymer — nylon 30% glass	342
14.7	Data for a metal-matrix composite (MMC) — Al/SiC_p	344
14.8	Data for a polymer-matrix composite — CFRP	345
14.9	Data for a natural material — balsa wood	347
14.10	Summary and conclusions	349
14.11	Further reading	350
15	Materials, aesthetics and industrial design	351
15.1	Introduction and synopsis	351
15.2	Aesthetics and industrial design	351
15.3	Why tolerate ugliness? The bar code	354
15.4	The evolution of the telephone	355
15.5	The design of hair dryers	357
15.6	The design of forks	359
15.7	Summary and conclusions	361
15.8	Further reading	361
16	Forces for change	363
16.1	Introduction and synopsis	363
16.2	The market pull: economy versus performance	363
16.3	The science-push: curiosity-driven research	366
16.4	Materials and the environment: green design	367
16.5	The pressure to recycle and reuse	373
16.6	Summary and conclusions	373
16.7	Further reading	374

APPENDIX A: Useful solutions to standard problems	375
A.1 Constitutive equations for mechanical response	376
A.2 Moments of sections	378
A.3 Elastic bending of beams	380
A.4 Failure of beams and panels	382
A.5 Buckling of columns and plates	384
A.6 Torsion of shafts	386
A.7 Static and spinning discs	388
A.8 Contact stresses	390
A.9 Estimates for stress concentrations	392
A.10 Sharp cracks	394
A.11 Pressure vessels	396
A.12 Vibrating beams, tubes and discs	398
A.13 Creep and creep fracture	400
A.14 Flow of heat and matter	402
A.15 Solutions for diffusion equations	404
A.16 Further reading	406
APPENDIX B: Material indices	407
APPENDIX C: Material and process selection charts	413
C.1 Introduction	413
C.2 The materials selection charts	418
Chart 1: Young's modulus, E against density, ρ	418
Chart 2: Strength, σ_f , against density, ρ	420
Chart 3: Fracture toughness, K_{Ic} , against density, ρ	422
Chart 4: Young's modulus, E , against strength, σ_f	424
Chart 5: Specific modulus, E/ρ , against specific strength, σ_f/ρ	426
Chart 6: Fracture toughness, K_{Ic} , against Young's modulus, E	428
Chart 7: Fracture toughness, K_{Ic} , against strength, σ_f	430
Chart 8: Loss coefficient, η , against Young's modulus, E	432
Chart 9: Thermal conductivity, λ , against thermal diffusivity, a	434
Chart 10: T-Expansion coefficient, α , against T-conductivity, λ	436
Chart 11: Linear thermal expansion, α , against Young's modulus, E	438
Chart 12: Normalized strength, σ_t/E , against linear expansion coeff., α	440
Chart 13: Strength-at-temperature, $\sigma(T)$, against temperature, T	442
Chart 14: Young's modulus, E , against relative cost, $C_R\rho$	444
Chart 15: Strength, σ_f , against relative cost, $C_R\rho$	446
Chart 16: Dry wear rate against maximum bearing pressure, P_{max}	448
Chart 17: Young's modulus, E , against energy content, $q\rho$	450
Chart 18: Strength, σ_f , against energy content, $q\rho$	452
C.3 The process-selection charts	454
Chart P1: The material–process matrix	454
Chart P2: Hardness, H , against melting temperature, T_m	456
Chart P3: Volume, V , against slenderness, S	458
Chart P4: The shape classification scheme	460

x Contents

Chart P5: The shape–process matrix	462
Chart P6: Complexity against volume, V	464
Chart P7: Tolerance range, T , against RMS surface roughness, R	466

APPENDIX D: Problems

D1 Introduction to the problems	469
D2 Use of materials selection charts	469
D3 Deriving and using material indices	472
D4 Selection with multiple constraints	480
D5 Selecting material and shape	483
D6 Selecting processes	488
D7 Use of data sources	490
D8 Material optimization and scale	491

INDEX	495
--------------	-----

Introduction

1.1 Introduction and synopsis

‘Design’ is one of those words that means all things to all people. Every manufactured thing, from the most lyrical of ladies’ hats to the greasiest of gearboxes, qualifies, in some sense or other, as a design. It can mean yet more. Nature, to some is Divine Design; to others it is design by Natural Selection, the ultimate genetic algorithm. The reader will agree that it is necessary to narrow the field, at least a little.

This book is about mechanical design, and the role of materials in it. Mechanical components have mass; they carry loads; they conduct heat and electricity; they are exposed to wear and to corrosive environments; they are made of one or more materials; they have shape; and they must be manufactured (Figure 1.1). The book describes how these activities are related.

Materials have limited design since man first made clothes, built shelters and waged wars. They still do. But materials and processes to shape them are developing faster now than at any previous time in history; the challenges and opportunities they present are greater than ever before. The book develops a strategy for exploiting materials in design.

1.2 Materials in design

Design is the process of translating a new idea or a market need into the detailed information from which a product can be manufactured. Each of its stages requires decisions about the materials from which the product is to be made and the process for making it. Normally, the choice of material is dictated by the design. But sometimes it is the other way round: the new product, or the evolution of the existing one, was suggested or made possible by the new material. The number of materials available to the engineer is vast: something between 40 000 and 80 000 are at his or her (from here on ‘his’ means both) disposal. And although standardization strives to reduce the number, the continuing appearance of new materials with novel, exploitable, properties expands the options further.

How, then, does the engineer choose, from this vast menu, the material best suited to his purpose? Must he rely on experience? Or can a *systematic procedure* be formulated for making a rational choice? The question has to be answered at a number of levels, corresponding to the stage the design has reached. At the beginning the design is fluid and the options are wide; all materials must be considered. As the design becomes more focused and takes shape, the selection criteria sharpen and the shortlist of materials which can satisfy them narrows. Then more accurate data are required (although for a lesser number of materials) and a different way of analysing the choice must be used. In the final stages of design, precise data are needed, but for still fewer materials — perhaps only one. The procedure must recognize the initial richness of choice, narrow this to a small subset, and provide the precision and detail on which final design calculations can be based.

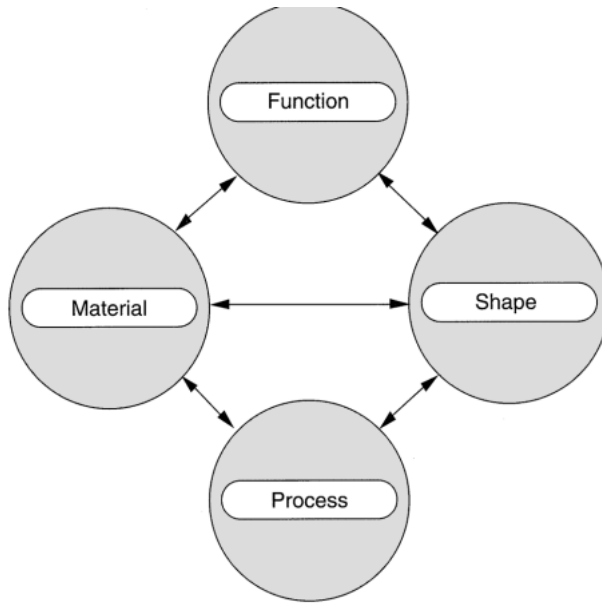


Fig. 1.1 Function, material, process and shape interact. Later chapters deal with each in turn.

The choice of material cannot be made independently of the choice of process by which the material is to be formed, joined, finished, and otherwise treated. Cost enters, both in the choice of material and in the way the material is processed. And — it must be recognized — good engineering design alone is not enough to sell a product. In almost everything from home appliances through automobiles to aircraft, the form, texture, feel, colour, decoration of the product — the satisfaction it gives the person who buys or uses it — are important. This aesthetic aspect (known confusingly as ‘industrial design’) is not treated in most courses on engineering, but it is one that, if neglected, can lose the manufacturer his market. Good designs work; excellent designs also give pleasure.

Design problems, almost always, are open-ended. They do not have a unique or ‘correct’ solution, although some solutions will clearly be better than others. They differ from the analytical problems used in teaching mechanics, or structures, or thermodynamics, or even materials, which generally do have single, correct answers. So the first tool a designer needs is an open mind: the willingness to consider all possibilities. But a net cast widely draws in many fish. A procedure is necessary for selecting the excellent from the merely good.

This book deals with the materials aspects of the design process. It develops a methodology which, properly applied, gives guidance through the forest of complex choices the designer faces. The ideas of material and process attributes are introduced. They are mapped on material and process selection charts which show the lay of the land, so to speak, and simplify the initial survey for potential candidate materials. The interaction between material and shape can be built into the method, as can the more complex aspects of optimizing the balance between performance and cost. None of this can be implemented without data for material properties and process attributes: ways to find them are described. The role of aesthetics in engineering design is discussed. The forces driving change in the materials world are surveyed. The Appendices contain useful information.

The methodology has further applications. It suggests a strategy for material development, particularly of composites and structured materials like sandwich panels. It points to a scheme for identifying the most promising applications for new materials. And it lends itself readily to computer implementation, offering the potential for interfaces with computer-aided design, function modelling, optimization routines and so forth.

All this will be found in the following chapters, with case studies illustrating applications. But first, a little history.

1.3 The evolution of engineering materials

Throughout history, materials have limited design. The ages in which man has lived are named for the materials he used: stone, bronze, iron. And when he died, the materials he treasured were buried with him: Tutankhamen with shards of coloured glass in his stone sarcophagus, Agamemnon with his bronze sword and mask of gold, each representing the high technology of his day.

If they had lived and died today, what would they have taken with them? Their titanium watch, perhaps; their carbon-fibre reinforced tennis racquet, their metal-matrix composite mountain bike, their polyether-ethyl-ketone crash helmet. This is not the age of one material; it is the age of an immense range of materials. There has never been an era in which the evolution of materials was faster and the range of their properties more varied. The menu of materials available to the engineer has expanded so rapidly that designers who left college twenty years ago can be forgiven for not knowing that half of them exist. But not-to-know is, for the designer, to risk disaster. Innovative design, often, means the imaginative exploitation of the properties offered by new or improved materials. And for the man in the street, the schoolboy even, not-to-know is to miss one of the great developments of our age: the age of advanced materials.

This evolution and its increasing pace are illustrated in Figure 1.2. The materials of pre-history (>10 000 BC, the Stone Age) were ceramics and glasses, natural polymers and composites. Weapons — always the peak of technology — were made of wood and flint; buildings and bridges of stone and wood. Naturally occurring gold and silver were available locally but played only a minor role in technology. The discovery of copper and bronze and then iron (the Bronze Age, 4000 BC–1000 BC and the Iron Age, 1000 BC–AD 1620) stimulated enormous advances, replacing the older wooden and stone weapons and tools (there is a cartoon on my office door, put there by a student, presenting an aggrieved Celt confronting a swordsmith with the words ‘You sold me this bronze sword last week and now I’m supposed to upgrade to iron!’). Cast iron technology (1620s) established the dominance of metals in engineering; and the evolution of steels (1850 onward), light alloys (1940s) and special alloys since then consolidated their position. By the 1960s, ‘engineering materials’ meant ‘metals’. Engineers were given courses in metallurgy; other materials were barely mentioned.

There had, of course, been developments in the other classes of material. Portland cement, refractories, fused silica among ceramics, and rubber, bakelite, and polyethylene among polymers, but their share of the total materials market was small. Since 1960 all that has changed. The rate of development of new metallic alloys is now slow; demand for steel and cast iron has in some countries actually fallen*. The polymer and composite industries, on the other hand, are growing rapidly, and projections of the growth of production of the new high-performance ceramics suggests rapid expansion here also.

* Do not, however, imagine that the days of steel are over. Steel production accounts for 90% of all world metal output, and its unique combination of strength, ductility, toughness and low price makes steel irreplaceable.

4 Materials Selection in Mechanical Design

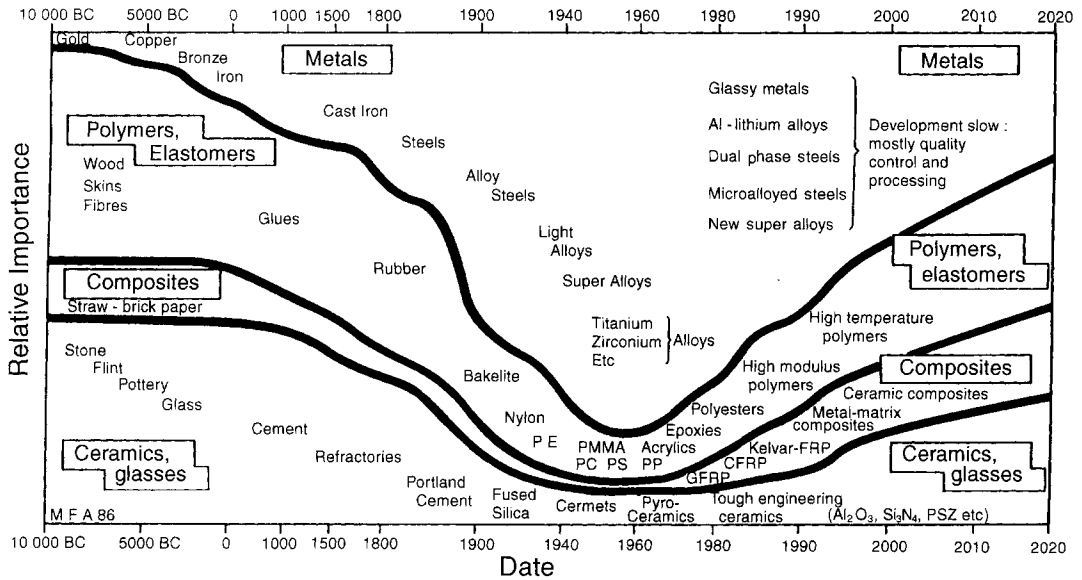


Fig. 1.2 The evolution of engineering materials with time. 'Relative Importance' in the stone and bronze ages is based on assessments of archaeologists; that in 1960 is based on allocated teaching hours in UK and US universities; that in 2020 on predictions of material usage in automobiles by manufacturers. The time scale is non-linear. The rate of change is far faster today than at any previous time in history.

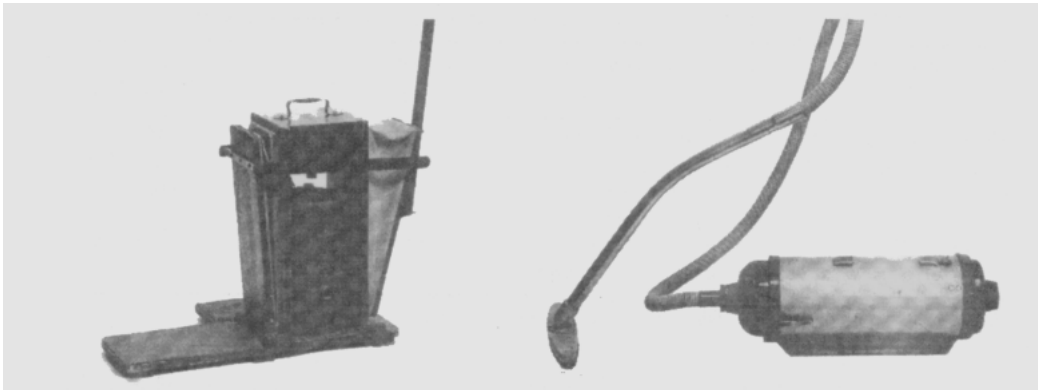
This rapid rate of change offers opportunities which the designer cannot afford to ignore. The following case study is an example. There are more in Chapter 15.

1.4 The evolution of materials in vacuum cleaners

'Sweeping and dusting are homicidal practices: they consist of taking dust from the floor, mixing it in the atmosphere, and causing it to be inhaled by the inhabitants of the house. In reality it would be preferable to leave the dust alone where it was.'

That was a doctor, writing about 100 years ago. More than any previous generation, the Victorians and their contemporaries in other countries worried about dust. They were convinced that it carried disease and that dusting merely dispersed it where, as the doctor said, it became yet more infectious. Little wonder, then, that they invented the vacuum cleaner.

The vacuum cleaners of 1900 and before were human-powered (Figure 1.3(a)). The housemaid, standing firmly on the flat base, pumped the handle of the cleaner, compressing bellows which, with leather flap-valves to give a one-way flow, sucked air through a metal can containing the filter at a flow rate of about 1 litre per second. The butler manipulated the hose. The materials are, by today's standards, primitive: the cleaner is made almost entirely from natural polymers and fibres; wood, canvas, leather and rubber. The only metal is the straps which link the bellows (soft iron) and the can containing the filter (mild steel sheet, rolled to make a cylinder). It reflects the use of materials in 1900. Even a car, in 1900, was mostly made of wood, leather, and rubber; only the engine and drive train had to be metal.



(a) 1905

(b) 1950



(c) 1985

(d) 1997

Fig. 1.3 Vacuum cleaners: (a) The hand-powered bellows cleaner of 1900, largely made of wood and leather. (b) The cylinder cleaner of 1950. (c) The lightweight cleaner of 1985, almost entirely polymer. (d) A centrifugal dust-extraction cleaner of 1997.

The electric vacuum cleaner first appeared around 1908*. By 1950 the design had evolved into the cylinder cleaner shown in Figure 1.3(b) (flow rate about 10 litres per second). Air flow is axial, drawn through the cylinder by an electric fan. The fan occupies about half the length of the cylinder; the rest holds the filter. One advance in design is, of course, the electrically driven air pump. The motor, it is true, is bulky and of low power, but it can function continuously without tea breaks or housemaid's elbow. But there are others: this cleaner is almost entirely made of metal: the case, the endcaps, the runners, even the tube to suck up the dust are mild steel: metals have replaced natural materials entirely.

Developments since then have been rapid, driven by the innovative use of new materials. The 1985 vacuum cleaner of Figure 1.3(c) has the power of roughly 18 housemaids working flat out

* Inventors: Murray Spengler and William B. Hoover. The second name has become part of the English language, along with those of such luminaries as John B. Stetson (the hat), S.F.B. Morse (the code), Leo Henrik Bakeland (Bakelite) and Thomas Crapper (the flush toilet).

Table 1.1 Comparison of cost, power and weight of vacuum cleaners

<i>Cleaner and Date</i>	<i>Dominant materials</i>	<i>Power (W)</i>	<i>Weight (kg)</i>	<i>Cost*</i>
Hand powered, 1900	Wood, canvas, leather	50	10	£240/\$380
Cylinder, 1950	Mild Steel	300	6	£96/\$150
Cylinder, 1985	Moulded ABS and polypropylene	800	4	£60/\$95
Dyson, 1995	Polypropylene, polycarbonate, ABS	1200	6.3	£190/\$300

*Costs have been adjusted to 1998 values, allowing for inflation.

(800 watts) and a corresponding air flow rate; cleaners with twice that power are now available. Air flow is still axial and dust removal by filtration, but the unit is smaller than the old cylinder cleaners. This is made possible by a higher power-density in the motor, reflecting better magnetic materials and higher operating temperatures (heat-resistant insulation, windings and bearings). The casing is entirely polymeric, and is an example of good design with plastics. The upper part is a single moulding, with all additional bits attached by snap fasteners moulded into the original component. No metal is visible anywhere; even the straight part of the suction tube, metal in all earlier models, is now polypropylene. The number of components is enormously reduced: the casing has just four parts, held together by just one fastener, compared with 11 parts and 28 fasteners for the 1950 cleaner. The saving on weight and cost is enormous, as the comparison in Table 1.1 shows.

It is arguable that this design (and its many variants) is near-optimal for today's needs; that a change of working principle, material or process could increase performance but at a cost penalty unacceptable to the consumer. We will leave the discussion of balancing performance against cost to a later chapter, and merely note here that one manufacturer disagrees. The cleaner shown in Figure 1.3(d) exploits a different concept: that of centrifugal separation, rather than filtration. For this to work, the power and rotation speed have to be high; the product is larger, noisier, heavier and much more expensive than the competition. Yet it sells — a testament to good industrial design and imaginative, aggressive marketing.

All this has happened within one lifetime. Competitive design requires the innovative use of new materials and the clever exploitation of their special properties, both engineering and aesthetic. There have been many manufacturers of vacuum cleaners who failed to innovate and exploit; now they are extinct. That sombre thought prepares us for the chapters which follow, in which we consider what they forgot: the optimum use of materials in design.

1.5 Summary and conclusions

The number of engineering materials is large: estimates range from 40 000 to 80 000. The designer must select from this vast menu the material best suited to his task. This, without guidance, can be a difficult and tedious business, so there is a temptation to choose the material that is 'traditional' for the application: glass for bottles; steel cans. That choice may be safely conservative, but it rejects the opportunity for innovation. Engineering materials are evolving faster, and the choice is wider than ever before. Examples of products in which a novel choice of material has captured a market are as common as — well — as plastic bottles. Or aluminium cans. It is important in the early stage of design, or of re-design, to examine the full materials menu, not rejecting options merely because they are unfamiliar. And that is what this book is about.

1.6 Further reading

The history and evolution of materials

Connoisseurs will tell you that in its 11th edition the *Encyclopaedia Britannica* reached a peak of excellence which has not since been equalled, although subsequent editions are still usable. On matters of general and technical history it, and the seven-volume *History of Technology*, are the logical starting points. More specialized books on the history and evolution of metals, ceramics, glass, and plastics make fascinating browsing. A selection of the most entertaining is given below.

- '*Encyclopaedia Britannica*', 11th edition. The Encyclopaedia Britannica Company, New York 1910.
 Davey, N. (1960) *A History of Building Materials*. Camelot Press, London, UK.
 Delmonte, J. (1985) *Origins of Materials and Processes*. Technomic Publishing Company, Pennsylvania.
 Derry, T.K. and Williams, T.I. (1960) *A Short History of Technology*. Oxford University Press, Oxford.
 Dowson, D. (1979) *History of Tribology*. Longman, London.
 Michaelis, R.R. (1992) Gold: art, science and technology, *Interdisciplinary Science Reviews*, **17**(3), 193.
 Singer, C., Holmyard, E.J., Hall, A.R. and Williams, T.I. (eds) (1954–1978) *A History of Technology* (7 volumes plus annual supplements). Oxford University Press, Oxford.
 Tylecoate, R.F. (1992) *A History of Metallurgy*, 2nd edition. The Institute of Materials, London.

Vacuum cleaners

- Forty, A. (1986) *Objects of Desire: Design and Society since 1750*, Thames and Hudson, London, p.174 et seq.