MATERIALS SELECTION

IN

MECHANICAL DESIGN

SECOND EDITION

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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 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

Chapter 1

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.

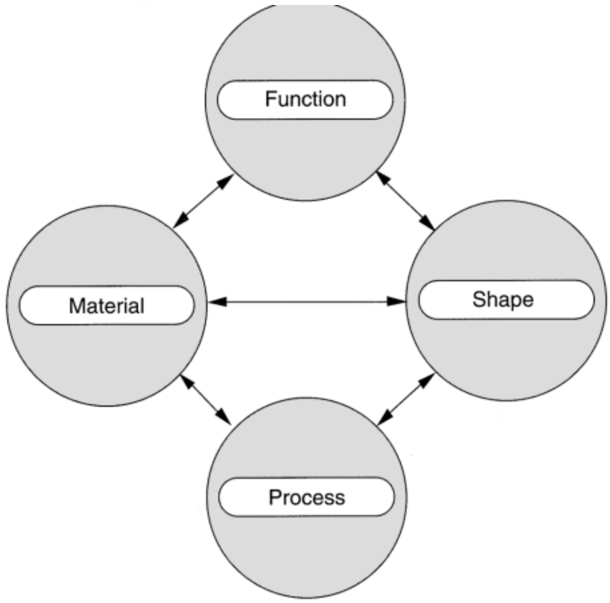


Fig. 1.1 Function, material, process and shape interact. Later chapters deal with each in turn.

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.

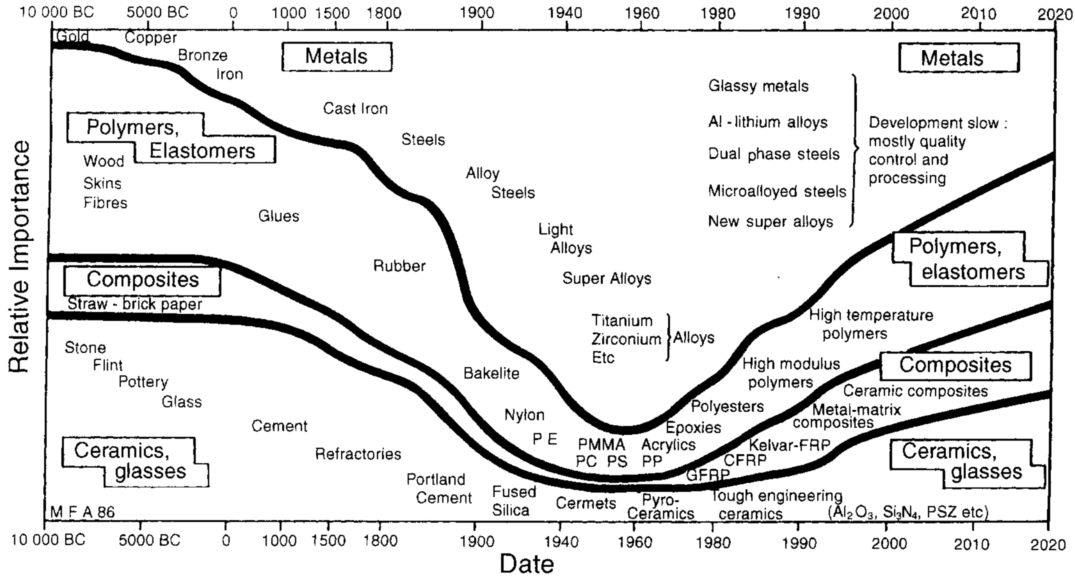


Fig. 1.2 The evolution of engineering materials with time. 'Relative Importance' in the stone and bronze ages is based on assessments of archaeologists; that in 1960 is based on allocated teaching hours in UK and US universities; that in 2020 on predictions of material usage in automobiles by manufacturers.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

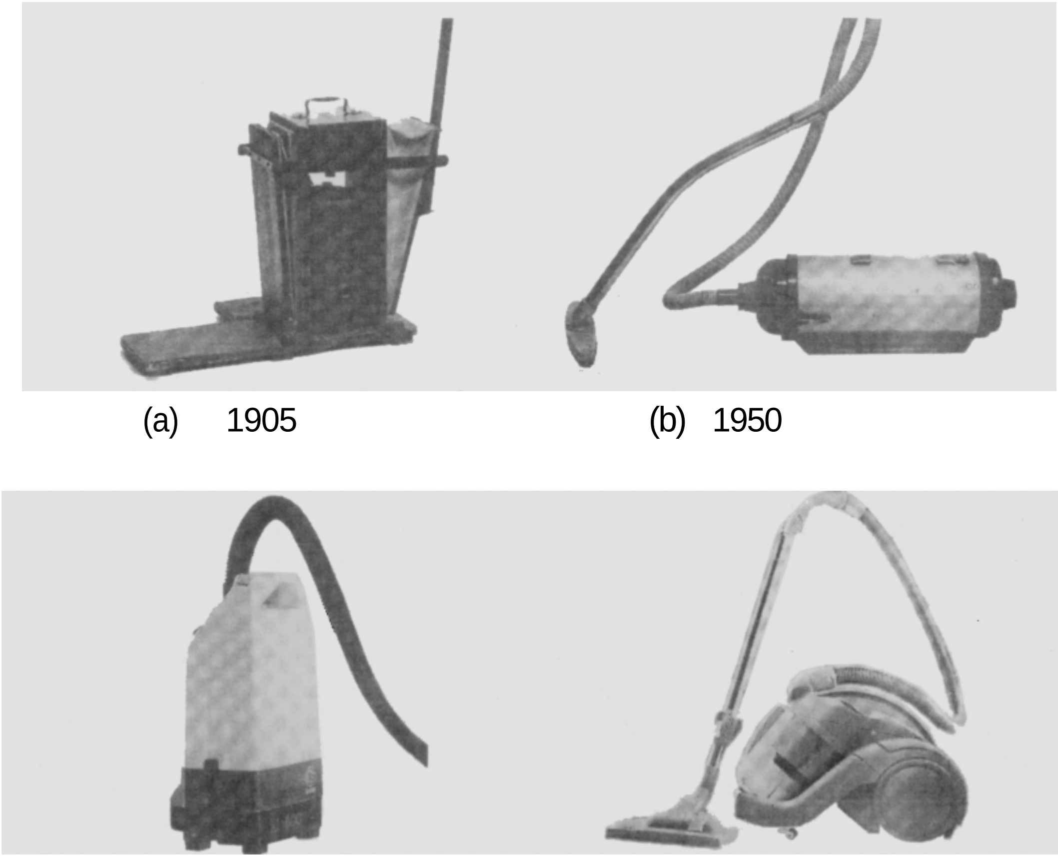
This rapid rate of change offers opportunities which the designer cannot afford to ignore. The following case study is an example. There are more in Chapter 15.

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 Baikeland (Bakelite) and Thomas Crapper (the flush toilet).

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

Cleaner and Date	*Dominant materials*	*Power (W)*	*Weight (kg)*	*Cost**
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.
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Vacuum cleaners

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