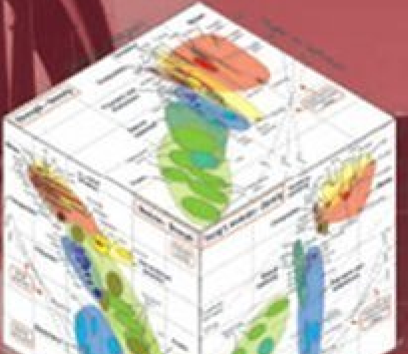
Third edition

Materials Selection in Mechanical Design



Michael F. Ashby

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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 allows the user great freedom in exploring the potential of choice. The method is available as software,[1] giving 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 eight chapters require little prior knowledge: a first-year grasp 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 6–10 lecture unit can be based on Chapters 1–6; 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 (and the software) 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 penalty 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 most chapters, and by a set of exercises in Appendix E 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 materials from a copyrighted source. But the best way to use the charts that are a central 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 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 unlimited copies of the charts, and to reproduce these, with proper reference to their source, as he or she wishes.

M.F. Ashby
Cambridge, July 2004

1 The *CES materials and process selection platform*, available from Granta Design Ltd, Rustat House, 62 Clifton Road, Cambridge CB1 7EG, UK (www.grantadesign.com).

Acknowledgements

Many colleagues have been generous in discussion, criticism, and constructive suggestions. I particularly wish to thank Professor Yves Bréchet of the University of Grenoble; Professor Anthony Evans of the University of California at Santa Barbara; Professor John Hutchinson of Harvard University; Dr David Cebon; Professor Norman Fleck; Professor Ken Wallace; Dr. John Clarkson; Dr. Hugh Shercliff of the Engineering Department, Cambridge University; Dr Amal Esawi of the American University in Cairo, Egypt; Dr Ulrike Wegst of the Max Planck Institute for Materials Research in Stuttgart, Germany; Dr Paul Weaver of the Department of Aeronautical Engineering at the University of Bristol; Professor Michael Brown of the Cavendish Laboratory, Cambridge, UK, and the staff of Granta Design Ltd, Cambridge, UK.

Features of the Third Edition

Since publication of the Second Edition, changes have occurred in the fields of materials and mechanical design, as well as in the way that these and related subjects are taught within a variety of curricula and courses. This new edition has been comprehensively revised and reorganized to address these. Enhancements have been made to presentation, including a new layout and two-colour design, and to the features and supplements that accompany the text. The key changes are outlined below.

Key changes

New and fully revised chapters:

- Processes and process selection (Chapter 7)
- Process selection case studies (Chapter 8)
- Selection of material and shape (Chapter 11)
- Selection of material and shape: case studies (Chapter 12)
- Designing hybrid materials (Chapter 13)
- Hybrid case studies (Chapter 14)
- Information and knowledge sources for design (Chapter 15)
- Materials and the environment (Chapter 16)
- Materials and industrial design (Chapter 17)
- Comprehensive appendices listing useful formulae; data for material properties; material indices; and information sources for materials and processes.

Supplements to the Third Edition

Material selection charts

Full color versions of the material selection charts presented in the book are available from the following website. Although the charts remain copyright of the author, users of this book are authorized to download, print and make unlimited copies of these charts, and to reproduce these for teaching and learning purposes only, but not for publication, with proper reference to their ownership and source. To access the charts and other teaching resources, visit www.grantadesign.com/ashbycharts.htm

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://books.elsevier.com/manuals and follow the instructions on screen.

Image bank

The Image Bank provides adopting tutors and lecturers with PDF versions of the figures from the book that may be used in lecture slides and class presentations. To access this material please visit http://books.elsevier.com/manuals 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 Selection in Mechanical 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.

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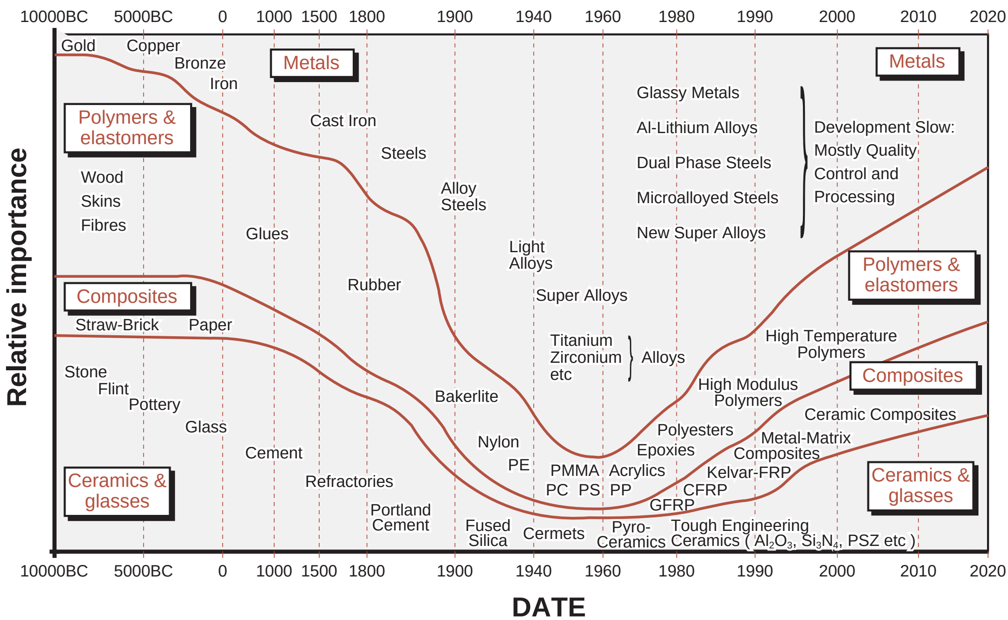
Chapter 1

Introduction



Chapter contents

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 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. 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 confronting the challenges and seizing the opportunities.

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 of 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 over 120,000 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? In the past he did, passing on this precious commodity to apprentices who, much later in their lives, might assume his role as the in-house materials guru who knows all about the things the company makes. But many things have changed in the world of engineering design, and all of them work against the success of this model. There is the drawn-out time scale of apprentice-based learning. There is job mobility, meaning that the guru who is here today is gone tomorrow. And there is the rapid evolution of materials information, already mentioned.

There is no question of the value of experience. But a strategy relying on experience-based learning is not in tune with the pace and re-dispersion of talent that is part of the age of information technology. We need a *systematic* procedure — one with steps that can be taught quickly, that is robust in the decisions it reaches, that allows of computer implementation, and with the ability to interface with the other established tools of engineering design. The question has to be addressed 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 short-list of materials that can satisfy them narrows. Then more accurate data are required (though for a lesser number of materials) and a different way of analyzing 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, and at the same time provide the precision and detail on which final design calculations can be based.

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. So, too, does the influence material usage on the environment in which we live. And it must be recognized that good engineering design alone is not enough to sell products. In almost everything from home appliances through automobiles to aircraft, the form, texture, feel, color, decoration of the product — the satisfaction it gives the person who owns or uses it — are important. This aspect, known confusingly as "industrial design", 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, though some solutions will clearly be better than others. They differ from the analytical problems used in teaching mechanics, or structures, or thermodynamics, 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 that, 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* that show the lay of the land, so to speak, and simplify the initial survey for potential candidate-materials. Real life always involves *conflicting objectives* — minimizing mass while at the same time minimizing cost is an example — requiring the use of *trade-off methods*. The interaction between *material and shape* can be built into the method. Taken together, these suggest schemes for expanding the boundaries of material performance by creating *hybrids* — combinations of two or more materials, shapes and configurations with unique property profiles. 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 most obvious of which is that dealing with environmental concerns. The appendices contain useful information.

The methods lend themselves readily to implementation as computer-based tools; one, *The CES materials and process selection platform*,[1] has been used for the case studies and many of the figures in this book. They offer, too, potential for interfacing with other computer-aided design, function modeling, optimization routines, but this degree of integration, though under development, is not yet commercially available.

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 in his enameled sarcophagus, Agamemnon with his bronze sword and mask of gold, each representing the high technology of their day.

If they had lived and died today, what would they have taken with them? Their titanium watch, perhaps; their carbon-fiber reinforced tennis racquet, their metal-matrix composite mountain bike, their shape-memory alloy eye-glass frames with diamond-like carbon coated lenses, 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 their evolution was faster and the range of their properties more varied. The menu of materials has expanded so rapidly that designers who left college 20 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 1.1. 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 and, through their rarity, assumed great influence as currency, but their role in technology was small. The development of rudimentary thermo-chemistry allowed the

[1] Granta Design Ltd, Rustat House, 62 Clifton Road, Cambridge CB1 7EG, UK (www.grantadesign.com).

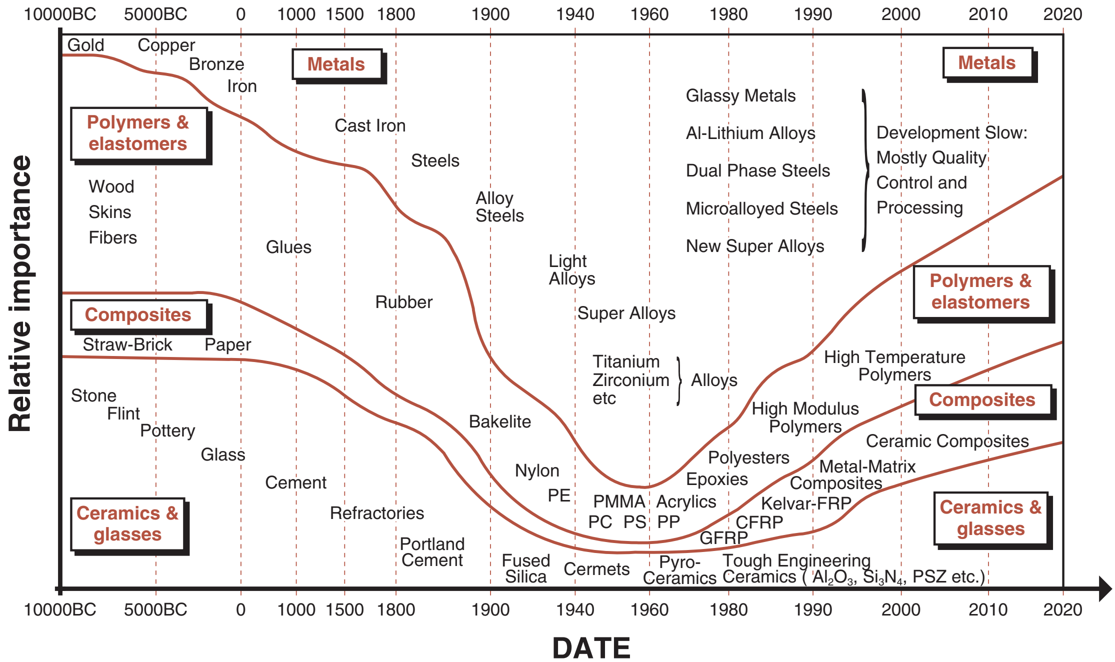


Figure 1.1 The evolution of engineering materials with time. "Relative importance" is based on information contained in the books listed under "Further reading", plus, from 1960 onwards, data for the teaching hours allocated to each material family in UK and US Universities. The projections to 2020 rely on estimates of material usage in automobiles and aircraft by manufacturers. The time scale is non-linear. The rate of change is far faster today than at any previous time in history.

extraction of, first, copper and bronze, then iron (the Bronze Age, 4000–1000 BC and the Iron Age, 1000 BC–1620 AD) stimulating enormous advances, in technology. (There is a cartoon on my office door, put there by a student, showing an aggrieved Celt confronting a sword-smith 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 since then the evolution of steels (1850 onward), light alloys (1940s) and special alloys, has 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. Improved cements, refractories, and glasses, 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.[2] 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 continued expansion here also.

This rapid rate of change offers opportunities that the designer cannot afford to ignore. The following case study is an example.

1.4 Case study: 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 when, 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 1.2(a)). The housemaid, standing firmly on the flat base, pumped the handle of the cleaner, compressing bellows that, via 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 l/s. The butler manipulated the hose. The materials are, by today's standards, primitive: the cleaner is made almost entirely from natural materials: wood, canvas, leather and rubber. The only metal is the straps that 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.

The electric vacuum cleaner first appeared around 1908.[3] By 1950 the design had evolved into the cylinder cleaner shown in Figure 1.2(b) (flow rate about 10 l/s). 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 end-caps, the runners, even the tube to suck up the dust are mild steel: metals have entirely replaced natural materials.

Developments since then have been rapid, driven by the innovative use of new materials. The 1985 vacuum cleaner of Figure 1.2(c) has the power of roughly 16 housemaids working flat out (800 W) and a corresponding air

[2] 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.

[3] 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 Baikeland (Bakelite), and Thomas Crapper (the flush toilet).

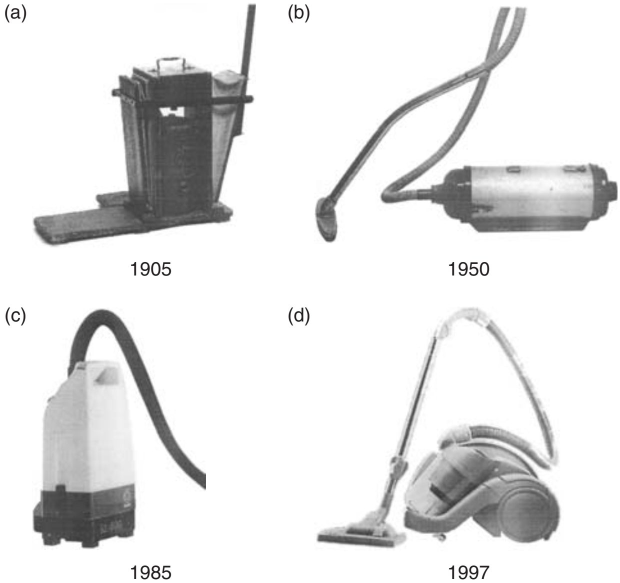


Figure 1.2 Vacuum cleaners: (a) the hand-powered bellows cleaner of 1900, largely made of wood and leather; (b) the cylinder cleaner of 1950; (c) the lightweight cleaner of 1985, almost entirely made of polymer; and (d) a centrifugal dust-extraction cleaner of 1997.

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 molding, with all additional bits attached by snap fasteners molded 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 dramatically reduced: the casing has just 4 parts, held together by just 1 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 1.2(d) exploits a different concept: that of inertial separation rather than filtration. For this to work, the power and rotation speed have to be high; the product is larger, heavier and more expensive than the competition. Yet it sells — a testament to good industrial design and imaginative marketing.

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

Cleaner and date	Dominant materials	Power (W)	Weight (kg)	Approximate cost*
Hand powered, 1900	Wood, canvas, leather	50	10	£240–$380
Cylinder, 1950	Mild steel	300	6	£96–$150
Cylinder, 1985	Molded 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.

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. Many manufacturers of vacuum cleaners failed to innovate and exploit; now they are extinct. That sombre thought prepares us for the chapters that 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: tens of thousands, at a conservative estimate. The designer must select, from this vast menu, the few best suited to his task. This, without guidance, can be a difficult and haphazard 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 new material has captured a market are as common as—well—as plastic bottles. Or aluminium cans. Or polycarbonate eyeglass lenses. Or carbon-fiber golf club shafts. 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. That is what this book is about.

1.6 Further reading

The history and evolution of materials

A History of Technology (21 volumes), edited by Singer, C., Holmyard, E.J., Hall, A.R., Williams, T.I., and Hollister-Short, G. Oxford University Press (1954–2001)

Oxford, UK. ISSN 0307–5451. *(A compilation of essays on aspects of technology, including materials.)*

Delmonte, J. (1985) *Origins of Materials and Processes*, Technomic Publishing Company, Pennsylvania, USA. ISBN 87762-420-8. *(A compendium of information on when materials were first used, any by whom.)*

Dowson, D. (1998) *History of Tribology*, Professional Engineering Publishing Ltd., London, UK. ISBN 1-86058-070-X. *(A monumental work detailing the history of devices limited by friction and wear, and the development of an understanding of these phenomena.)*

Emsley, J. (1998), *Molecules at an Exhibition*, Oxford University Press, Oxford, UK. ISBN 0-19-286206-5. *(Popular science writing at its best: intelligible, accurate, simple and clear. The book is exceptional for its range. The message is that molecules, often meaning materials, influence our health, our lives, the things we make and the things we use.)*

Michaelis, R.R. (1992) editor "Gold: art, science and technology", and "Focus on gold", *Interdisciplinary Science Reviews*, volume 17 numbers 3 and 4. ISSN 0308–0188. *(A comprehensive survey of the history, mystique, associations and uses of gold.)*

The *Encyclopaedia Britannica*, 11th edition (1910). The Encyclopaedia Britannica Company, New York, USA. *(Connoisseurs will tell you that in its 11th edition the Encyclopaedia Britannica reached a peak of excellence which has not since been equalled, though subsequent editions are still usable.)*

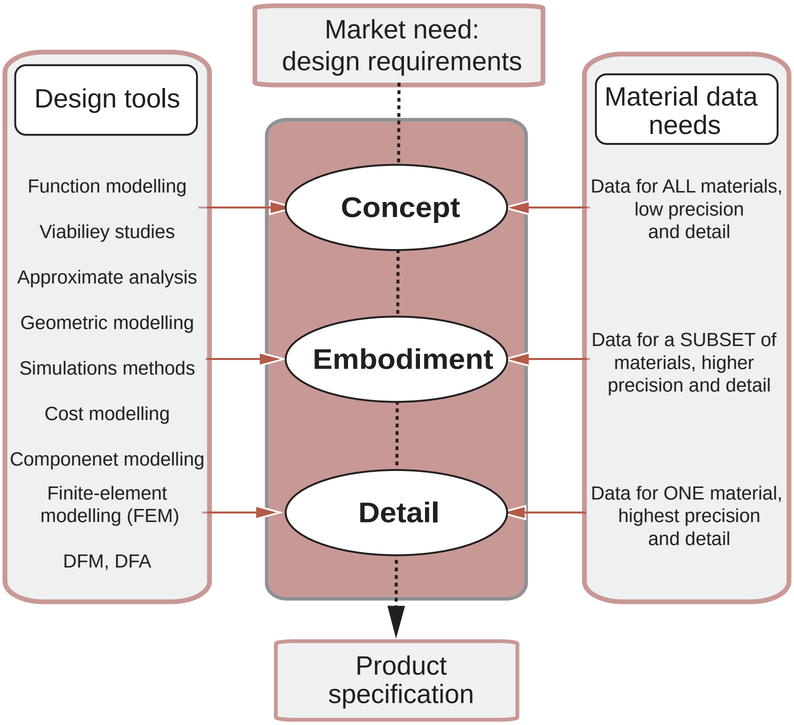
Tylecoate, R.F. (1992) *A History of Metallurgy*, 2nd edition, The Institute of Materials, London, UK. ISBN 0-904357-066. *(A total-immersion course in the history of the extraction and use of metals from 6000BC to 1976, told by an author with forensic talent and love of detail.)*

And on vacuum cleaners

Forty, A. (1986) *Objects of Desire — design in society since 1750*, Thames and Hudson, London, UK, p. 174 *et seq*. ISBN 0-500-27412-6. *(A refreshing survey of the design history of printed fabrics, domestic products, office equipment and transport system. The book is mercifully free of eulogies about designers, and focuses on what industrial design does, rather than who did it. The black and white illustrations are disappointing, mostly drawn from the late 19th or early 20th centuries, with few examples of contemporary design.)*

Chapter 2

The design process



Chapter contents

2.1 Introduction and synopsis

It is *mechanical design* with which we are primarily concerned here; it deals with the physical principles, the proper functioning and the production of mechanical systems. This does not mean that we ignore *industrial design*, which speaks of pattern, color, texture, and (above all) consumer appeal — but that comes later. The starting point is good mechanical design, and the ways in which the selection of materials and processes contribute to it.

Our aim is to develop a methodology for selecting materials and processes that is *design-led*; that is, the selection uses, as inputs, the functional requirements of the design. To do so we must first look briefly at design itself. Like most technical fields it is encrusted with its own special jargon, some of it bordering on the incomprehensible. We need very little, but it cannot all be avoided. This chapter introduces some of the words and phrases — the vocabulary — of design, the stages in its implementation, and the ways in which materials selection links with these.

2.2 The design process

The starting point is a *market need* or a *new idea*; the end point is the full *product specification* of a product that fills the need or embodies the idea. A need must be identified before it can be met. It is essential to define the need precisely, that is, to formulate a *need statement*, often in the form: "a device is required to perform task X", expressed as a set of *design requirements*. Writers on design emphasize that the statement and its elaboration in the design requirements should be *solution-neutral* (i.e. they should not imply how the task will be done), to avoid narrow thinking limited by pre-conceptions. Between the need statement and the product specification lie the set of stages shown in Figure 2.1: the stages of *conceptual*, *embodiment* and *detailed designs*, explained in a moment.

The product itself is called a *technical system*. A technical system consists of *sub-assemblies* and *components*, put together in a way that performs the required task, as in the breakdown of Figure 2.2. It is like describing a cat (the system) as made up of one head, one body, one tail, four legs, etc. (the sub-assemblies), each composed of components — femurs, quadriceps, claws, fur. This decomposition is a useful way to analyze an existing design, but it is not of much help in the design process itself, that is, in the synthesis of new designs. Better, for this purpose, is one based on the ideas of systems analysis. It thinks of the inputs, flows and outputs of information, energy, and materials, as in Figure 2.3. The design converts the inputs into the outputs. An electric motor converts electrical into mechanical energy; a forging press takes and reshapes material; a burglar alarm collects information and converts it to noise. In this approach, the system is broken down into connected sub-systems each of

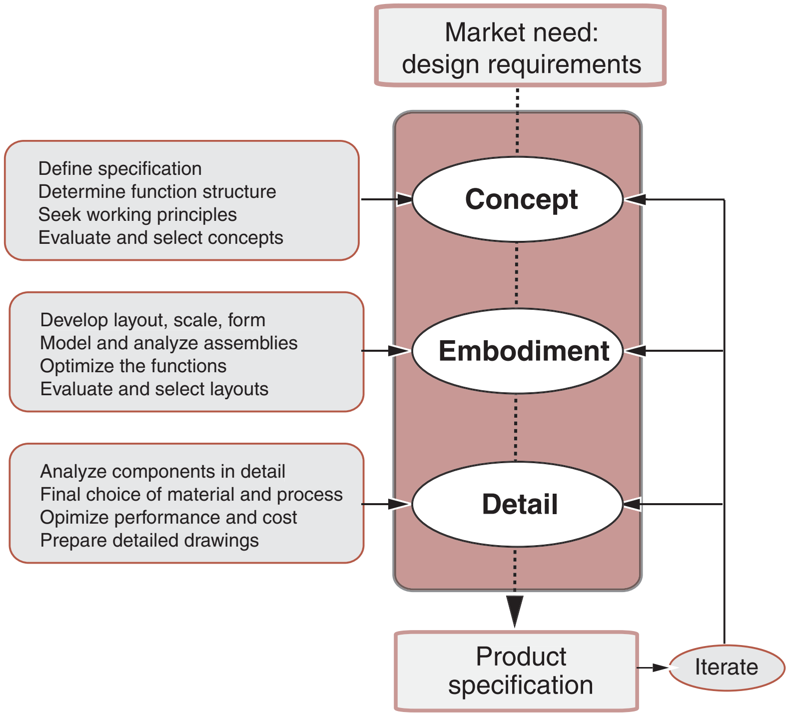


Figure 2.1 The design flow chart. The design proceeds from the identification of a *market need*, clarified as a set of *design requirements*, through *concept, embodiment* and *detailed* analysis to a *product specification*.

which performs a specific function, as in Figure 2.3; the resulting arrangement is called the *function-structure* or *function decomposition* of the system. It is like describing a cat as an appropriate linkage of a respiratory system, a cardio-vascular system, a nervous system, a digestive system and so on. Alternative designs link the unit functions in alternative ways, combine functions, or split them. The function-structure gives a systematic way of assessing design options.

The design proceeds by developing concepts to perform the functions in the function structure, each based on a *working principle*. At this, the conceptual design stage, all options are open: the designer considers alternative concepts and the ways in which these might be separated or combined. The next stage, embodiment, takes the promising concepts and seeks to analyze their operation at an approximate level. This involves sizing the components, and selecting materials that will perform properly in the ranges of stress, temperature, and environment suggested by the design requirements, examining the implications for performance and cost. The embodiment stage ends with a feasible layout, which is then passed to the detailed design stage. Here specifications for each

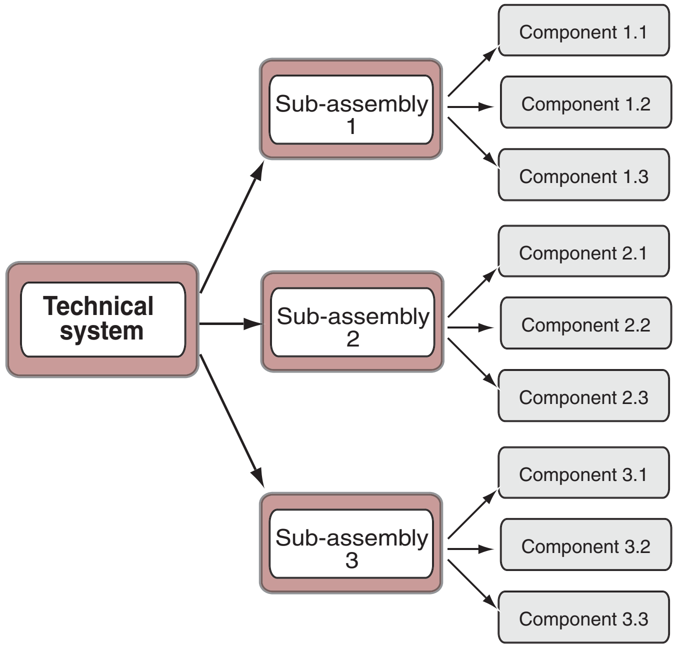


Figure 2.2 The analysis of a technical system as a breakdown into assemblies and components. Material and process selection is at the component level.

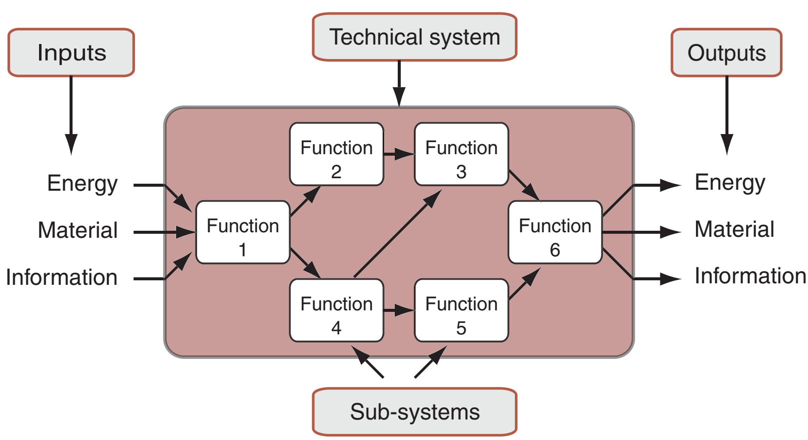


Figure 2.3 The systems approach to the analysis of a technical system, seen as transformation of energy, materials and information (signals). This approach, when elaborated, helps structure thinking about alternative designs.

component are drawn up. Critical components may be subjected to precise mechanical or thermal analysis. Optimization methods are applied to components and groups of components to maximize performance. A final choice of geometry and material is made and the methods of production are analyzed and costed. The stage ends with a detailed production specification.

All that sounds well and good. If only it were so simple. The linear process suggested by Figure 2.1 obscures the strong coupling between the three stages. The consequences of choices made at the concept or embodiment stages may not become apparent until the detail is examined. Iteration, looping back to explore alternatives, is an essential part of the design process. Think of each of the many possible choices that *could* be made as an array of blobs in design space as suggested by Figure 2.4. Here C1, C2, . . . are possible concepts, and E1, E2, . . . , and D1, D2, . . . are possible embodiments and detailed

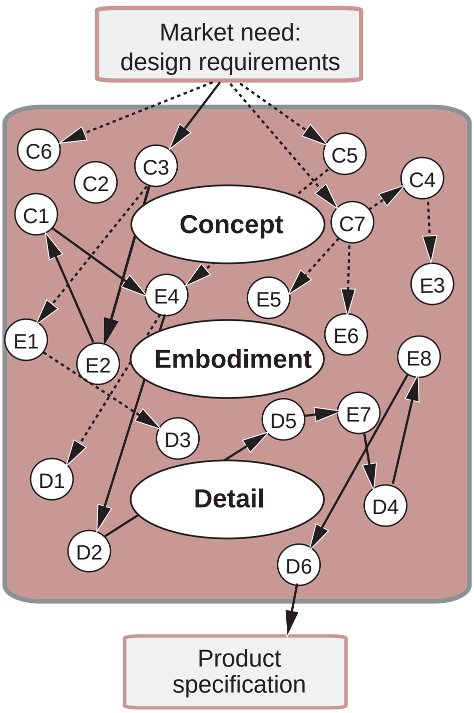


Figure 2.4 The previous figure suggests that the design process is logical and linear. The reality is otherwise. Here the C-blobs represent possible concepts, the E-blobs possible embodiments of the Cs, and the D-blobs possible detailed realizations of the Es. The process is complete when a compatible path form “Need” to “Specification” can be identified. The extreme coupling between the idealized design “stages” leads to a devious path (the full line) and many dead-ends (the broken lines). This creates the need for tools that allow fluid access to materials information at differing levels of breadth and detail.

elaborations of them. Then the design process becomes one of creating paths, linking compatible blobs, until a connection is made from the top ("market need") to the bottom ("product specification"). The trial paths have dead-ends, and they loop back. It is like finding a track across difficult terrain — it may be necessary to go back many times if, in the end, we are to go forward. Once a path is found, it is always possible to make it look linear and logical (and many books do this), but the reality is more like Figure 2.4, not Figure 2.1. Thus a key part of design, and of selecting materials for it, is *flexibility*, the ability to explore alternatives quickly, keeping the big picture as well as the details in focus. Our focus in later chapters is on the selection of materials and processes, where exactly the same need arises. This requires simple mappings of the "kingdoms" of materials and processes that allow quick surveys of alternatives while still providing detail when it is needed. The selection charts of Chapter 4 and the methods of Chapter 5 help do this.

Described in the abstract, these ideas are not easy to grasp. An example will help — it comes in Section 2.6. First, a look at types of design.

2.3 Types of design

It is not always necessary to start, as it were, from scratch. *Original design* does: it involves a new idea or working principle (the ball-point pen, the compact disc). New materials can offer new, unique combinations of properties that enable original design. Thus high-purity silicon enabled the transistor; high-purity glass, the optical fiber; high coercive-force magnets, the miniature earphone, solid-state lasers the compact disc. Sometimes the new material suggests the new product; sometimes instead the new product demands the development of a new material: nuclear technology drove the development of a series of new zirconium-based alloys and low-carbon stainless steels; space technology stimulated the development of light-weight composites; turbine technology today drives development of high-temperature alloys and ceramics.

Adaptive or *developmental design* takes an existing concept and seeks an incremental advance in performance through a refinement of the working principle. This, too, is often made possible by developments in materials: polymers replacing metals in household appliances; carbon fiber replacing wood in sports goods. The appliance and the sports-goods market are both large and competitive. Markets here have frequently been won (and lost) by the way in which the manufacturer has adapted the product by exploiting new materials.

Variant design involves a change of scale or dimension or detailing without change of function or the method of achieving it: the scaling up of boilers, or of pressure vessels, or of turbines, for instance. Change of scale or circumstances of use may require change of material: small boats are made of fiberglass, large ships are made of steel; small boilers are made of copper, large ones of steel; subsonic planes are made of one alloy, supersonic of another; and for good reasons, detailed in later chapters.

2.4 Design tools and materials data

To implement the steps of Figure 2.1, use is made of *design tools*. They are shown as inputs, attached to the left of the main backbone of the design methodology in Figure 2.5. The tools enable the modeling and optimization of a design, easing the routine aspects of each phase. Function-modelers suggest viable function structures. Configuration optimizers suggest or refine shapes. Geometric and 3D solid modeling packages allow visualization and create files that can be down-loaded to numerically controlled prototyping and manufacturing systems. Optimization, DFM, DFA,[1] and cost-estimation

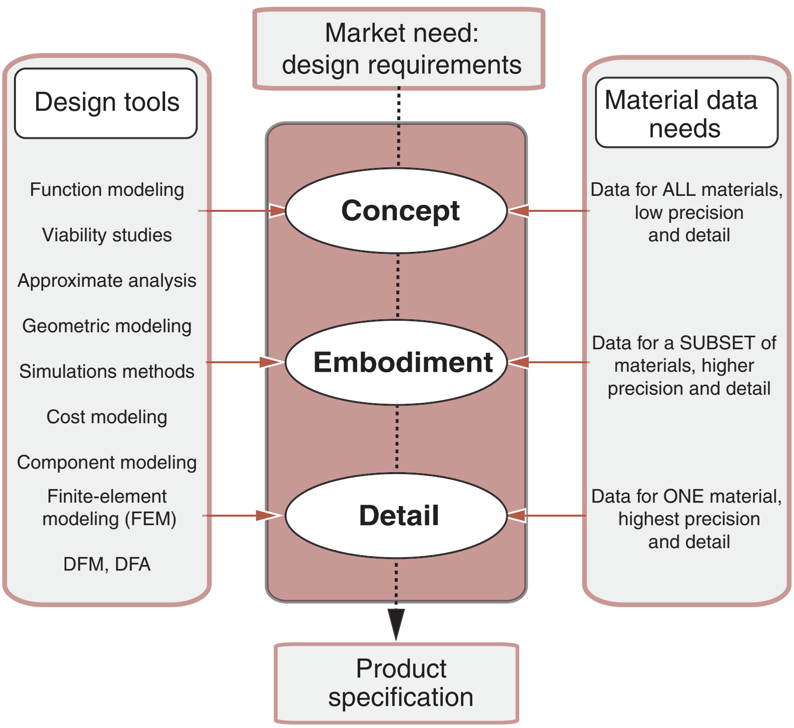


Figure 2.5 The design flow chart, showing how design tools and materials selection enter the procedure. Information about materials is needed at each stage, but at very different levels of breadth and precision.

[1] Design for Manufacture and Design for Assembly.

software allows manufacturing aspects to be refined. Finite element (FE) and Computational Fluid Dynamics (CFD) packages allow precise mechanical and thermal analysis even when the geometry is complex and the deformations are large. There is a natural progression in the use of the tools as the design evolves: approximate analysis and modeling at the conceptual stage; more sophisticated modeling and optimization at the embodiment stage; and precise ("exact"—but nothing is ever that) analysis at the detailed design stage.

Materials selection enters each stage of the design. The nature of the data needed in the early stages differs greatly in its level of precision and breadth from that needed later on (Figure 2.5, right-hand side). At the concept-stage, the designer requires approximate property-values, but for the widest possible range of materials. All options are open: a polymer may be the best choice for one concept, a metal for another, even though the function is the same. The problem, at this stage, is not precision and detail; it is breadth and speed of access: how can the vast range of data be presented to give the designer the greatest freedom in considering alternatives?

At the embodiment stage the landscape has narrowed. Here we need data for a subset of materials, but at a higher level of precision and detail. These are found in the more specialized handbooks and software that deal with a single class or sub-class of materials—metals, or just aluminum alloys, for instance. The risk now is that of loosing sight of the bigger spread of materials to which we must return if the details do not work out; it is easy to get trapped in a single line of thinking—a single set of "connections" in the sense described in the last section—when other combinations of connections offer a better solution to the design problem.

The final stage of detailed design requires a still higher level of precision and detail, but for only one or a very few materials. Such information is best found in the data-sheets issued by the material producers themselves, and in detailed databases for restricted material classes. A given material (polyethylene, for instance) has a range of properties that derive from differences in the ways different producers make it. At the detailed design stage, a supplier must be identified, and the properties of his product used in the design calculations; that from another supplier may have slightly different properties. And sometimes even this is not good enough. If the component is a critical one (meaning that its failure could, in some sense or another, be disastrous) then it may be prudent to conduct in-house tests to measure the critical properties, using a sample of the material that will be used to make the product itself.

It's all a bit like choosing a bicycle. You first decide which concept best suits your requirements (street bike, mountain bike, racing, folding, shopping, reclining, ...), limiting the choice to one subset. Then comes the next level of detail. What frame material? What gears? Which sort of brakes? What shape of handlebars? At this point you consider the trade-off between performance and cost, identifying (usually with some compromise) a small subset that meet both your desires and your budget. Finally, if your bicycle is important to you, you seek further information in bike magazines, manufacturers' literature or the views of enthusiasts, and try out candidate-bikes yourself. And if you do not like them you go back one or more steps. Only when a match between your need and an available product is found do you make a final selection.

The materials input does not end with the establishment of production. Products fail in service, and failures contain information. It is an imprudent manufacturer who does not collect and analyze data on failures. Often this points to the misuse of a material, one that redesign or re-selection can eliminate.

2.5 Function, material, shape, and process

The selection of a material and process cannot be separated from the choice of shape. We use the word "shape" to include the external, *macro-shape*, and—when necessary—the internal, or *micro-shape*, as in a honeycomb or cellular structure. To make the shape, the material is subjected to processes that, collectively, we shall call *manufacture*: they include primary forming processes (like casting and forging), material removal processes (machining, drilling), finishing processes (such as polishing) and joining processes (e.g. welding). Function, material, shape and process interact (Figure 2.6). Function dictates the choice of both material and shape. Process is influenced by the material: by its formability, machinability, weldability, heat-treatability, and so on. Process obviously interacts with shape—the process determines the shape, the size, the precision and, of course, the cost. The interactions are two-way: specification of shape restricts the choice of material and process; but equally the

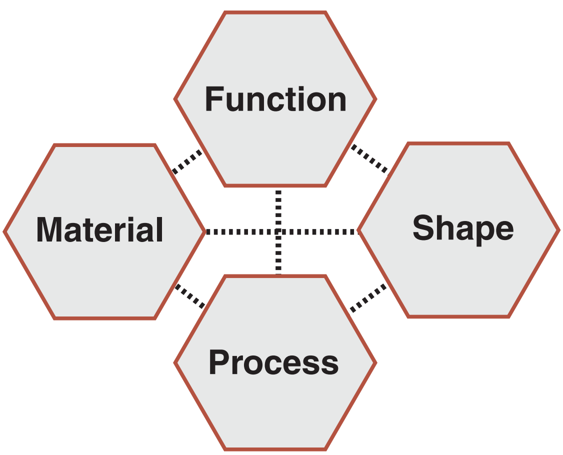


Figure 2.6 The central problem of materials selection in mechanical design: the interaction between function, material, shape and process.

specification of process limits the materials you can use and the shapes they can take. The more sophisticated the design, the tighter the specifications and the greater the interactions. It is like making wine: to make cooking wine, almost any grape and fermentation process will do; to make champagne, both grape and process must be tightly constrained.

The interaction between function, material, shape, and process lies at the heart of the material selection process. But first, a case study to illustrate the design process.

2.6 Case study: devices to open corked bottles

Wine, like cheese, is one of man's improvements on nature. And ever since man has cared about wine, he has cared about cork to keep it safely sealed in flasks and bottles. "Corticum . . . demovebit amphorae . . . " — "Uncork the amphora . . . " sang Horace[2] (27 BC) to celebrate the anniversary of his miraculous escape from death by a falling tree. But how did he do it?

A corked bottle creates a market need: it is the need to gain access to the wine inside. We might state it thus: "A device is required to pull corks from wine bottles." But hold on. The need must be expressed in solution-neutral form, and this is not. The aim is to gain access to the wine; our statement implies that this will be done by removing the cork, and that it will be removed by pulling. There could be other ways. So we will try again: "A device is required to allow access to wine in a corked bottle" (Figure 2.7) and one might add, "with convenience, at modest cost, and without contaminating the wine."

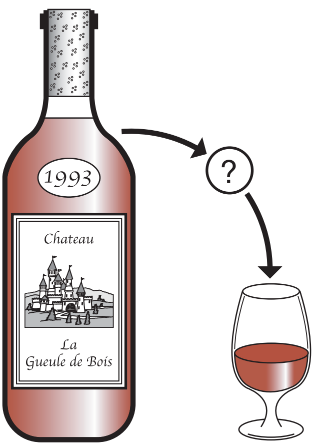


Figure 2.7 The market need: a device is sought to allow access to wine contained in a corked bottle.

[2] Horace, Q. 27 BC, *Odes*, Book III, Ode 8, line 10.

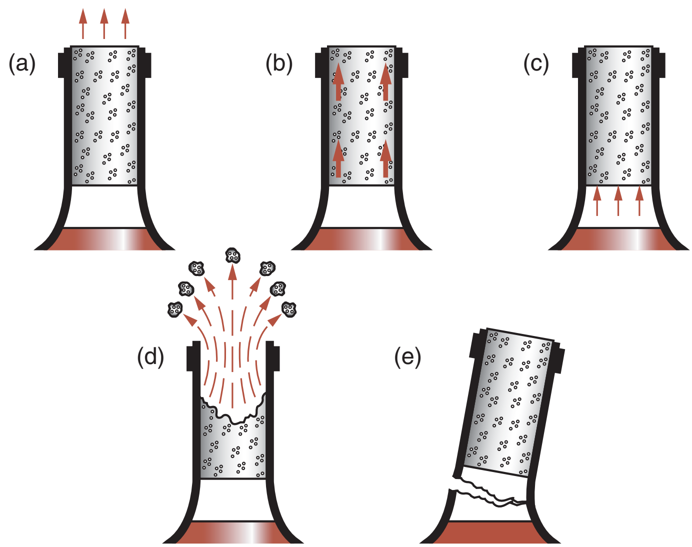


Figure 2.8 Five possible concepts, illustrating physical principles, to fill the need expressed by Figure 2.7.

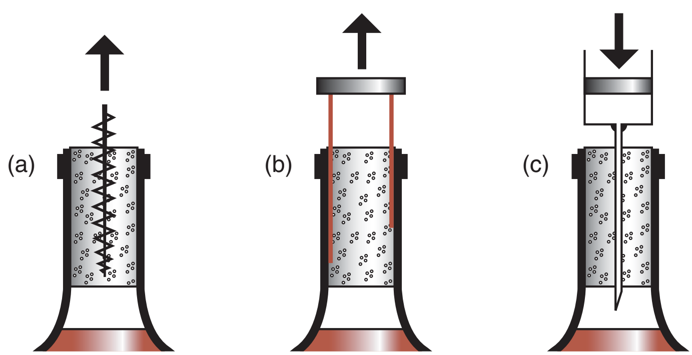


Figure 2.9 Working principles for implementing the first three schemes of Figure 2.8.

Five concepts for doing this are shown in Figure 2.8. In order, they are to remove the cork by axial traction (= pulling); to remove it by shear tractions; to push it out from below; to pulverizing it; and to by-pass it altogether — by knocking the neck off the bottle[3] perhaps.

[3] A Victorian invention for opening old port, the cork of which may become brittle with age and alcohol-absorption, involved ring-shaped tongs. The tongs were heated red on an open fire, then clamped onto the cold neck of the bottle. The thermal shock removed the neck cleanly and neatly.

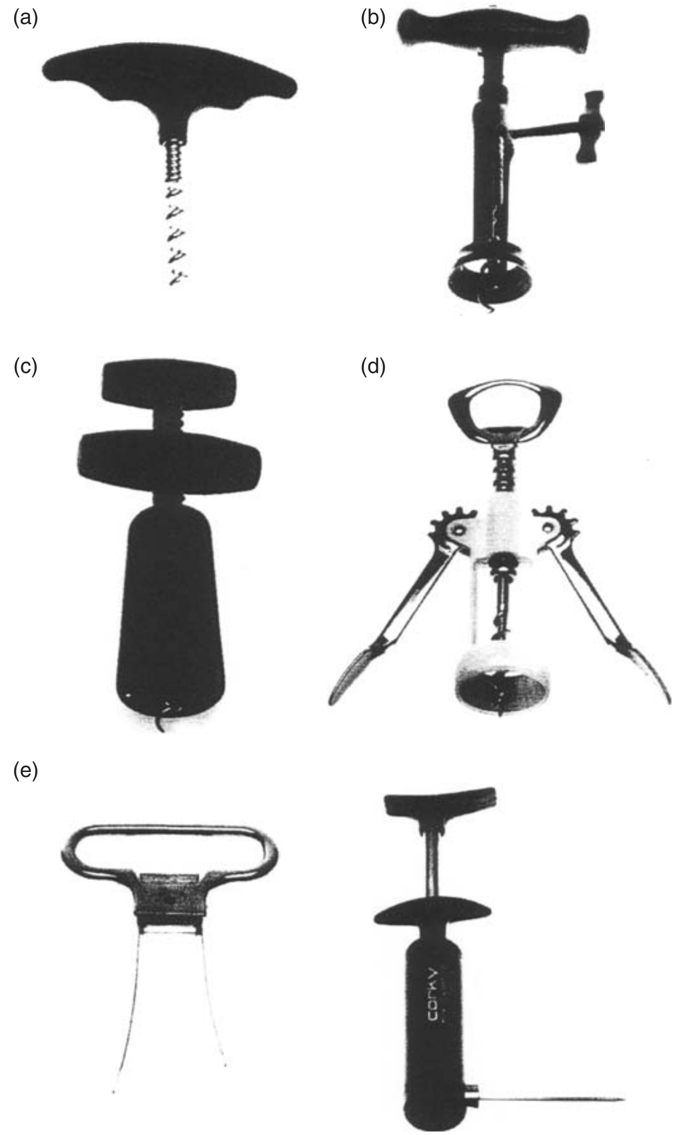


Figure 2.10 Cork removers that employ the working principles of Figure 2.9: (a) direct pull; (b) gear lever, screw-assisted pull; (c) spring-assisted pull (a spring in the body is compressed as the screw is driven into the cork; (d) shear blade systems; (e) pressure-induced removal systems.

Numerous devices exist to achieve the first three of these. The others are used too, though generally only in moments of desperation. We shall eliminate these on the grounds that they might contaminate the wine, and examine the others more closely, exploring working principles. Figure 2.9 shows one for each of

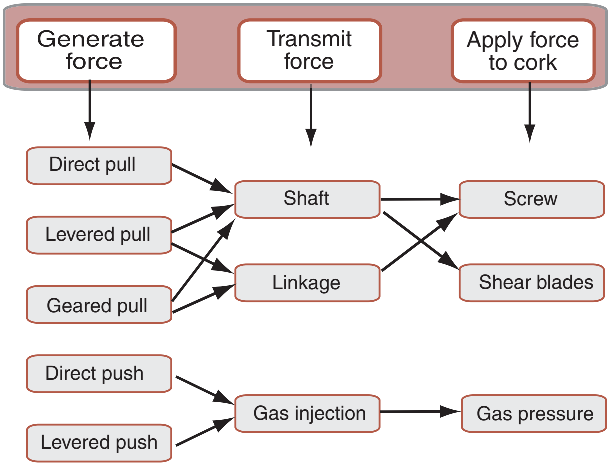


Figure 2.11 The function structure and working principles of cork removers.

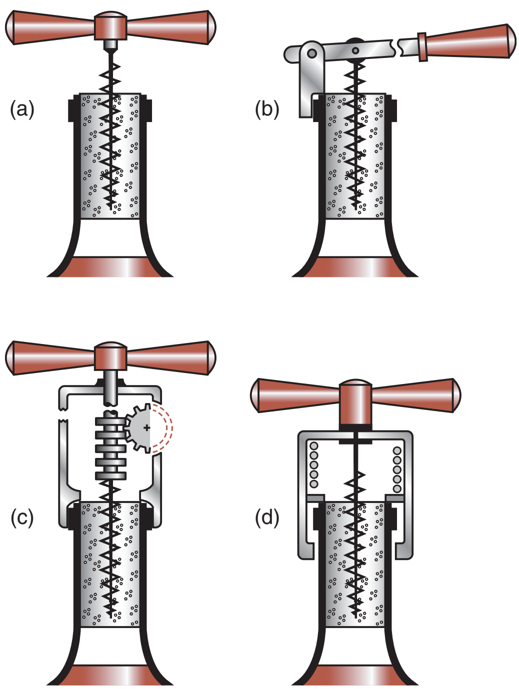


Figure 2.12 Embodiment sketches for four concepts: direct pull, levered pull, geared pull and spring-assisted pull. Each system is made up of components that perform a sub-function. The requirements of these sub-functions are the inputs to the materials selection method.

the first three concepts: in the first, a screw is threaded into the cork to which an axial pull is applied; in the second, slender elastic blades inserted down the sides of the cork apply shear tractions when pulled; and in the third the cork is pierced by a hollow needle through which a gas is pumped to push it out.

Figure 2.10 shows examples of cork removers using these working principles. All are described by the function-structure sketched in the upper part of Figure 2.11: create a force, transmit a force, apply force to cork. They differ in the working principle by which these functions are achieved, as indicated in the lower part of the figure. The cork removers in the photos combine working principles in the ways shown by the linking lines. Others could be devised by making other links.

Figure 2.12 shows embodiment sketches for devices based on just one concept — that of axial traction. The first is a direct pull; the other three use some sort of mechanical advantage — levered-pull, geared pull and spring-assisted pull; the photos show examples of all of these.

The embodiments of Figure 2.9 identify the *functional requirements* of each component of the device, which might be expressed in statements like:

- a cheap screw to transmit a prescribed load to the cork;
- a light lever (i.e. a beam) to carry a prescribed bending moment;
- a slender elastic blade that will not buckle when driven between the cork and bottle-neck;
- a thin, hollow needle, stiff and strong enough to penetrate a cork;

and so on. The functional requirements of each component are the inputs to the materials selection process. They lead directly to the *property limits* and *material indices* of Chapter 5: they are the first step in optimizing the choice of material to fill a given requirement. The procedure developed there takes requirements such as “light strong beam” or “slender elastic blade” and uses them to identify a subset of materials that will perform this function particularly well. That is what is meant by *design-led materials selection*.

2.7 Summary and conclusions

Design is an iterative process. The starting point is a market need captured in a set of design requirements. Concepts for a products that meet the need are devised. If initial estimates and exploration of alternatives suggest that the concept is viable, the design proceeds to the embodiment stage: working principles are selected, size and layout are decided, and initial estimates of performance and cost are made. If the outcome is successful, the designer proceeds to the detailed design stage: optimization of performance, full analysis of critical components, preparation of detailed production drawings (usually as a CAD file), specification of tolerance, precision, joining and finishing methods, and so forth.

Materials selection enters at each stage, but at different levels of breadth and precision. At the conceptual stage all materials and processes are potential candidates, requiring a procedure that allows rapid access to data for a wide range of each, though without the need for great precision. The preliminary selection passes to the embodiment stage, the calculations and optimizations of which require information at a higher level of precision and detail. They eliminate all but a small short-list candidate-materials and processes for the final, detailed stage of the design. For these few, data of the highest quality are necessary.

Data exist at all these levels. Each level requires its own data-management scheme, described in the following chapters. The management is the skill: it must be design-led, yet must recognize the richness of choice and embrace the complex interaction between the material, its shape, the process by which it is given that shape, and the function it is required to perform. And it must allow rapid iteration — back-looping when a particular chain of reasoning proves to be unprofitable. Tools now exist to help with all of this. We will meet one — the CES materials and process selection platform—later in this book.

But given this complexity, why not opt for the safe bet: stick to what you (or others) used before? Many have chosen that option. Few are still in business.

2.8 Further reading

A chasm exists between books on design methodology and those on materials selection: each largely ignores the other. The book by French is remarkable for its insights, but the word 'material' does not appear in its index. Pahl and Beitz has near-biblical standing in the design camp, but is heavy going. Ullman and Cross take a more relaxed approach and are easier to digest. The books by Budinski and Budinski, by Charles, Crane and Furness and by Farag present the materials case well, but are less good on design. Lewis illustrates material selection through case studies, but does not develop a systematic procedure. The best compromise, perhaps, is Dieter.

General texts on design methodology

Cross, N. (2000) *Engineering Design Methods*, 3rd edition, Wiley, Chichester, UK. ISBN 0-471-87250-4. *(A durable text describing the design process, with emphasis on developing and evaluating alternative solutions.)*

French, M.J. (1985) *Conceptual Design for Engineers*, The Design Council, London, UK, and Springer, Berlin, Germany. ISBN 0-85072-155-5 and 3-540-15175-3. *(The origin of the "Concept — Embodiment — Detail" block diagram of the design process. The book focuses on the concept stage, demonstrating how simple physical principles guide the development of solutions to design problems.)*

Pahl, G. and Beitz, W. (1997) *Engineering Design*, 2nd edition, translated by K. Wallace and L. Blessing, The Design Council, London, UK and Springer-Verlag, Berlin, Germany. ISBN 0-85072-124-5 and 3-540-13601-0. *(The Bible — or perhaps more exactly the Old Testament — of the technical design field, developing formal methods in the rigorous German tradition.)*

Ullman, D.G. (1992) *The Mechanical Design Process*, McGraw-Hill, New York, USA. ISBN 0-07-065739-4. *(An American view of design, developing ways in which an initially ill-defined problem is tackled in a series of steps, much in the way suggested by Figure 2.1 of the present text.)*

Ulrich, K.T. and Eppinger, S.D. (1995) *Product Design and Development*, McGraw-Hill, New York, USA. ISBN 0-07-065811-0. *(A readable, comprehensible text on product design, as taught at MIT. Many helpful examples but almost no mention of materials.)*

General texts on materials selection in design

Budinski, K.G. and Budinski, M.K. (1999) *Engineering Materials, Properties and Selection* 6th edition, Prentice-Hall, Englewood Cliffs, NJ, USA. ISBN 0-13-904715-8. *(A well-established materials text that deals well with both material properties and processes.)*

Charles, J.A., Crane, F.A.A. and Furness, J.A.G. (1997) *Selection and Use of Engineering Materials*, 3rd edition, Butterworth-Heinemann Oxford, UK. ISBN 0-7506-3277-1. *(A materials-science, rather than a design-led, approach to the selection of materials.)*

Dieter, G.E. (1991) *Engineering Design, a Materials and Processing Approach*, 2nd edition, McGraw-Hill, New York, USA. ISBN 0-07-100829-2. *(A well-balanced and respected text focusing on the place of materials and processing in technical design.)*

Farag, M.M. (1989) *Selection of Materials and Manufacturing Processes for Engineering Design*, Prentice-Hall, Englewood Cliffs, NJ, USA. ISBN 0-13-575192-6. *(Like Charles, Crane and Furness, this is Materials-Science approach to the selection of materials.)*

Lewis, G. (1990) *Selection of Engineering Materials*, Prentice-Hall, Englewood Cliffs, N.J., USA. ISBN 0-13-802190-2. *(A text on materials selection for technical design, based largely on case studies.)*

And on corks and corkscrews

McKearin, H. (1973) “On ‘stopping’, bottling and binning”, *International Bottler and Packer*, April issue, pp 47–54.

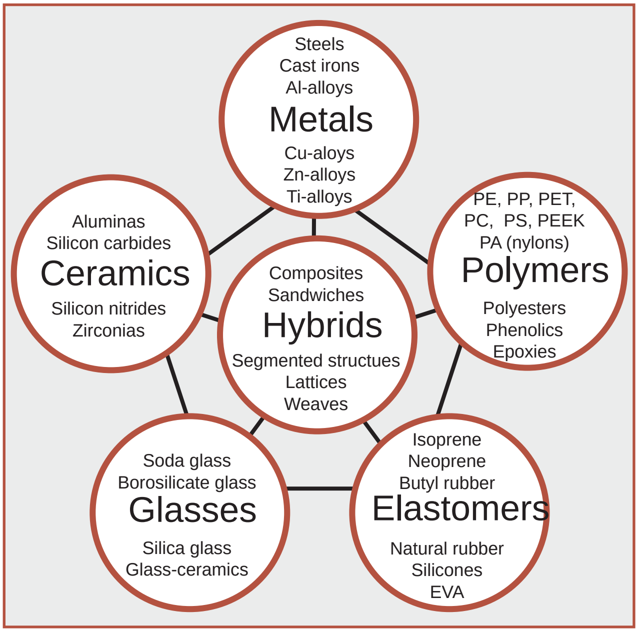
Perry, E. (1980) *Corkscrews and Bottle Openers*, Shire Publications Ltd, Aylesbury, UK.

The Design Council (1994) Teaching aids program EDTAP DE9, The Design Council, 28 Haymarket, London SW1Y 4SU, UK.

Watney, B.M. and Babbige, H.D. (1981) *Corkscrews*. Sotheby’s Publications, London, UK.

Chapter 3

Engineering materials and their properties



Chapter contents

3.1 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 3.2. 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 3.3. 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 3.2 — it sets up the classification structure that is used throughout the book. The chapter ends, in the usual way, with a summary.

3.2 The families of engineering materials

It is helpful to classify the materials of engineering into the six broad families shown in Figure 3.1: 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.

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

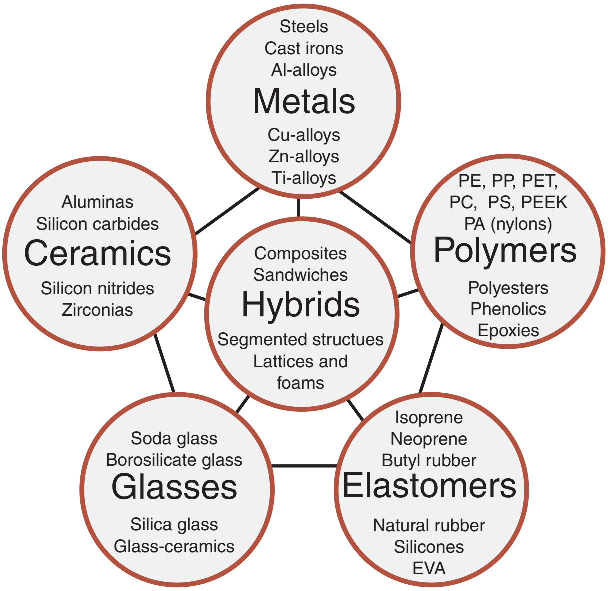


Figure 3.1 The menu of engineering materials. The basic families of metals, ceramics, glasses, polymers, and elastomers can be combined in various geometries to create hybrids.

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 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.

3.3 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 3.1). For

Table 3.1 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.

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 3.5, 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 3.2). 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

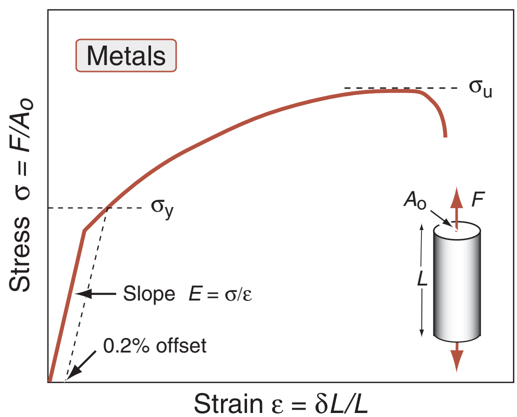


Figure 3.2 The stress–strain curve for a metal, showing the modulus, E, the 0.2 percent yield strength, σ_y, and the ultimate strength, σ_u.

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:

$$E = \frac{3G}{1 + G/3K}; \quad G = \frac{E}{2(1+\nu)}; \quad K = \frac{E}{3(1-2\nu)} \tag{3.1}$$

Commonly $\nu \approx 1/3$ when

$$G \approx \frac{3}{8}E \text{ and } K \approx E \tag{3.2a}$$

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

$$G \approx \frac{1}{3}E \text{ and } K \gg E \tag{3.2b}$$

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 (3.2) 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 3.2), 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 3.3). 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

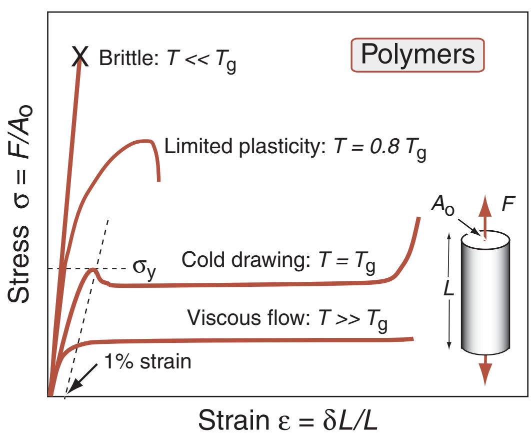


Figure 3.3 Stress–strain curves for a polymer, below, at and above its glass transition temperature, T_g.

are a little stronger (≈20 percent) in compression than in tension. Strength, for ceramics and glasses, depends strongly on the mode of loading (Figure 3.4). In tension, "strength" means the fracture strength, σ_t. In compression it means the crushing strength σ_c, which is much larger; typically

$$\sigma_c = 10 \text{ to } 15\,\sigma_t \tag{3.3}$$

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 3.5).

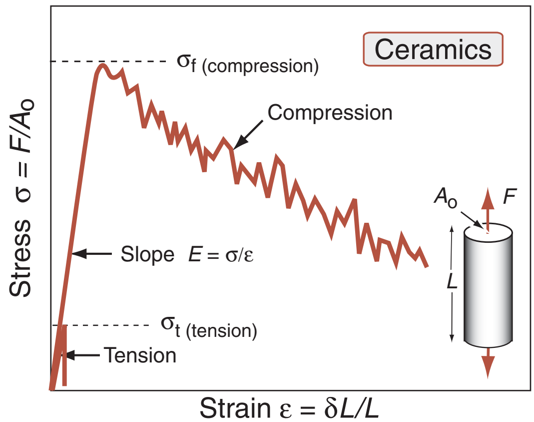


Figure 3.4 Stress–strain curves for a ceramic in tension and in compression. The compressive strength σ_c is 10 to 15 times greater than the tensile strength σ_t.

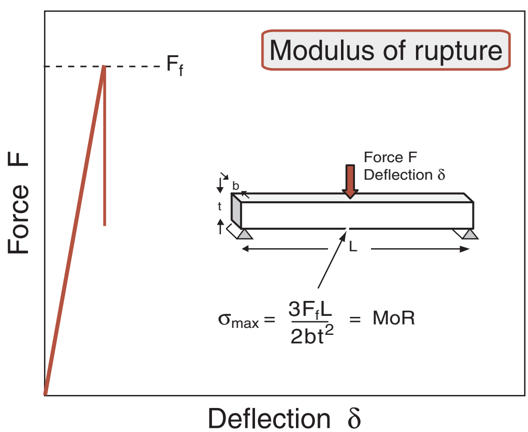


Figure 3.5 The MoR is the surface stress at failure in bending. It is equal to, or slightly larger than the failure stress in tension.

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

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2\sigma_f^{\,2} \tag{3.4}$$

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:

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2\sigma_f^{\,2}\left(1 + \frac{\beta p}{K}\right)^2 \tag{3.5}$$

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:

$$\sigma_1 - B\sigma_2 = C \tag{3.6}$$

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 3.2). 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 3.6. It is the stress amplitude $\Delta\sigma$ 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 3.7). The hardness is defined as the indenter force

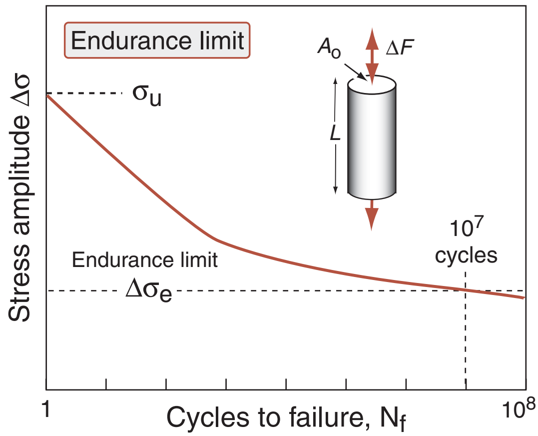


Figure 3.6 The endurance limit, $\Delta\sigma_e$, is the cyclic stress that causes failure in $N_f = 10^7$ cycles.

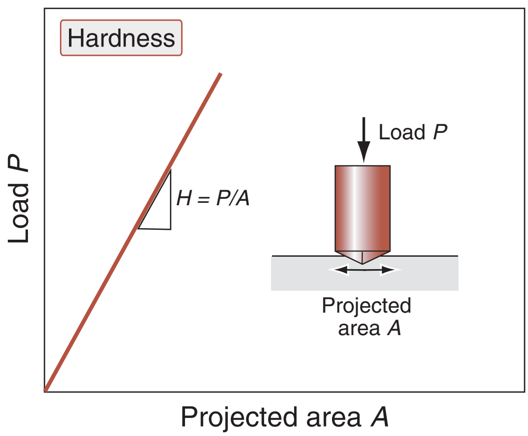


Figure 3.7 Hardness is measured as the load *P* divided by the projected area of contact, A, when a diamond-shaped indenter is forced into the surface.

divided by the projected area of the indent. It is related to the quantity we have defined as σ_f by

$$H \approx 3\sigma_f \tag{3.7}$$

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

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

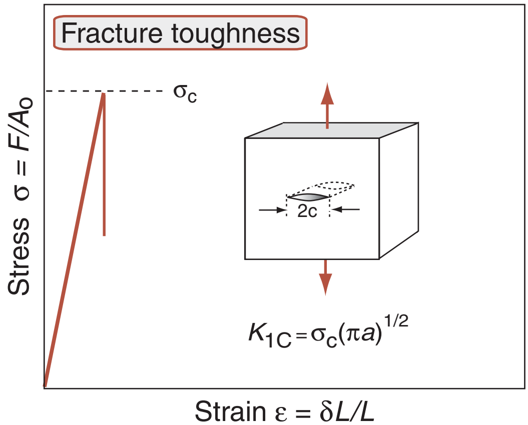


Figure 3.8 The fracture toughness, K_{IC}, measures the resistance to the propagation of a crack. The failure strength of a brittle solid containing a crack of length $2c$ is $K_{IC} = Y(\sigma_c/\sqrt{\pi c})$ where Y is a constant near unity.

The *toughness*, G_{1C}, *(units: kJ/m²), and the fracture toughness,* K_{1C}, *(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 3.8), recording the tensile stress* σ_c *at which the crack propagates. The quantity* K_{1C} *is then calculated from*

$$K_{1C} = Y\sigma_c\sqrt{\pi c} \tag{3.8}$$

and the toughness from

$$G_{1C} = \frac{K_{1C}^2}{E(1+\nu)} \tag{3.9}$$

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 3.9). If a material is loaded elastically to a stress, σ_{max}, it stores an elastic energy

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

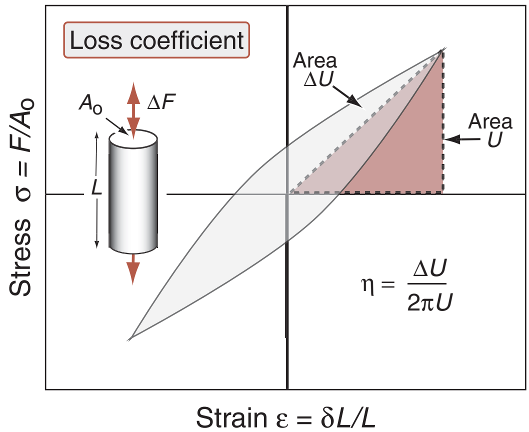


Figure 3.9 The loss coefficient η measures the fractional energy dissipated in a stress–strain cycle.

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

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

The loss coefficient is

$$\eta = \frac{\Delta U}{2\pi U} \tag{3.10}$$

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

$$\eta = \frac{D}{2\pi} = \frac{\Delta}{\pi} = \tan\delta = \frac{1}{Q} \tag{3.11}$$

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