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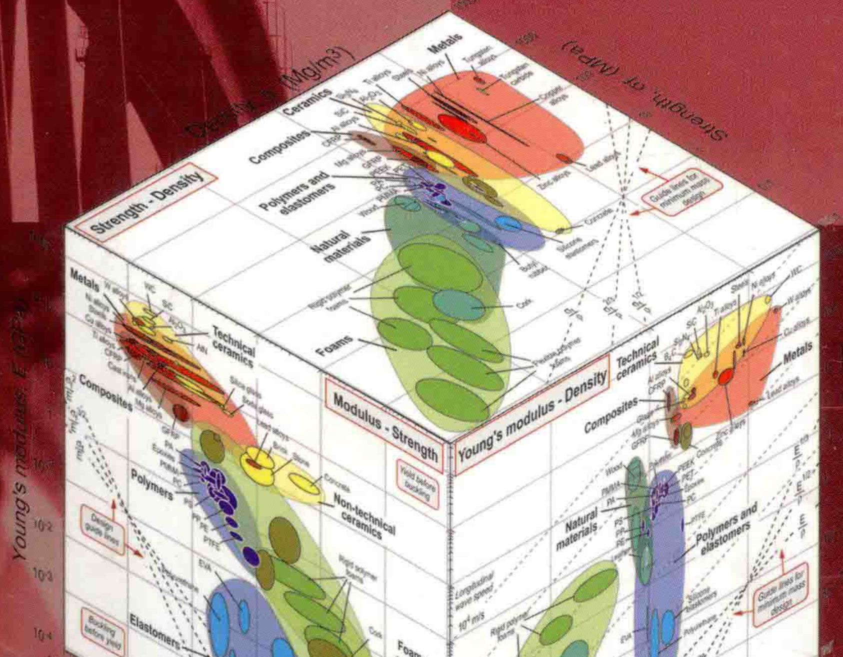
Third edition

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).

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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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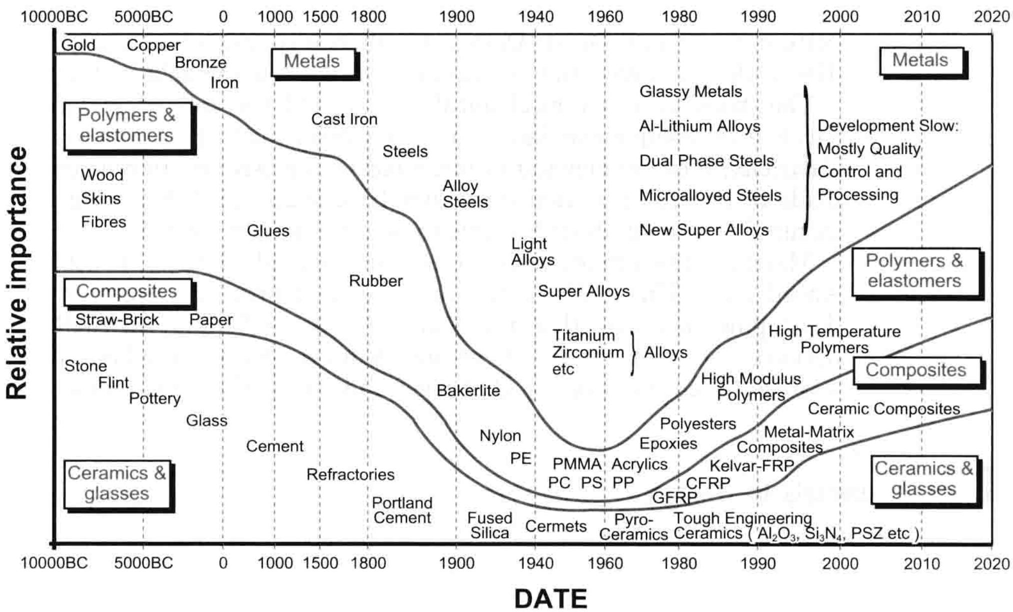
Chapter 1

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).