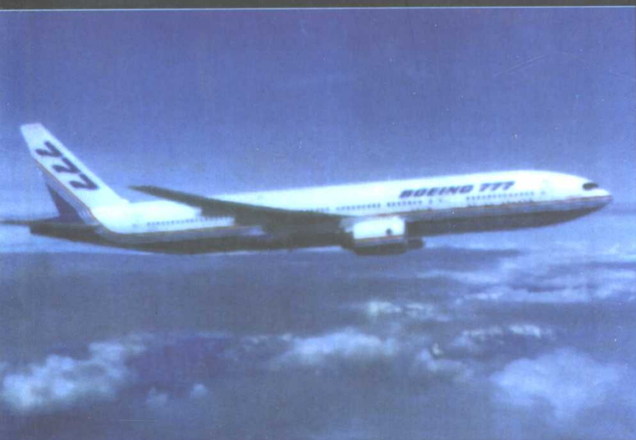
THIRD EDITION

Selection and Use of Engineering Materials



J A CHARLES • F A A CRANE • J A G FURNESS

工程材料的选择和使用

第3版

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Selection and Use of Engineering Materials

Third edition

J. A. Charles ScD, FEng, FIM
University of Cambridge

F. A. A. Crane PhD, CEng, FIM
Late of Imperial College of Science and Technology

J. A. G. Furness MA, PhD
Quo-Tec Ltd

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Preface to the third edition

The continuing success of this book has required reprints of the second edition, and now a third edition. In its preparation great attention has been paid to the invaluable comments made by reviewers and users of the earlier editions. The continuing development of design engineering, the growing importance of plastics, ceramics and composite materials, has required additional text and rewriting in many chapters. Also, since the second edition, there has been a marked growth in the availability of materials databases and in computerized materials selectors. Thus Chapter 14, on the formalization of selection procedures, has been substantially modified to take account of this. Other new features are the explanation of the Weibull modulus in describing the variability of strength to be expected in a material, materials for springs and the influence of hydrogen on the performance of steels and the relevance to sour gas service in the petroleum industry.

As the text has evolved we hope that it will not only be a useful overview of materials usage for students, but suitable also for continuing development in a range of engineering professions. A recommendation was that future editions should provide questions to be undertaken by students. This is easiest to do in a text which is concerned primarily with the aspects of engineering design, giving questions which have a purely mathematical solution. This book is, however, concerned with the understanding of materials usage as well, and many of the questions that could be selected require essay or part-essay answers to reveal that understanding. For this reason, the questions now included, mainly from recent examinations in UK universities, are accompanied by a bibliography of useful texts which should assist response to fully satisfactory answers.

In this regard it is valuable that this book and that by M. F. Ashby, *Materials Selection in Mechanical Design*, come now from the same publisher and could even be regarded as complementary volumes. Ashby's approach is primarily through design considerations, identifying design criteria for different systems and assessing general classes of materials in this respect, whereas the present volume places more emphasis on the details of the materials available and their service.

In preparing this edition, on the recommendation of Mr Rod Wilshaw of the Institute of Materials, J. A. C. has been joined by Dr. J. Furness of Quo-Tec Ltd, and previously the Design Council and the Materials Information Service at the Institute of Materials.

We are most grateful to the various University Departments who gave us permission to reproduce questions from past examination papers. The investigative case studies have again been checked by the manufacturing companies to ensure accuracy in relation to current practice, and we are most grateful to the staff concerned.

February 1997

J. A. Charles
J. A. G. Furness

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Preface to the second edition

Sadly, Dr. F. A. A. Crane died at the end of 1984, only a few months after the publication of the first edition. Thankfully by then, however, it was clear that the book on which he had expended so much effort, in a time when effort cost dear, was going to be successful. He was thus able to know the sense of achievement and satisfaction in having our approach to the subject on record and welcomed, which has to be the main reward for the authors of specialized textbooks.

Thus it has been left to me alone to modify and add to the original text where subsequent comment from colleagues and friends and personal reflection on developments has led me. I can only hope Andy Crane would have approved.

The text has been widely modified in relation to the properties and use of non-metallic materials. Joining has been widened to include a more detailed consideration of the weldability of steels, the welding of plastics and adhesion. The sections on high temperature materials and materials for aircraft structures, the latter to include a consideration of aluminium-lithium and magnesium and its alloys, have been revised.

A completely new chapter on materials for automobile structures is now included, mainly as a method of introducing a consideration of a typical field in which there is growing competition between the traditional use of steel and the increasing application of reinforced polymers.

Since writing the first edition there has been a substantial development of data bases for materials and of associated materials selection programmes. This is reflected in the enlargement of Chapter 14, although this is a fast-moving and complex area in which there is, as yet, little integration or cohesion and only general comments are appropriate in this context. Undoubtedly, however, the use of graphical relationships for selection based on computer data bases, is ideally student-friendly and is a valuable aid to understanding and 'grasp'.

I am very grateful for the help of those who have made suggestions for improvements and up-dating. Although others have helped, in particular I wish to thank Dr. J. Campbell, Dr. B. L. English, Dr. J. E. Restall, Dr. C. A. Stubbington and D. A. Taylor for full comments in specialized areas. The investigative case studies have all been checked against present manufacturing practice and I am grateful to R. M. Airey, D. Carr and B. F. Easton for help in this respect.

Cambridge 1988 J. A. Charles

Preface to the first edition

With international competition in every field intensified by industrial recession, the importance of materials selection as part of the design process continues to grow. The need for clear recognition of the service requirements of a component or structure in order to provide the most technically advanced and economic means of meeting those requirements points to the benefits that can follow from better communication between design engineers on the one hand and materials engineers and scientists on the other, most effectively achieved by the inclusion of materials selection as a subject in engineering courses.

When we were students, the teaching of materials selection involved little more than the recitation of specifications, compositions and properties with little comment as to areas of use. It was, regrettably, a rather boring exercise. Much later, faced with the task of lecturing in the same subject at Imperial College and Cambridge University respectively, we naturally tried to provide a more rational, and lively, understanding of materials selection. Although we were unaware of it, we each independently chose to base our teaching method on case studies – discussing how the selection process has worked out in specific examples of engineering manufacture.

Discovering that there were no introductory texts dealing with the subject in the way that we preferred, we independently, and very slowly, started to write our own. It was a mutual friend, Dr D. R. F. West of Imperial College, who suggested that we should join together in a collaborative effort. We are greatly indebted to him for that – left to ourselves we would almost certainly have found the lone task too daunting for completion. Our colleagues and friends have been very helpful in making useful comments on various parts of the text, notably Drs T. J. Baker, J. P. Chilton, C. Edeleanu, H. M. Flower, D. Harger, I. M. Hutchings, W. T. Norris, G. A. Webster and D. Ll. Thomas.

We must thank our wives too, for their encouragement and understanding and for keeping us company at our working meetings, held not infrequently at a hostelry situated conveniently midway between our homes. A mixed authorship can also create problems for the typist, and we are most grateful to Mrs P. Summerfield for her cheerful acceptance of the task and to Mrs Angela Walker who was also very helpful as the deadline loomed. We are also indebted to Mr B. Barber for assistance with the photographs.

Where a book like this is based on lectures given over many years it is not always easy to recall the original sources of materials or attitudes. We have tried throughout to acknowledge the work of others. Where our memories and records have failed we ask forgiveness.

January 1984

F. A. A. Crane
J. A. Charles

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Selection for Surface Durability

Case studies in materials selection

The background to decision

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1
Introduction

There are two important principles that should apply to materials selection in engineering manufacture:

(1) materials selection should be an integral part of the design process;
(2) materials selection should be numerate.

It is therefore necessary first of all to examine the nature of the design process and the way in which it is carried out.

Then it is necessary to consider how the selection of materials can be made numerate. We choose to do this by defining and describing all of the individually important properties that materials are required to have and then categorizing the useful materials in terms of these properties.

Initially, this can only be done in quite broad terms but as specific applications come to be considered it emerges that the materials engineer must possess a rather deep understanding of the frequently idiosyncratic ways in which basic properties are exhibited by individual materials, and also of the ways in which those properties are influenced by the manufacturing processes to which the material has been subjected prior to entering service.

The properties of materials

It has been estimated that there are more than 100,000 materials available for the designer to choose from and a correspondingly wide range of properties. Although a material may be chosen mainly because it is able to satisfy a predominant requirement for one property above all others, every useful material must possess a *combination* of properties. The desired cluster of properties will not necessarily be wide-ranging and the exact combination required will depend upon the given application. These may be categorized in an elementary way as shown in Table 1.1.

TABLE 1.1

Category	*Typical desirable properties*	*Main applications*
Mechanical	Strength Toughness Stiffness	Machinery Load-bearing structures
Chemical	Oxidation resistance Corrosion resistance UV radiation resistance	Chemical plant Power plant Marine structures Outdoor structures
Physical	Density	Aerospace, outer space Reciprocating and rotating machinery
	Thermal conductivity Electrical conductivity Magnetic properties	Power transmission Instrumentation Electrical machinery Electronics

TABLE 1.2

Plastics	*Metals*	*Ceramics*	*Composites*
Weak Compliant Durable Temperature-sensitive Electrically insulating	Strong Stiff Tough Electrically conducting High thermal conductivity	Strong Brittle Durable Refractory Electrically insulating Low thermal conductivity	Strong Stiff Low density Anisotropic

Certain types of materials can be broadly generalized as characteristically possessing certain combinations of properties (see Table 1.2).

As always, there are important exceptions to these generalizations. Plastics are indeed frequently extremely durable, but some are subject to stress corrosion. Metals are generally tough; indeed the widespread use of metallic materials for engineering purposes is due largely to the fact that they are mostly able to combine strength and toughness. But there is, nevertheless, a general inverse relationship between strength and toughness, and certain steels are vulnerable to catastrophic brittle fracture.

The brief conspectus of property characteristics given in Table 1.3 offers an overall view of the range that is available.

At an early stage in the design process it should become apparent that several different materials are capable of performing a particular function. It is then necessary to choose between them. This requires that the important properties be measured in an unambiguous, rational manner.

This is easy if a property is well-understood in terms of fundamental science, but not all material properties are of this sort. For example, it is essential to be able to measure the weldability of metals but no single parameter can do this because weldability measures the overall response of a material to a particular process and there are many processes. Other examples of the same type are drawability in the case of forming sheet material and injection mouldability of a thermoplastic. Even so, some attempt has to be made to put a number to any differentiating property, since this is the only way of making the selection process properly rational.

Property parameters are therefore of two types:

(1) *Fundamental parameters*. These measure basic properties of materials such as electrical resistivity or stiffness. They generally have the advantage that they can be used directly in design calculations.
(2) *Ranking parameters*. These generally do not measure single fundamental properties and can only be used to rank materials in order of superiority. They cannot be used directly in design calculations, but could be used in formalized selection procedures.

Failure in service

Since one of the aims of manufacture is to ensure that failure does not occur in service, it is necessary to be clear concerning the possible mechanisms of failure. Broadly, in engineering components, failure occurs either mechanically or by some form of corrosive attack.

There are three main ways in which a component can fail mechanically:

(1) Ductile collapse because the material does not have a yield stress high enough to withstand the stresses imposed. The fracture properties of the material are not important here and the failure is usually the result of faulty design or (especially in the case of high-temperature service) inadequate data.

TABLE 1.3

Strong	Alloys of Fe, Ti and the transition metals				Concrete in compression		
Permissible stress MPa	200–1500				70		
Weak	Plastics		Pb	Alloys of Al			Concrete in tension
Permissible stress MPa	~ 100		10	200			1.5
Stiff	SiC	HM Carbon fibre	Fe	Cu	Diamond		C-fibre composite laminate
Young's Modulus GPa	450	400	200	124	1000		200
Flexible	LDPE	Natural rubber	Butyl rubber	Neoprene			
Young's modulus GPa	0.2	0.002	0.001	0.001			
Light	Plastics		Mg	Be	Al	Ti	Concrete
Specific gravity	0.9–2.2		1.74	1.85	2.7	4.5	2.3
Dense	Fe	Ni	Cu	Pb	Ta	W	
Specific gravity	7.8	8.9	8.9	11.3	16.6	19.3	
Refractory	Fe	Ti	Cr	Mo	Ta	W	Ceramics
Melting point °C	1537	1660	1850	2625	3000	3380	
Fusible	Lipowitz's alloy		Pb	Sn	Zn	Al	Plastics, glass
Melting point °C	60		327	232	420	660	
Corrosion-resistant	Au	Ta	Ti	Al	PTFE		
Conductive	Ag	Cu	Al	Ni	Fe		
Electrical resistivity $\mu\Omega$ cm (20°C)	1.4	1.7	2.8	7.2	9.8		
Non-conductive	LDPE	PTFE	MgO	Mullites	Sialon		
Electrical resistivity $\mu\Omega$.cm (20°C)	$>10^{15}$	$>10^{18}$	$>10^{14}$	$>10^{13}$	$>10^{12}$		
Cheap	Fe	Concrete	Plastics	Pb	Zn	Al	
Price/tonne (Fe = 1)	1	0.1	2–80	3	4.5	4	
Price/m^3 (Fe = 1)	1	0.03	0.2–16	4	4.0	1.3	
Expensive	Cu	Ni	Sn	Ti	Be	Diamond	C-fibre composite laminate
Price/tonne (Fe = 1)	12	40	44	94	700	2,000,000	250

(2) Failure by a fatigue mechanism as a result of a component being subject to repeated loading which initiates and propagates a fatigue crack.

(3) Catastrophic or brittle failure, with a crack propagating in an unstable and rapid manner. Any existing flaw, crack or imperfection can propagate if the total energy of the system is decreased, i.e. if the increase in energy to form the two new surfaces and consumed in any plastic work involved is less than the decrease in stored elastic energy caused by the growth of the crack. The significance of ductile yield in blunting cracks and reducing elastic stress concentration is immediately apparent. Beware, then, materials where there is little difference between the yield stress and the maximum stress.

The evaluation of maximum tensile strength does not indicate anything about the way in which the object is going to fail. It is obviously desirable that failure, should it occur, is by deformation rather than by catastrophic disintegration and this has led to the whole concept of fracture toughness testing: it is vital to know in high-strength materials what size of internal defect can be tolerated before instability develops and brittle fracture occurs, a feature determinable by fracture toughness testing which can then be interpreted with non-destructive testing and inspection.

There are too many different corrosion mechanisms for them to be listed in an introductory chapter, and they will be dealt with later. Generalized superficial corrosion is rarely a problem; greater hazards are presented by specialized mechanisms of corrosion damage such as pitting corrosion in chemical plant, stress corrosion in forgings, fuel ash corrosion in gas turbines, and the introduction of embrittling hydrogen as a result of corrosion. (see Chapter 11.2)

Failure records show that the bulk of mechanical failures are due to fatigue mechanisms. Overall, fatigue and corrosion, and especially the combination of the two, are the most significant causes. Aspects of failure analysis are dealt with in Chapter 4.

Cost

The achievement of satisfactory properties in his chosen materials is only part of the materials engineer's task – it is necessary also that they be achieved at acceptable cost. For this reason cost is sometimes incorporated into property parameters to facilitate comparisons. For example, the expression $C_R\rho/\sigma_{YS}$ relates to parts loaded in tension where C_R is price per unit mass, σ_{YS} is yield strength and ρ is density. It gives the cost of unit length of a bar having sufficient area to support unit load. This is a minimum-cost criterion and examples of corresponding criteria for different loading systems are given in Table 1.4. Some of these materials selection criteria are discussed in later chapters. The example given can also be put equal to C_V/σ_{YS} where C_V is the price per unit volume. Timber and concrete are the only materials sold traditionally in terms of volume, all other materials being sold in units of weight, even though, as the expression shows, P_v is the more meaningful parameter.

Space filling

It is remarkable how frequently cost per unit volume is the sole criterion for materials selection. The usage requirements specify the size the object shall be, and the materials employed are chosen on the grounds of minimum cost at that size: the mechanical properties of the material are then irrelevant. Examples range from push-buttons to dams. Sometimes, however, the space-filling requirement is met at reduced weight and cost by making the shape hollow – we are then back to the mechanical property parameter, since the thickness of a hollow shell must be determined from considerations of strength and/or rigidity.

Fabrication route

Where there is a competitive situation, particularly with fairly cheap materials – for example on the basis of cost per unit volume – then fabrication costs can be of great significance in

TABLE 1.4. Performance-maximizing property groups

Component	*Minimize unit cost for given:*		
	Stiffness	*Ductile strength*	*Brittle strength*
Rod in tension	$\frac{E}{C_R\rho}$	$\frac{\sigma_f}{C_R\rho}$	$\frac{K_{1c}}{C_R\rho}$
Short column in compression	$\frac{E}{C_R\rho}$	$\frac{\sigma_f}{C_R\rho}$	$\frac{K_{1c}}{C_R\rho}$
Thin-walled pipe or pressure vessel under internal pressure	$\frac{E}{C_R\rho}$	$\frac{\sigma_f}{C_R\rho}$	$\frac{K_{1c}}{C_R\rho}$
Flywheel for maximum kinetic energy storage at a given speed	$\frac{E}{C_R\rho}$	$\frac{\sigma_f}{C_R\rho}$	$\frac{K_{1c}}{C_R\rho}$
Sphere under internal pressure	$\frac{E}{C_R(1-v)\rho}$	$\frac{\sigma_f}{C_R\rho}$	$\frac{K_{1c}}{C_R\rho}$
Rod or tube in bending	$\frac{E^{1/2}}{C_R\rho}$	$\frac{\sigma_f^{2/3}}{C_R\rho}$	$\frac{K_{1c}^{2/3}}{C_R\rho}$
Plate in bending	$\frac{E^{1/3}}{C_R\rho}$	$\frac{\sigma_f^{1/2}}{C_R\rho}$	$\frac{K_{1c}^{1/2}}{C_R\rho}$
Plate in buckling	$\frac{E^{1/2}}{C_R\rho}$		
Slender column or tube in buckling	$\frac{E^{1/2}}{C_R\rho}$		
Bar or tube in torsion	$\frac{G^{1/2}}{C_R\rho}$	$\frac{\sigma_f^{2/3}}{C_R\rho}$	$\frac{K_{1c}^{2/3}}{C_R\rho}$
Helical spring for specified load and stiffness		$\frac{\tau_m}{C_R\rho}$	
Rod or pin in shear		$\frac{\tau_m}{C_R\rho}$	
Thin-wall shafts in torsion		$\frac{\tau_m}{C_R\rho}$	
Spring for specified load and stiffness		$\frac{\tau_m^2}{C_R G\rho}$	
Long heavy rod in tension		$\frac{(\sigma_f - lg\rho)}{C_R\rho}$	

Table used with permission from the Fulmer Materials Optimizer

Key:

E	Young's modulus	C_R	Cost per unit mass
σ_f	Yield strength	ρ	Density
K_{1c}	Fracture toughness	l	Length
G	Shear modulus	v	Poisson's ratio
τ_m	Shear yield strength	g	Acceleration due to gravity

determining the final cost in the job. Shape and allowable dimensional tolerances are factors that may play a key role in deciding how, and of what material, a component should be made. The level of tolerances required must be matched up to those that can be obtained readily with the fabrication techniques suited to the material, unless the costs are to escalate. For example, attempts to cast spheroidal graphite cast-iron tuyere nosecaps of awkward design for a blast furnace producing lead or zinc, where the dimensions of the water passages must be uniform to a high degree of accuracy around the nose so as to achieve suitable water flow, will almost certainly result in a high proportion of rejected castings since it is very difficult to position cores with the required accuracy and to be sure that they will not move slightly during casting.

Surface durability

The requirement of surface durability, i.e. resistance to corrosion and surface wear or abrasion is sometimes important enough to determine the final choice, particularly in relation to aggressive chemical attack. More often it is a conditional consideration which indicates the initial range of choice. Further, this range of choice may well include composite structures – i.e. bulk materials coated with a corrosion-resistant or abrasion-resistant surface or chemically treated in such a way that the surface stability is altered.

As an example there is the competition between tool steels and case-hardened or surface heat-treated steel for such components as palls and ratchets, where a cheaper, more easily formed material of lower intrinsic strength is given a hard surface by localized carburizing and a heat treatment. This question is dealt with more fully under 'The Sturmey Archer gear' on p. 316, a component in which surface treatments on steel are widely utilized. Interesting examples also arise in the chemical engineering and food industries, where anti-corrosion linings to plant have frequently to be employed.

Physical properties

There are numerous instances, of course, where materials selection is primarily based on required physical properties. Whilst some instances are quoted in this text, for example in the case of electrical conductors (p. 51) and in components for a high-power gridded tube (p. 320), the thrust of this book is towards structural and mechanical engineering considerations. Within the field of physical properties the development of materials systems for electronic devices, sensor systems, etc. (many of which might be called micro-composites) is a large and rapidly developing area.

Future trends

The pattern of materials usage is constantly changing and the rate of change is increasing. Whereas the succession of Stone, Bronze and Steel Ages can be measured in millennia, the flow of present-day materials development causes changes in decades; there may also be changes in the criteria that determine whether or not a particular material can be put into large-scale use. In the past these criteria have been simply the availability of the basic raw materials and the technological skills of the chemist, metallurgist and engineer in converting them into useful artefacts at acceptable cost, leading to the present situation in which the most important materials in terms of market size are still steel, concrete and timber but supplemented by a constantly increasing range of others. These include metals (copper, aluminium, zinc, magnesium and titanium); plastics (thermoplastics and thermosets); ceramics; and composites (based on plastics, metals and ceramics).

However, two additional criteria may assume increasing importance in the future, arising out of the concept 'Spaceship Earth' (meaning the limited resources of the planet on which we live): these are the total energy cost of a given material and the ease with which it may be recycled. Concrete is a low-energy material but cannot be recycled: in contrast, titanium is a high-energy material which is difficult and expensive to

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