**Republic of Iraq Ministry of
Higher Education and
Scientific Research University
of Babylon College of
Engineering/Al-Musaysb**

The Selection of the Optimum Materials for Some Engineering Applications Based On the ASHBY Selection Technique

A graduation project

Submitted to the College of Engineering/Al- Muasyab / Automobile Engineering Department in Partial Fulfillment of Requirements for the Degree of Bachelor of Science in Automobile Engineering

By

Ahmed Aabbas Faker

Tabark Ghalib Ali

Supervised by

Asst. LEC. Ahmed A. Toman

Babylon _ Iraq

1443 هجري　　　　**2022 _ م**

وَيَرَى الَّذِينَ أُوتُوا الْعِلْمَ الَّذِي أُنْزِلَ إِلَيْكَ مِنْ رَبِّكَ هُوَ الْحَقَّ
وَيَهْدِي إِلَى صِرَاطِ الْعَزِيزِ الْحَمِيد

سورة سبأ، آية: 6

إِنَّمَا يَخْشَى اللَّهَ مِنْ عِبَادِهِ الْعُلَمَاءُ إِنَّ اللَّهَ عَزِيزٌ غَفُورٌ

سورة فاطر، آية: 28 " ".

DEDICATION

We dedicate this work to our dear parents who instilled in me from a young age, the love of science and knowledge...our God prolong their life.

To all of our brothers and friends and those who supported us in carrying the burden of this work.

To all of them, we dedicate my work.

ACKNOWLEDGMENTS

First and foremost, we would like to thank the supervisor of our project Dr. Ahmed Toman for his support, outstanding guidance, and encouragement throughout our work on the project.

We would also like to express our gratitude and appreciation to the Academic family of Automobile Engineering, College of Engineering /Al-Muasyab.

ABSTRACT

Material selection is a step in the process of designing any physical object. In the context of product design, the main goal of material selection is to minimize cost while meeting product performance.

As well as selecting the most appropriate material, it is important to consider the chain of custody of the material and the environmental credentials of the product supplier. One of the most common ways to innovate is through material selection. The materials you choose affect everything from functionality to usability and even consumer satisfaction. Material selection plays such an important role in that process.

In the past, the traditional selection process of an optimum material for an engineering application usually required the cooperation of a team of highly experienced engineers with help of use of extensive material properties tables.

In the recent years, an alternative material selection method, which enables the selection of the optimum materials with much less effort, time, experience and cost, proposed by Michael F. Ashby.

This research introduce the reader to material selection method proposed by Michael F. Ashby. In addition this research discus and illustrate the required charts, steps, techniques, analytical and graphical methods used by the Ashby method.

In addition, in this research, the practical application of the Ashby selection method has been employed to select the optimum materials for seven important engineering applications.

CONTENT LIST

CONTENT **NO. PAGE**

Chapter One - Introduction

Chapter Two

Chapter Three -

Chapter Four - Case studies

Chapter Five - Result and discussion

REFRENCES

List of Figures

NOMENCLATURES

Class	Property	Symbol and Units
General	Density	ρ(kg/m3 or Mg/m3)
		Cm($/kg)
Mechanical	Elastic moduli (Young's, shear, bulk)	$E, G, K(GPa)$
	Yield strength	σ_y(MPa)
	Tensile (ultimate) strength	$\sigma_B(MPa)$
	Compressive strength	σ_c(MPa)
	Failure strength	σ_f(MPa)
	Hordness	H(Vickers)
	Elongation	$\varepsilon(-)$
	Fotigue endurance limit	$a_e(MPa)$
	Fracture toughness	$K_{1c}(\mathrm{MPa}^{m}\ \mathrm{m}^{1/2})$
	Toughness	G_{1k}(k)/m2)
	Loss coefficient (damping capacity	$\eta(-)$
	Wear rate (Archard) constant	KAMPa^{-1}
Thermal	Melting point	T_m(*C or K)

	Glass temperature	T_9(°C or K)
	Maximum service temperature	$T_{\max}$(°C or K)
	Minimum service temperature	$T_{\min}$(°C or K)
	Thermal conductivity	$\lambda(W/m, K)$
	Specific heat	$C_{\varphi}(J/\text{kg}. K)$
	Thermal expansion coefficient	$\alpha(K-1)$
	Thermal shock resistance	$\Delta T_s/$°C or K)
Electrical	**Electrical resistivity**	$\rho_e(\Omega. m$ or $\mu\Omega$cm)
	Dielectric constant	$\varepsilon r(-)$
	Breakdown potential	$V_b(10^6$ V/m)
	Power factor	$P(-)$
Optical	**Refractive index**	$n(-)$
Eco-properties	**Embodied energy**	**Hm(MJ/kg)**
	Carbon footprint	**CO2(kg/kg)**

List of Tables

Chapter one

INTRODUCTION

1.1.1 The history of material:

Material science has shaped the development of civilization since the down of mankind.

i) Better material for tools and weapons has allowed making to speared and conquer
ii) steel and al production impact society today.
iii) periods of time have defined by the predominate material used (Stone age, bronze age, iron age …. Etc.) .
v) the term “silicon age “is sometimes used to refer to modern period of history during the late 20th to early 21th centuries .
iv) the innovation of smelling and casting metals in the bronze age started to change the way the culuters developed and interacted with each other
iiv) today, the evolution of nations consumption by their steel production and nation consumption of it.
ivv) material have the final word on much of the current civilization progress

Examples:

- Without the ceramic material, the space shuttle could return to the earth could not be built
- Lithium made the mode telecommunication’s industry possible

1.1.2.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 reserch 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 research 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 research develops a strategy for confronting the challenges and seizing the opportunities.

1.1.3.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.

In addition, although standardization strives to reduce the number, the continuing appearance of new materials with novel, exploitable, properties expand 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.

Nevertheless, 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.

Moreover, there is the rapid evolution of materials information, already mentioned. There is no question of the value of experience. However, 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. Chapter 1 Introduction 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 reserch 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 1.2 Materials in design 3 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 research. 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.

1.2.1 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 notto-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

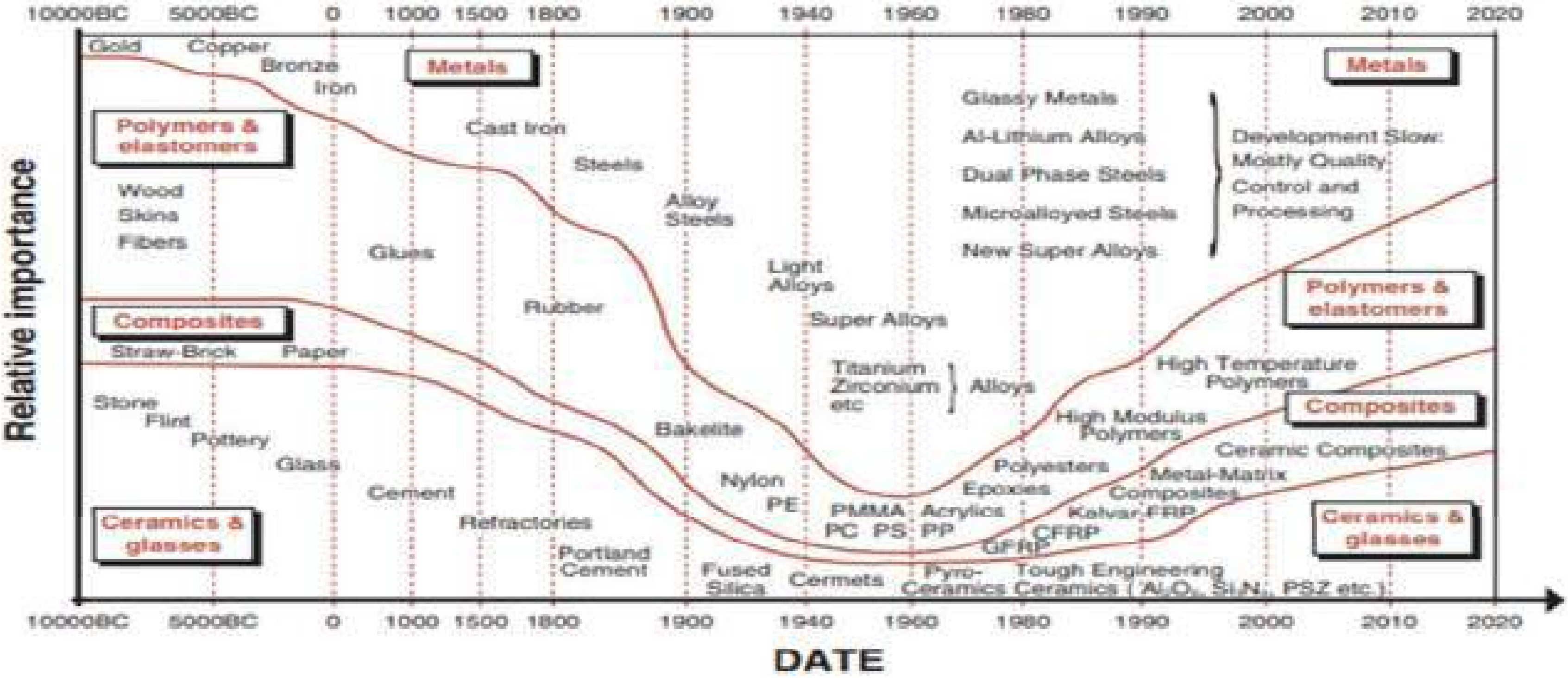


Figure (1.1) The evolution of engineering materials with time. ''Relative importance'' is based on information contained in the books listed under ''Further reading'', plus, from 1960 onwards, data for the teaching hours allocated to each material family in UK and US Universities.

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 10000BC 0 1000 1500 1800 1900 1940 1960 1980 1990 2000 2010 2020 5000BC 10000BC 0 1000 1500 1800 1900 1940 1960 1980 1990 2000 2010 2020 5000BC Gold Copper Bronze Iron Cast Iron Cast Iron Wood Skins Fibers Glues Rubber Straw-Brick Straw-Brick Paper Bakelite Bakelite Stone Flint Pottery Pottery Glass Cement Refractories Refractories Portland Portland Cement Fused Silica PyroCeramics Ceramics Steels Alloy Steels Light Alloys Super Alloys Super Alloys Titanium Titanium Zirconium Zirconium Alloys etc. Nylon PE PMMA Acrylics Acrylics PC PS PP Cermets Cermets Epoxies Epoxies Polyesters Polyesters Tough Engineering Tough Engineering Ceramics (Al Ceramics (Al2O3, Si3N4, PSZ etc.) , PSZ etc.) GFRP CFRP Kevlar-

FRP Kevlar-FRP Composites Composites Metal-Matrix Metal-Matrix Ceramic Composites Ceramic Composites High Modulus High Modulus Polymers Polymers High Temperature High Temperature Polymers Polymers Development Slow: Development Slow: Mostly Quality Mostly Quality Control and Control and Processing Processing Glassy Metals Glassy Metals Al-Lithium Alloys Al-Lithium Alloys Dual Phase Steels Dual Phase Steels Microalloyed Steels Microalloyed Steels New Super Alloys New Super Alloys Gold Copper Bronze Iron Cast Iron Wood Skins Fibers Glues Rubber Straw-Brick Paper Bakelite Stone Flint Pottery Glass Cement Refractories Portland Cement Fused Silica PyroCeramics Steels Alloy Steels Light Alloys Super Alloys Titanium Zirconium Alloys etc. Nylon PE PMMA Acrylics PC PS PP Cermets Epoxies Polyesters Tough Engineering Ceramics (Al2O3, Si3N4, PSZ etc.) GFRP CFRP Kevlar-FRP Composites Metal-Matrix Ceramic Composites High Modulus Polymers High Temperature Polymers Development Slow: Mostly Quality Control and Processing Glassy Metals Al-Lithium Alloys Dual Phase Steels Micro alloyed Steels New Super Alloys DATE Relative importance Polymers & elastomers Polymers & elastomers Composites Composites Ceramics & glasses Ceramics & glasses Metals Metals 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. 1.3 The evolution of engineering materials 5 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.

1.2.2. 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 e 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

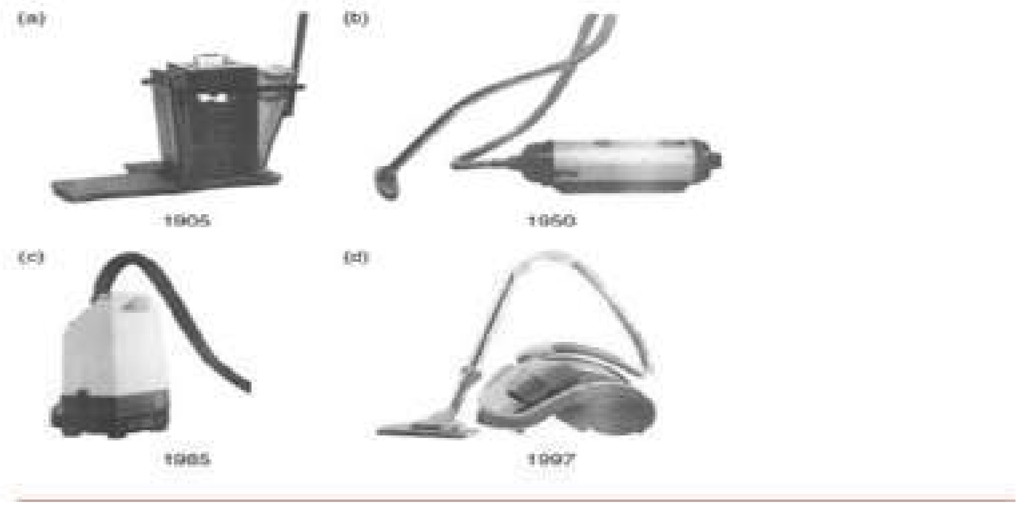


Figure 1.2 Vacuum cleaners: (a) the hand-powered bellows cleaner of 1900, largely made of wood and leather; (b) the cylinder cleaner of 1950; (c) the lightweight cleaner of 1985, almost entirely made of polymer; and (d) a centrifugal dust-extraction cleaner of 1997.

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 (heatresistant 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 — at 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 designestament to good industrial design and imaginative marketing.

1.2.3.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 research is about.

Chapter two

Literature review

Previous Researchers' Works:

From our surfing to the literature, here are some of the main works that their major are in common with this research subjects of analysis:

In 2019 Paolo Ferro *, Franco Bonollo search and found Ashby's proposed method for selecting metallic alloys in a critical raw materials perspective is based on the definition of the alloy criticality index (CIA). This method allows selecting the alloy for the current application that minimizes its criticality associated to CRMs. Additionally, a material index, M*, can be obtained and used as the excellence criterion for materials selection. The process is illustrated with examples and it is observed that the CIA values may change during time and should thus be updated accordingly.

In 2017 M.A. Maleque and S. Dyuti search about materials selection of a bicycle frame using cost per unit property and digital logic methods .The aim of this paper is to develop the material selection method and select the optimum material for the application of folding bicycle frame. The Ashby's material selection chart was used for the initial screening of the candidate materials and the results showed that AISI 1020 steel, Tialloy, carbon fiber reinforced polymer, kevlar fiber reinforced polymer (KFRP) and glass fiber reinforced polymer are the candidate materials. The cost per unit property method showed that KFRP was the least cost material, while the digital logic method showed the highest figure of merit value for KFRP. The proper material selection and design are important before manufacturing the component.

The importance of materials selection in design and manufacturing has increased in recent years. The bicycle frame consists of two triangles, a main triangle and a paired rear triangle. The Ashby's material selection chart was used for the initial screening of the candidate materials. The cost per unit property (CUP) method showed that KFRP material was a better selection followed by AISI 1020 steel material. In the digital logic method, the strength and density were considered twice for determining the performance index and the cost of unit strength. Higher strength and lower density are advantageous for this type of application.

In 2015 Renato Altobelli Antunesa , search about Materials selection for hot stamped automotive body parts: an application of the Ashby approach based on the strain hardening exponent and stacking fault energy of materials The Ashby approach was used to develop a materials selection strategy for hot stamped automotive body parts using the strain hardening exponent (n) and the stacking fault energy (SFE). The strategy was based on the manganese and silicon contents of the high-Mn steels, while increasing aluminum and carbon concentrations had an opposite effect.

In 2012 Mara Cristina Lopes de Oliveiraa, Gerhard Ett a, ate search about Materials selection for bipolar plates for polymer electrolyte membrane fuel cells using the Ashby approach The Ashby approach was used to select materials for bipolar plates for PEM fuel cells, based on the development of a trade-off strategy and analyzing relevant performance attributes. Data was collected from the scientific literature and commercial products to compare graphite–polymer composites and metals due to their mechanical, electrical and corrosion properties. The results showed its suitability as a reliable method to assist the designer of bipolar plates in the complex task of selecting materials that allow for the best overall performance. The selection process was divided into two distinct parts: selection of materials for polymer–graphite composite bipolar plates and for metallic based ones. Despite its simplicity, the Ashby scale proved to be effective, evidencing the weaknesses and strengths of particular options.

The objectives for selecting materials for polymer–graphite composite plates are to maximize both electrical conductivity and flexural strength, while avoiding interfacial contact resistance and corrosion current density. A trade-off strategy is employed to achieve these objectives. The top ranked materials for metallic bipolar plates were those described in Refs. [64,68,72]. Phenolic, epoxy and vinyl ester thermosetting resins and thermoplastic PPS are the most attractive materials, while pack chaotization, nitridation and PVD-based multi-layered films may yield high performance surfaces.

In 1998 Leigh HollowayU ,search about Materials selection for optimal environmental impact in mechanical design by ahby approach Ashby's method of material selection in mechanical design is an important factor in engineering design, as it allows for activities such as minimum weight design, design for minimisation of thermal distortion and minimum cost design. This paper looks at the methods used to calculate both air and water pollution indices and how they can be used to plot charts. The limitations of the charts presented in this paper are discussed in Q 1998 by Elsevier Science Ltd. Ashby's materials and process selection charts are a simple and quick way of assessing whether a material is suitable for the case in hand. They are an important addition to a designers tool kit, as they can be used by designers who need not have extensive knowledge of factors affecting design and the environment.

By developing such methods and approaches now when environmental information becomes readily available, the tools with which to manipulate this data will already be in place. This helps to accelerate the environmental impact assessment of decisions and readily integrate them into existing mechanical design procedures.

In 2010 Prathamesh Surnis1, Dr. Pravin Kulkarni search about Material Selection for Spur Gear Design Using Ashby Chart Ashby's Chart is an efficient and advanced technique of material selection used in this study. It was formulated by Michael F. Ashby and outlines the material properties such as Strength, Density, Young's Modulus, etc. The basic Objective was set to Minimize the mass and Maximize the Strength. The Lewis Equation was used to determine the Bending Strength and to calculate the Material Index. After implementing this technique, a significant accuracy was found.

The Ashby Charts have proven to be of great use for Optimizing the Structural element and thus increasing its performance. For instance, new generation materials such as titanium alloys or beryllium alloys provided approximately 36% to 63% weight reduction compared to conventional gear materials. The charts summarize material properties in a compact, easily accessible way. This study used the Ashby method to investigate lightweight, high strength materials for spur gear design. Material index values of the materials based on the bending fatigue strength were determined and ranked.

In 2011 Kurmendra1 , Rajesh Kumar search about Dielectric Material Selection for High Capacitance Ratio and Low Loss in MEMS Capacitive Switch using Ashby’s Methodology The performance of a RF MEMS capacitive switch is determined by capacitance ratio and loss in the dielectric layer. This article presents a method to find out the best dielectric material using Ashby's methodology. Material indices such as dielectric constant, resistivity, conductivity, and loss tangent are used to get a material that improves performance in the switch. Si3N4, Al2O3, ZnO, and AlN are the good choices for the switch, as they offer good isolation and improve reliability. A trade off is needed between performance and reliability when selecting a material for MEMS switches.

In 2020 Ribu Mathew1 • A. Ravi Sankar search about Temperature drift-aware material selection of composite piezoresistive micro-cantilevers using Ashby’s methodology Ashby's methodology is used to devise an approach for material selection of constituent layers of a composite piezoresistive cantilever sensor. Material selection is performed by identifying the performance metrics that govern the sensor performance and incorporating the interplay between the material constants and geometrical parameters. The coupled effects of electro-mechanical parameters and joule heating induced self-heating effects are also incorporated into the material selection process. Results show that a silicon cantilemer with a doped p-type Piezoresistor, a silicon dioxide isolation layer and a gold immobilization layer is relatively better considering performance characteristics and reliability than an SU-8 polymeric and other solid-state semiconductor based piezorell surface stress sensors. This paper explains how material selection is done using Ashby's method of material selection.

Ashby's method is used to identify and resolve performance metrics that govern the thermo-electro-mechanical response of a sensor. Materials for constituent layers of cantilever sensors are chosen from the literature, such as metals, polymers and solid-state semiconductors. It is found that p-SCS and silicon are the most suitable materials combination to realize the piezoresistor element and structural layer respectively. Additionally, silicon dioxide is the apt choice for isolation layer, while gold metal suites better as the immobilization surface. Computations using analytical models show that silicon cantilevers with doped p.-SCS piezo resistor give the highest sensitivity ratio. This method is useful for chemical and biological sensing applications.

In 2020 Zahid Mehmooda, b , Ibraheem Haneefa search about MATERIAL SELECTION FOR MICRO-ELECTRO-MECHANICAL-SYSTEMS (MEMS) USING ASHBY'S APPROACH This paper presents a comprehensive review and critical analysis of MEMS material selection studies using Ashby's approach. Performance and Material Indices derived for various microsystems and MEMS devices have been summarized, all MEMS materials reported in the literature and the most suitable materials proposed for a variety of MEMS systems and devices have been consolidated, and a material selection case study has been presented to demonstrate that the use of different materials' bulk properties is not the best choice for MEMS materials selection. This paper highlights the unique strengths and limitations of Ashby's materials selection methodology when applied to selecting the best suited materials for MEMS. To address this limitation, a comprehensive database containing micro-scale properties of MEMS materials has been developed. A case study on the selection of materials for conflicting performance requirements of MEMS pressure sensors showed that certain MEMS material (e.g. SiN and Si (110)) were incorrectly assessed and misplaced on the materials selection charts. This work allows Ashby's material selection methodology to be fully exploited for MEMS design by using the MEMS-compatible materials' properties and Performance Indices and Material Indices for different categories of microsystems / MEMS devices.

In 2011 A. Rashedi a , I. Sridhar a, ate search about Multi-objective material selection for wind turbine blade and tower: Ashby’s approach This article explores wind turbine blade and tower material selection strategies based on multiple constraints and conflicting objectives. It highlights the importance of structural rigidity, cost effectiveness, life cycle impact, and reduced mass for small and large scale horizontal axis wind turbines. It also distinguishes advanced blade and tower materials in agreement with multiple constraint, compound objective based design optimization procedure. The final onshore wind turbine blade material stands as PEEK/IM carbon and epoxy/HS carbon fiber, while hybrid natural materials like oak (quercus spp.), lignumvitae (l) are not suitable for offshore blade appli cations. The study found that BS 900/2 grade cast iron alloys provide superior yield, pressive and fatigue strength, while epoxy/HS carbon composite provides more weight savings, but at a higher cost.

To achieve a competitive edge in blade and tower categories, a better synergy in its multi-directional property and laminate sequence is necessary. Limitations of the study lay in variation of material properties and mate rial cost.

In 2012 Darshil U. Shah search about . Natural fibre composites: Comprehensive Ashby-type materials selection charts. This article provides comprehensive Ashby-type materials selection charts for plant fibre reinforced plastics (PFRPs) to facilitate product design and development. General tensile mechanical property profiles are presented for a variety of PFRPs to enable the design for optimal stiffness and strength, minimal weight, minimal cost, and minimal eco-impact. A materials property chart for a fatigue-limited design is also produced. Ashby-type materials selection charts for PFRPs have been produced to facilitate product design and development. The general tensile mechanical property profiles will enable the design for optimal stiffness and strength, minimal weight, minimal cost, and minimal eco-impact. Additionally, a materials property chart for a fatigue limited design and similar charts for impact critical structures and flexural- or compressive-stress dominated structures would be useful for demonstrative purposes.

Chapter Three

THEORY OF ASHBY METHODE

3.1. Engineering materials and their properties

3.1.1. 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. However, 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.

3.1.2. 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 ductility's 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.

In addition, 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

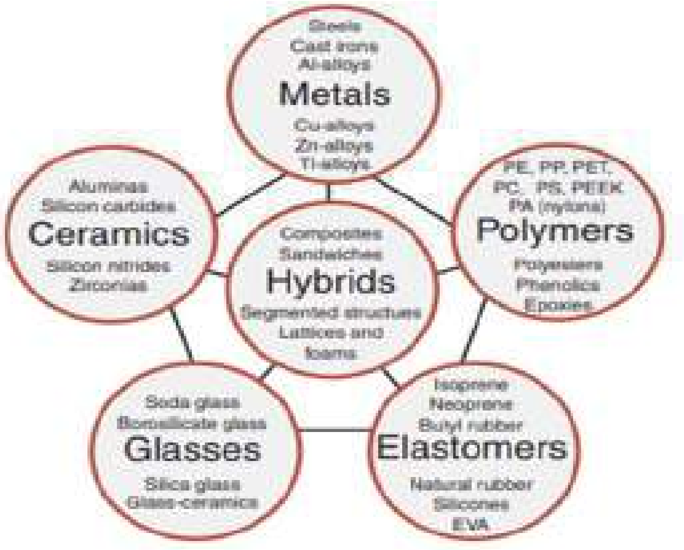


Figure 3.1 The menu of engineering materials. The basic families of metals, ceramics, glasses, polymers, and elastomers can be combined in various geometries to create hybrids.

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 bore-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 strongnearly 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 20C may be brittle at the 4C of a household refrigerator, yet creep rapidly at the 100C of boiling water. Few have useful strength above 200C. 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, Tg. The covalent bonds that link the units of the polymer chain remain intact, but the weaker Van der Waals and hydrogen bonds that, below Tg, bind the chains to each other, have melted. This gives elastomers unique property profiles: Young's moduli as low as 103GPa (105 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 reserch), 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. Moreover, 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

250C 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.

3.2. 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/m3 or Mg/m3)
		Cm($/kg)
Mechanical	**Elastic moduli (Young's, shear, bulk)**	$E, G, K(GPa)$
	Yield strength	σ_y(MPa)
	Tensile (ultimate) strength	$\sigma_B(MPa)$
	Compressive strength	σ_c(MPa)

	Failure strength	σ_f(MPa)
	Hordness	**H(Vickers)**
	Elongation	$\varepsilon(-)$
	Fotigue endurance limit	$a_e(MPa)$
	Fracture toughness	$K_{1c}\left(\mathrm{MPa}^m\ \mathrm{m}^{1/2}\right)$
	Toughness	$G_{1k}(\mathrm{k})/\mathrm{m2})$
	Loss coefficient (damping capacity	$\eta(-)$
	Wear rate (Archard) constant	KAMPa^{-1}
Thermal	**Melting point**	$T_m(\ ^*\mathrm{C}$ or K)
	Glass temperature	$T_9(\ ^\circ\mathrm{C}$ or K)
	Maximum service temperature	$T_{\max}(\ ^\circ\mathrm{C}$ or $K)$
	Minimum service temperature	$T_{\min}(\ ^\circ\mathrm{C}$ or $K)$
	Thermal conductivity	$\lambda(W/m, K)$
	Specific heat	$C_\varphi(J/\mathrm{kg}.K)$
	Thermal expansion coefficient	$\alpha(K-1)$
	Thermal shock resistance	$\Delta T_s/^\circ\mathrm{C}$ or K)
Electrical	**Electrical resistivity**	$\rho_e(\Omega.m$ or $\mu\Omega\mathrm{cm})$
	Dielectric constant	$\varepsilon r(-)$

	Breakdown potential	$V_b(10^6\ \mathrm{V/m})$
	Power factor	$P(-)$
Optical	**Refractive index**	$n(-)$
Eco-properties	**Embodied energy**	$\mathrm{Hm(MJ/kg)}$
	Carbon footprint	$\mathrm{CO2(\ kg/kg)}$

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.

3.2.1. General properties

The density (units: kg/m3) 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, Cm (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.

3.2.2. Mechanical properties

The elastic modulus (units: GPa or GN/m2) 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, , is dimensionless: it is the negative of the ratio of the lateral strain, E2, to the axial strain, E1, in axial loading: "2 "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

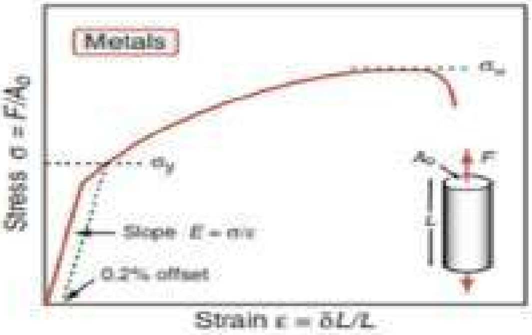


Figure 3.2 The stress–strain curve for a metal, showing the modulus, E, the 0.2 percent yield strength, y, and the ultimate strength, u

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:

$$\mathrm{E} = \frac{3\mathrm{G}}{1+\frac{\mathrm{G}}{3\mathrm{k}}}\ ;\ \mathrm{G} = \frac{\mathrm{E}}{2(1+\mathrm{v})}\ ;\ \mathrm{k} = \frac{\mathrm{E}}{3[1-2\mathrm{v}]} \qquad (3.1)$$

Commonly $\mathrm{v} \approx 1/3$ when

$$\mathrm{G} \approx 3/8\mathrm{E} \text{ and } \mathrm{K} \approx \mathrm{E} \qquad (3.2a)$$

Elastomers are exceptional. for these $\mathrm{v} \approx 1/2$ when

$$G \approx 1/3E \text{ and } K \gg E \qquad (3.2b)$$

Data sources like those described in Chapter 15 list values for all four moduli. In this research, we examine data for E; approximate values for the others can be derived from equation (3.2) when needed. The strength if, of a solid (units: MPa or MN/m2) requires careful definition. For metals, we identify if with the 0.2 percent offset yield strength 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, if 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 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

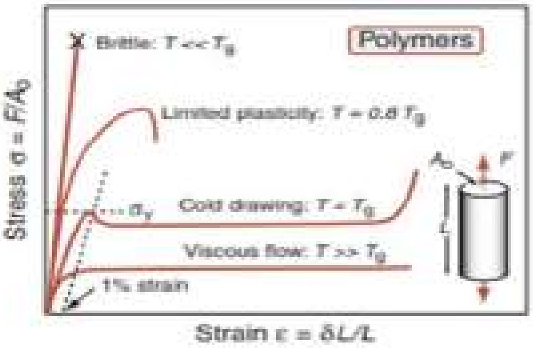


Figure 3.3 Stress–strain curves for a polymer, below, at and above its glass transition temperature, Tg.

tension, ‘‘strength’’ means the fracture strength, it. In compression it means the crushing strength c, which is much larger; typically

$$\sigma_C = 10 \text{ to } 15\sigma_T \qquad (3.3)$$

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).

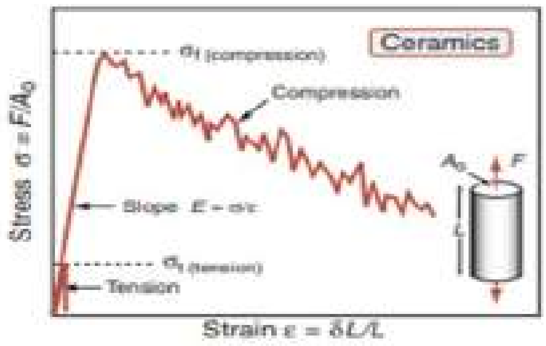


Figure 3.4 Stress–strain curves for a ceramic in tension and in compression. The compressive strength c is 10 to 15 times greater than the tensile strength t

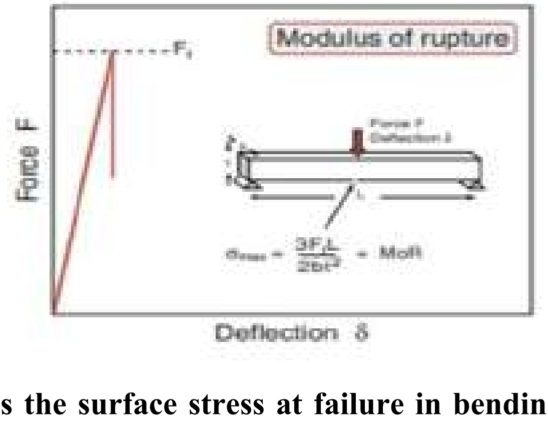


Figure 3.5 The MoR is the surface stress at failure in bending. It is equal to, or slightly larger than the failure stress in tension

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, if 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:

$$\left(\sigma_{1-\sigma_2}\right)^2 + (\sigma_2 - \sigma_3)^2 + \left(\sigma_{3-\sigma_1}\right)^2 = 2\sigma f^2 \quad (3.4)$$

Where $\sigma1$, $\sigma2$ and $\sigma3$ are the principal stresses , positive when tensile ; $\sigma1$, by convection is the largest or most positive , $\sigma3$ the smallest or least . for polymers the yield function is modified to include the effect of pressure :

$$\left(\sigma_{1-\sigma_2}\right)^2 + (\sigma_2 - \sigma_3)^2 + \left(\sigma_{3-\sigma_1}\right)^2 = 2\sigma f^2 \left(1 + \frac{B\rho}{k}\right)^2 \quad (3.5)$$

Where K is the bulk modulus of the polymer, $\beta \approx 2$ is a numerical coefficient that characetercerizes the pressure dependence of the flow strength and the pressure ρ is depend by

$$\rho = -\frac{1}{3}(\sigma1 + \sigma_2 + \sigma_3)$$

for ceramics, a coulomb flow law is used:

$$\sigma_{1-B\sigma 2} = C \quad (3.6)$$

Where B and C are constants. The ultimate (tensile) strength, 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, if, 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, e (units: MPa), illustrated by the $\mathrm{Nf}\rho = -\frac{1}{3}(\sigma, +\sigma_2 + \sigma_3)$ curve of Figure 3.6. It is the stress amplitude below which fracture does not occur, or occurs only after a very large number (Nf > 107) 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

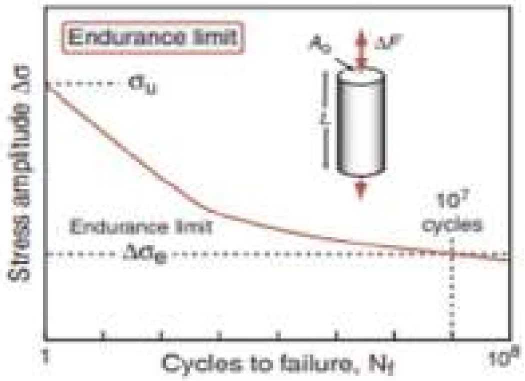


Figure 3.6   The endurance limit, e, is the cyclic stress that causes failure in Nf = 107 cycles

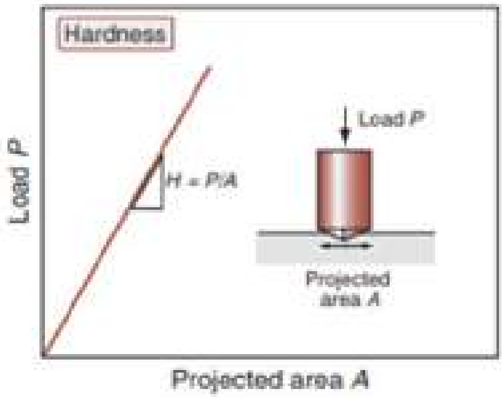


Figure 3.7 Hardness is measured as the load P divided by the projected area of contact, A, when a diamond-shaped indenter is forced into the surface.

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

$$H \approx 3\sigma_r$$

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 $\mathrm{kg/mm^2}$. It is related to H in the units used here by

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

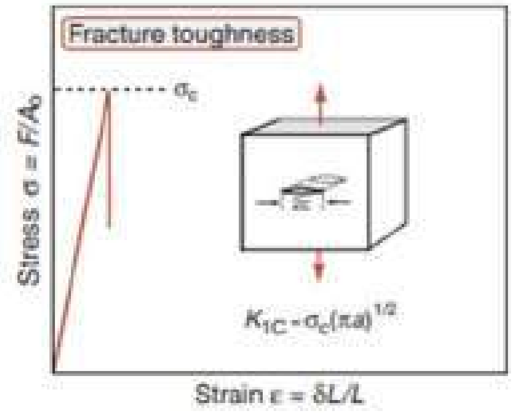


Figure 3.8 The fracture toughness, KIC, measures the resistance to the propagation of a crack. The failure strength of a brittle solid containing a crack of length 2c

The toughness, G_{1C}, (units: kJ/m^2), and the fracture toughness, K_{1C}, (units: of a crack. The fracture tonghness 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

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

and the toughness from

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

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, $\sigma_{\max}$, it stores an elastic energy

$$U = \int_0^{\sigma_{\min}} \sigma \mathrm{d}e \approx \frac{1}{2}\frac{\sigma_{\max}^2}{E}$$

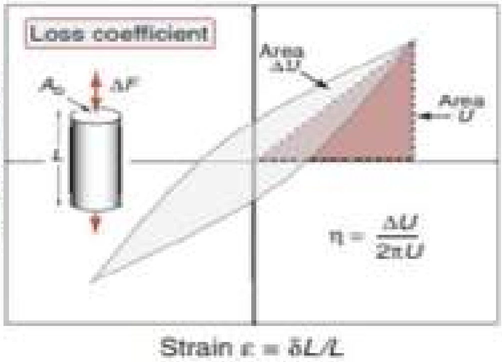


Figure 3.9 The loss coefficient measures the fractional energy dissipated in a stress–strain cycle.

3.2.3. Thermal properties

Two temperatures, the melting temperature, Tm, and the glass temperature, Tg (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, Tm. Non-crystalline solids do not; the temperature Tg characterizes the transition from true solid to very viscous liquid.

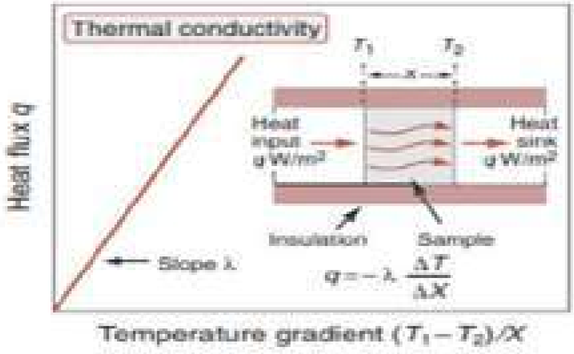


Figure 3.10 The thermal conductivity measures the flux of heat driven by a temperature gradient dT/dX

It is helpful, in engineering design, to define two further temperatures: the maximum and minimum service temperatures Tmax and Tmin (both: K or C). The first tells us the highest temperature at which the material can reasonably be used without oxidation, chemical change, or excessive creep becoming a problem.

The second is the temperature below which the material becomes brittle or otherwise unsafe to use. The rate at which heat is conducted through a solid at steady state (meaning that the temperature profile does not change with time) is measured by the thermal conductivity, (units: W/m.K). Figure 3.10 shows how it is measured: by recording the heat flux q (W/m2) flowing through the material from a surface at higher temperature T1 to a lower one at T2 separated by a distance X. The conductivity is calculated from Fourier's law:

$$q = -\lambda \frac{\mathrm{d}T}{\mathrm{dX}} = \lambda \frac{(T_1 - T_2)}{X}$$

The measurement is not, in practice, easy (particularly for materials with low conductivities), but reliable data are now generally available. When heat flow is transient, the flux depends instead on the thermal diffusivity, a (units: m2 /s), defined by

$$a = \frac{\lambda}{\rho C_\mathrm{p}}$$

Where ρ is the density and Cp is the specific heat at constant pressure (units: J/kg.K). The thermal diffusivity can be measured directly by measuring the decay of a temperature pulse when a heat source, applied to the material, is switched off; or it can be calculated from , via equation (3.13).

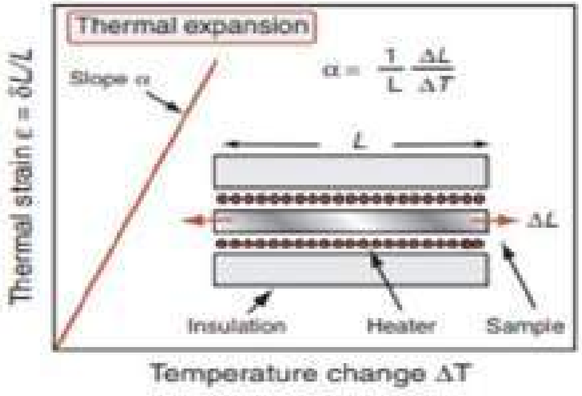


Figure 3.11 The linear-thermal expansion coefficient measures the change in length, per unit length, when the sample is heated.

This requires values for Cp. It is measured by the technique of calorimetry, which is also the standard way of measuring the glass temperature Tg. Most materials expand when they are heated (Figure 3.11). The thermal strain per degree of temperature change is measured by the linear thermal expansion coefficient, (units: K1 or, more conveniently, as ‘‘microstrain/C’’ or 106 C1).

If the material is thermally isotropic, the volume expansion, per degree, is 3 If it is anisotropic, two or more coefficients are required, and the volume expansion becomes the sum of the principal thermal strains. The thermal shock resistance Ts (units: K or C) is the maximum temperature difference through which a material can be quenched suddenly without damage. It, and the creep resistance, are important in high temperature design. Creep is the slow, time-dependent deformation that occurs when materials are loaded above about 1 3Tm or 2 3Tg. Design against creep is a specialized subject. Here we rely instead on avoiding the use of a material above its maximum service temperature, Tmax, or, for polymers, its ‘‘heat deflection temperature’

3.3. Summary and conclusions

There are six important families of materials for mechanical design: metals, ceramics, glasses, polymers, elastomers, and hybrids that combine the properties of two or more of the others. Within a family there is certain common ground: ceramics as a family are hard, brittle, and corrosion resistant; metals are ductile, tough, and good thermal and electrical conductors; polymers are light, easily shaped, and electrical insulators, and so on — that is what makes the classification useful. But in design we wish to escape from the constraints of family, and think, instead, of the material name as an identifier for a certain property-profile — one that will, in later chapters, be compared with an ‘‘ideal’’ profile suggested by the design, guiding our choice. To that end, the properties important in thermo-mechanical design were defined in this chapter. In Chapter 4 we develop a way of displaying these properties so as to maximize the freedom of choice.

3.4. Material property charts

3.4.1. Exploring material properties

The properties of engineering materials have a characteristic span of values. The span can be large: many properties have values that range over five or more decades. One way of displaying this is as a bar-chart like that of Figure 4.1 for thermal conductivity. Each bar represents a single material. The length of the bar shows the range of conductivity exhibited by that material in its various forms. The materials are segregated by class. Each class shows a characteristic range: metals, have high conductivities; polymers have low; ceramics have a wide range, from low to high. Much more information is displayed by an alternative way of plotting properties, illustrated in the schematic of Figure 4.2. Here, one property (the modulus, E, in this case) is plotted against another (the density) on logarithmic scales. The range of the axes is chosen to include all materials, from the

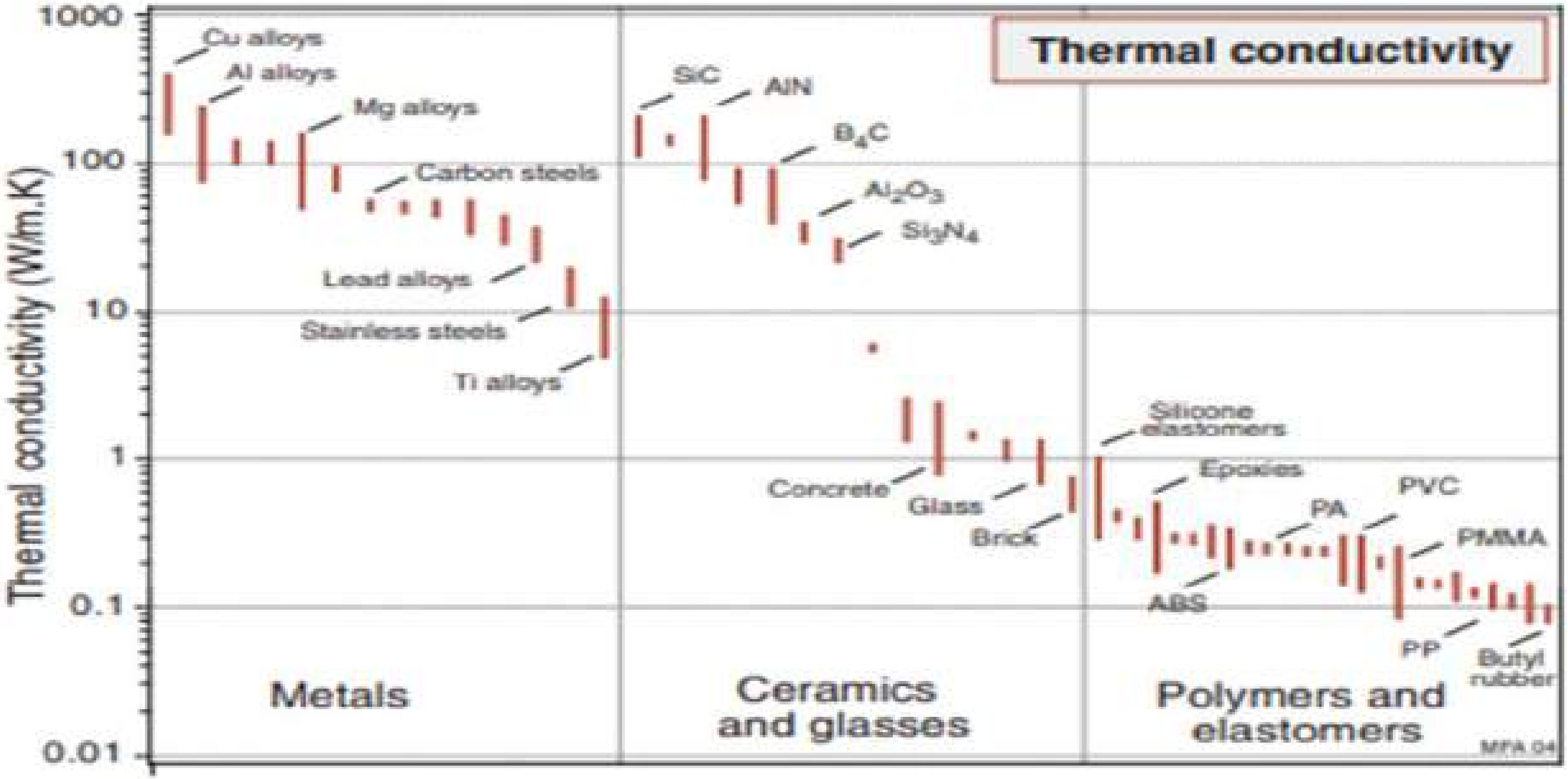


Figure 4.1 A bar-chart showing thermal conductivity for families of solid. Each bar shows the range of conductivity offered by a material, some of which are labeled.

lightest, flimsiest foams to the stiffest, heaviest metals. It is then found that data for a given family of materials (e.g. polymers) cluster together on the chart; the sub-range associated with one material family is, in all cases, much smaller than the full range of that property. Data for one family can be enclosed in a property-envelope, as Figure 4.2 shows. Within it lie bubbles enclosing classes and sub-classes. All this is simple enough — just a helpful way of plotting data. But by choosing the axes and scales appropriately, more can be added. The speed of sound in a solid depends on E and ; the longitudinal wave speed v, for instance, is

$$v = \left(\frac{E}{\rho}\right)^{1/2}$$

or (taking logs)

$$\log\ E = \log\ \rho + 2\log\ v$$

For a fixed value of v, this equation plots as a straight line of slope 1 on Figure 4.2. This allows us to add contours of constant wave velocity to the chart: they are the family of parallel diagonal lines, linking materials in which longitudinal waves travel with the same speed. All the charts allow additional fundamental relationships of this sort to be displayed. And there is more: design-optimizing parameters called material indices also plot as contours on to the charts.

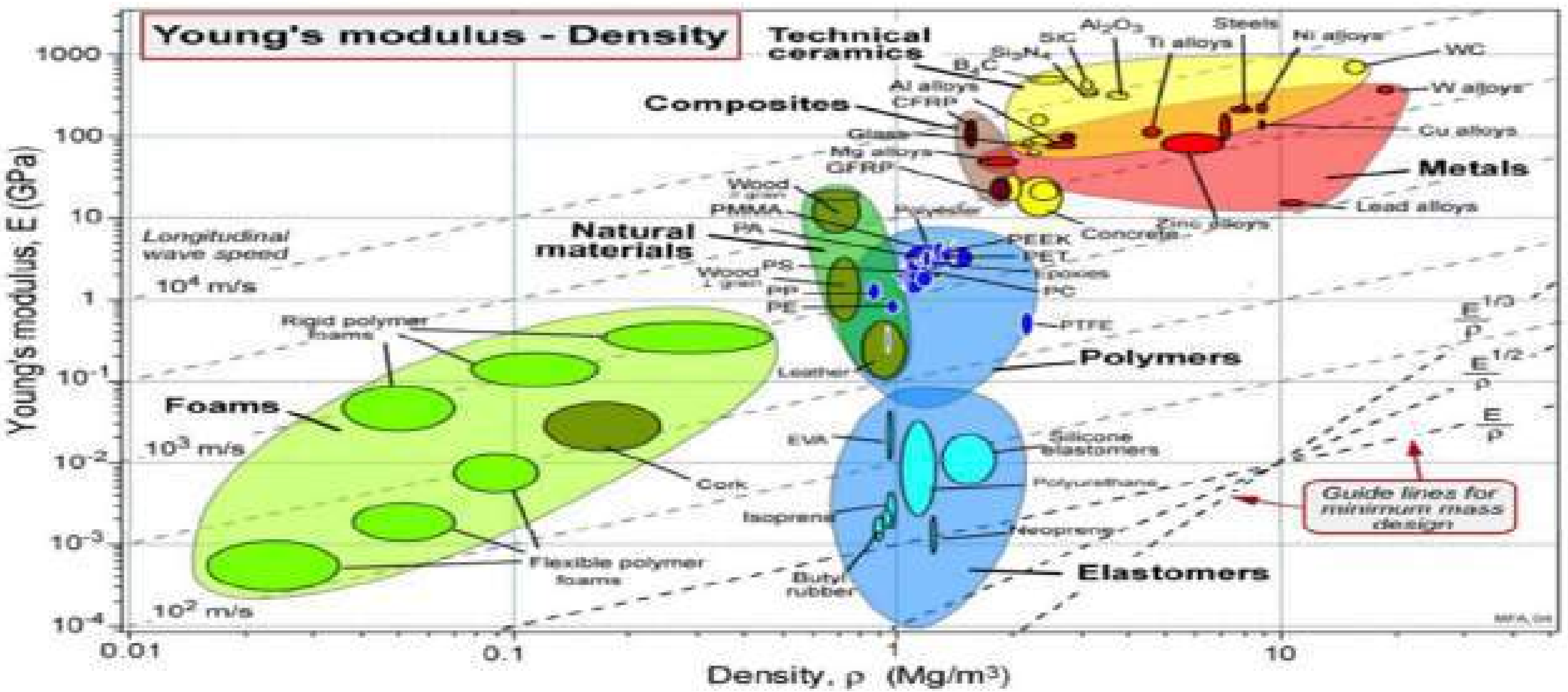


Figure 4.2 **The idea of a materials property chart: Young's modulus, E, is plotted against the density, on log scales. Each class of material occupies a characteristic part of the chart. The log scales allow the longitudinal elastic wave speed v ¼ to be plotted as a set of parallel contours.**

3.4.2. The Modulus–Density chart

Modulus and density are familiar properties. Steel is stiff, rubber is compliant: these are effects of modulus. Lead is heavy; cork is buoyant: these are effects of density. Figure 4.3 shows the full range of Young's modulus, E, and density, for engineering materials. Data for members of a particular family of material cluster together and can be enclosed by an envelope (heavy line).

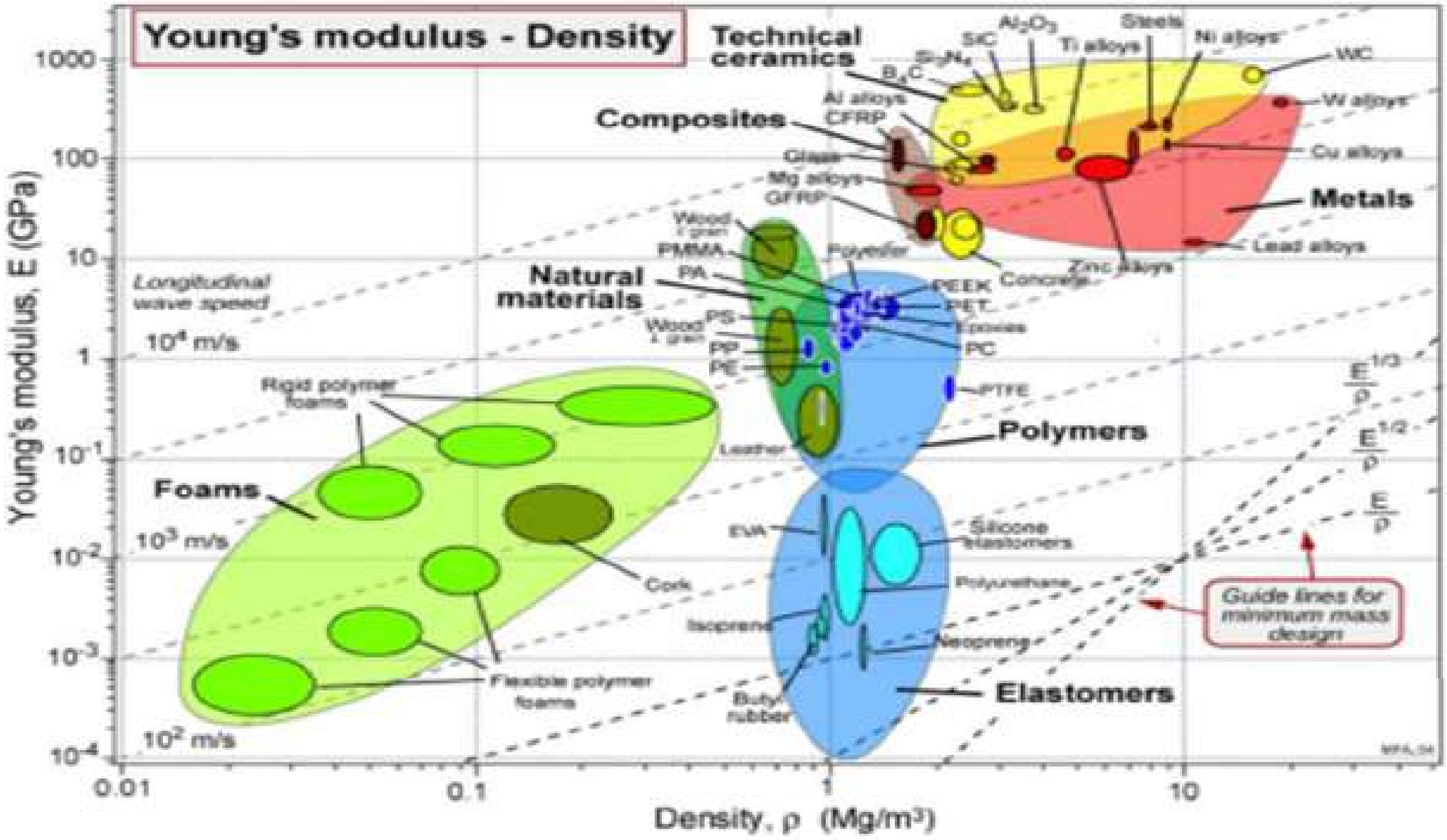


Figure 4.3 Young's modulus, E, plotted against density, The heavy envelopes enclose data for a given class of material. The diagonal contours show the longitudinal wave velocity

The same family-envelopes appear on all the diagrams: they correspond to the main headings in Table 4.1. The density of a solid depends on three factors: the atomic weight of its atoms or ions, their size, and the way they are packed. The size of atoms does not vary much: most have a volume within a factor of two of . Packing fractions do not vary much either a factor of two, more or less: close-packing gives a packing fraction of 0.74; open networks (like that of the diamond-cubic structure) give about 0.34.

The spread of density comes mainly from that of atomic weight, ranging from 1 for hydrogen to 238 for uranium. Metals are dense because they are made of heavy atoms, packed densely; polymers have low densities because they are largely made of carbon (atomic weight: 12) and hydrogen (atomic weight: 1) in low-density amorphous or crystalline packings.

Ceramics, for the most part, have lower densities than metals because they contain light O, N or C atoms. Even the lightest atoms, packed in the most open way, give solids with a density of around 1 Mg/m3 .

Materials with lower densities than this are foams — materials made up of cells containing a large fraction of pore space. The moduli of most materials depend on two factors: bond stiffness, and the density of bonds per unit volume. A bond is like a spring: it has a spring constant, S (units: N/m). Young's modulus, E, is roughly

$$E = \frac{S}{r_0}$$

where r0 is the ‘‘atom size’’ (r3 0 is the mean atomic or ionic volume). The wide range of moduli is largely caused by the range of values of S. The covalent bond is stiff (S ¼ 20–200 N/m); the metallic and the ionic a little less so (S ¼ 15– 100 N/m). Diamond has a very high modulus because the carbon atom is small (giving a high bond density) and its atoms are linked by very strong springs (S ¼ 200 N/m). Metals have high moduli because close-packing gives a high bond density and the bonds are strong, though not as strong as those of diamond. Polymers contain both strong diamond-like covalent bonds and weak hydrogen or Van-der-Waals bonds (S ¼ 0.5–2 N/m); it is the weak bonds that stretch when the polymer is deformed, giving low moduli.

But even large atoms bonded with the weakest bonds (S ¼ 0.5 N/m) have a modulus of roughly

$$E = \frac{0.5}{3 \times 10^{-10}} \approx 1\text{GPa}$$

This is the lower limit for true solids. The chart shows that many materials have moduli that are lower than this: they are either elastomers or foams. Elastomers have a low E because the weak secondary bonds have melted (their glass temperature, Tg, is below room temperature) leaving only the very weak ‘‘entropic’’ restoring force associated with tangled, long-chain molecules; and foams have low moduli because the cell walls bend easily (allowing large displacements) when the material is loaded. The chart shows that the modulus of engineering materials spans 7 decades,2 from 0.0001 GPa (low-density foams) to 1000 GPa (diamond); the density spans a factor of 2000, from less than 0.01 to 20 Mg/m3 .

Ceramics as a family are very stiff, metals a little less so — but none have a modulus less than 10 GPa. Polymers, by contrast, all cluster between 0.8 and 8 GPa. To have a lower modulus than this the material must be either an elastomer or a foam. At the level of approximation of interest here (that required to reveal the relationship between the properties of materials classes) we may approximate the shear modulus, G, by 3E/8 and the bulk modulus, K, by E, for all materials except elastomers (for which G ¼ E/3 and K >> E) allowing the chart to be used for these also.

The log-scales allow more information to be displayed. As explained in the last section, the velocity of elastic waves in a material, and the natural vibration frequencies of a component made of it, are proportional to (E/p) 1/2. Contours of this quantity are plotted on the chart, labeled with the longitudinal wave speed. It varies from less than 50 m/s (soft elastomers) to a little more than 104 m/s (stiff ceramics). We note that aluminum and glass, because of their low densities, transmit waves quickly despite their low moduli. One might have expected the wave velocity in foams to be low because of the low modulus, but the low density almost compensates. That in wood, across the grain, is low; but along the grain, it is high roughly the same as steel a fact made use of in the design of musical instruments. The chart helps in the common problem of material selection for applications in which mass must be minimized. Guidelines corresponding to three common geometries of loading are drawn on the diagram. They are used in the way described in Chapters 5 and 6 to select materials for elastic design at minimum weight

3.4.3. The strength–density chart

The modulus of a solid is a well-defined quantity with a sharp value. The strength is not. It is shown, plotted against density, p, in Figure 4.4. The word ‘‘strength’’ needs definition (see also Chapter 3, Section 3.3). For metals and polymers, it is the yield strength, but since the range of materials includes those that have been worked or hardened in some other way as well as those that have been annealed, the range is large. For brittle ceramics, the strength plotted here is the modulus of rupture: the strength in bending.

It is slightly greater than the tensile strength, but much less than the compression strength, which, for ceramics is 10 to 15 times larger. For elastomers, strength means the tensile tear-strength. For composites, it is the tensile failure strength (the compressive strength can be less by up to 30 percent because of fiber buckling). We will use the symbol if for all of these, despite the different failure mechanisms involved to allow a first-order comparison.

The considerable vertical extension of the strength-bubble for an individual material class reflects its wide range, caused by degree-of-alloying, work hardening, grain size, porosity and so forth. As before, members of a family cluster together and can be enclosed in an envelope, each of which occupies a characteristic area of the chart. The range of strength for engineering materials, like that of the modulus, spans about 6 decades: from less than 0.01 MPa (foams, used in packaging and energy absorbing systems) to 104MPa (the strength of diamond, exploited in the diamond-anvil press).

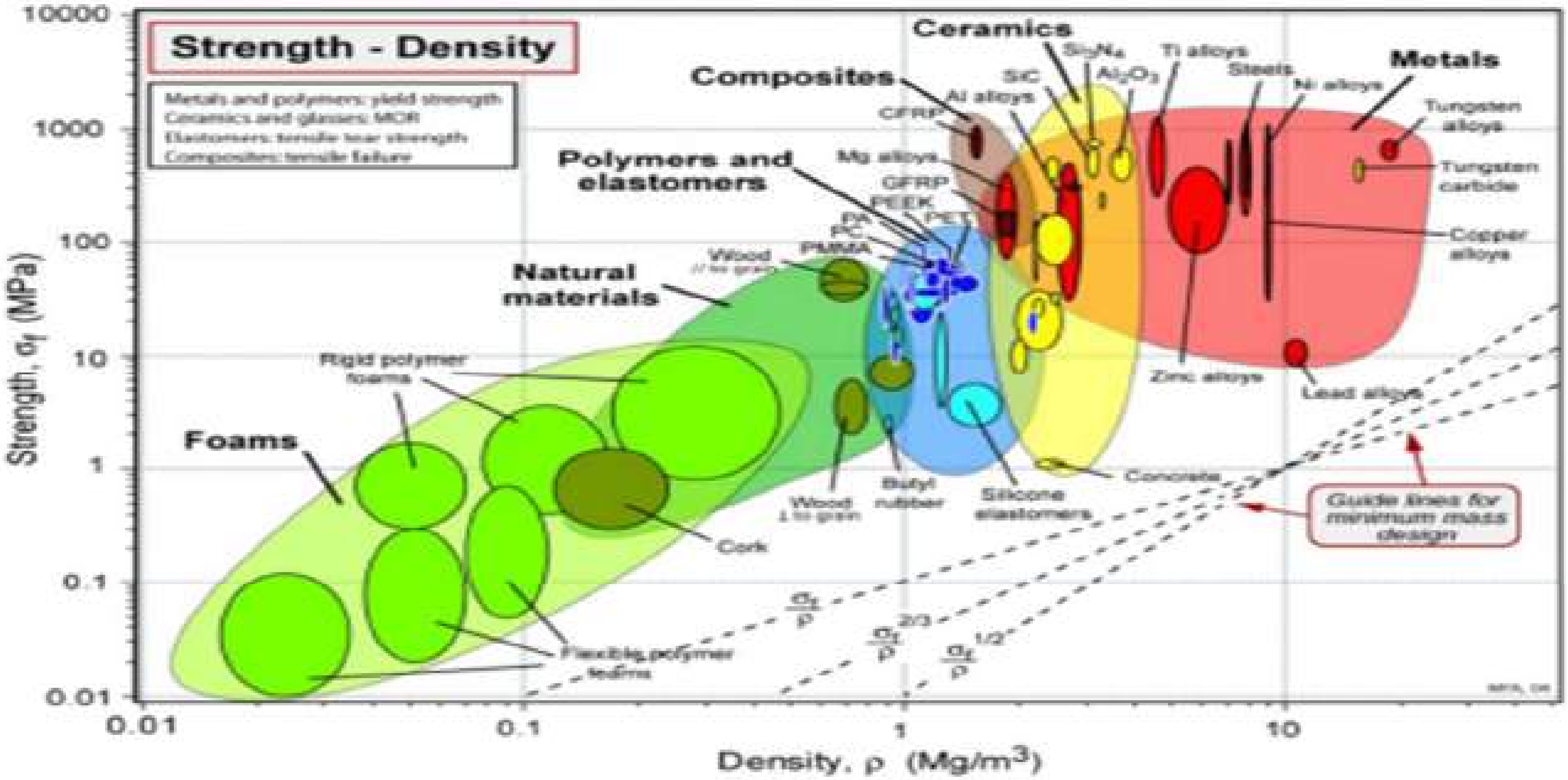


Figure 4.4 **Strength, Ϭf , plotted against density, Ƥ (yield strength for metals and polymers, compressive strength for ceramics, tear strength for elastomers and tensile strength for composites).**

The single most important concept in understanding this wide range is that of the lattice resistance or Peierls stress: the intrinsic resistance of the structure to plastic shear. Plastic shear in a crystal involves the motion of dislocations. Pure metals are soft because the non-localized metallic bond does little to prevent dislocation motion, whereas ceramics are hard because their more localized covalent and ionic bonds (which must be broken and reformed when the structure is sheared), lock the dislocations in place.

In non-crystalline solids we think instead of the energy associated with the unit step of the flow process: the relative slippage of two segments of a polymer chain, or the shear of a small molecular cluster in a glass network. Their strength has the same origin as that underlying the lattice resistance: if the unit step involves breaking strong bonds (as in an inorganic glass), the materials will be strong; if it only involves the rupture of weak bonds (e.g. the Van-der-Waals bonds in polymers), it will be weak.

Materials that fail by fracture do so because the lattice resistance or its amorphous equivalent is so large that atomic separation (fracture) happens first. wide range is that of the lattice resistance or Peierls stress: the intrinsic resistance of the structure to plastic shear. Plastic shear in a crystal involves the motion of dislocations. Pure metals are soft because the non-localized metallic bond does little to prevent dislocation motion, whereas ceramics are hard because their more localized covalent and ionic bonds (which must be broken and reformed when the structure is sheared), lock the dislocations in place. In non-crystalline solids we think instead of the energy associated with the unit step of the flow process: the relative slippage of two segments of a polymer chain, or the shear of a small molecular cluster in a glass network. Their strength has the same origin as that underlying the lattice resistance: if the unit step involves breaking strong bonds (as in an inorganic glass), the materials will be strong; if it only involves the rupture of weak bonds (e.g. the Van-der-Waals bonds in polymers), it will be weak. Materials that fail by fracture do so because the lattice resistance or its amorphous equivalent is so large that atomic separation (fracture) happens first.

When the lattice resistance is low, the material can be strengthened by introducing obstacles to slip. In metals this is achieved by adding alloying elements, particles, grain boundaries, and other dislocations (‘‘work hardening’’); and in polymers by cross-linking or by orienting the chains so that strong covalent as well as weak Van-der-Waals bonds must be broken when the material deforms. When, on the other hand, the lattice resistance is high, further hardening is superfluous the problem becomes that of suppressing fracture. An important use of the chart is in materials selection in light-weight plastic design. Guidelines are shown for materials selection in the minimum-weight design of ties, columns, beams and plates, and for yield-limited design of moving components in which inertial forces are important.

3.4.4. The modulus–strength chart

High tensile steel makes good springs. But so does rubber. How is it that two such different materials are both suited for the same task? This and other questions are answered by Figure 4.5, one of the most useful of all the charts. It shows Young’s modulus, E, plotted against strength, f. The qualifications on ‘‘strength’’ are the same as before: it means yield strength for metals and polymers, modulus of rupture for ceramics, tear strength for elastomers, and tensile strength for composite and woods; the symbol f is used for them all.

Contours of yield strain, f/E (meaning the strain at which the material ceases to be linearly elastic), appear as a family of straight parallel lines. Examine these first.

Engineering polymers have large yield strains of between 0.01 and 0.1; the values for metals are at least a factor of 10 smaller. Composites and woods lie on the 0.01 contour, as good as the best metals. Elastomers, because of their exceptionally low moduli, have values of Ϭf/E larger than any other class of material: typically 1 to 10. The distance over which inter-atomic forces act is small — a bond is broken if it is stretched to more than about 10 percent of its original length. So the force needed to break a bond is roughly

$$F \approx \frac{Sr_0}{10}$$

where S, as before, is the bond stiffness. If shear breaks bonds, the strength of a solid should be roughly

$$\sigma_{\mathrm{f}} \approx \frac{F}{r_0^2} = \frac{S}{10r_0} = \frac{E}{10}$$

or

$$\frac{\sigma_{\mathrm{f}}}{E} \approx \frac{1}{10}$$

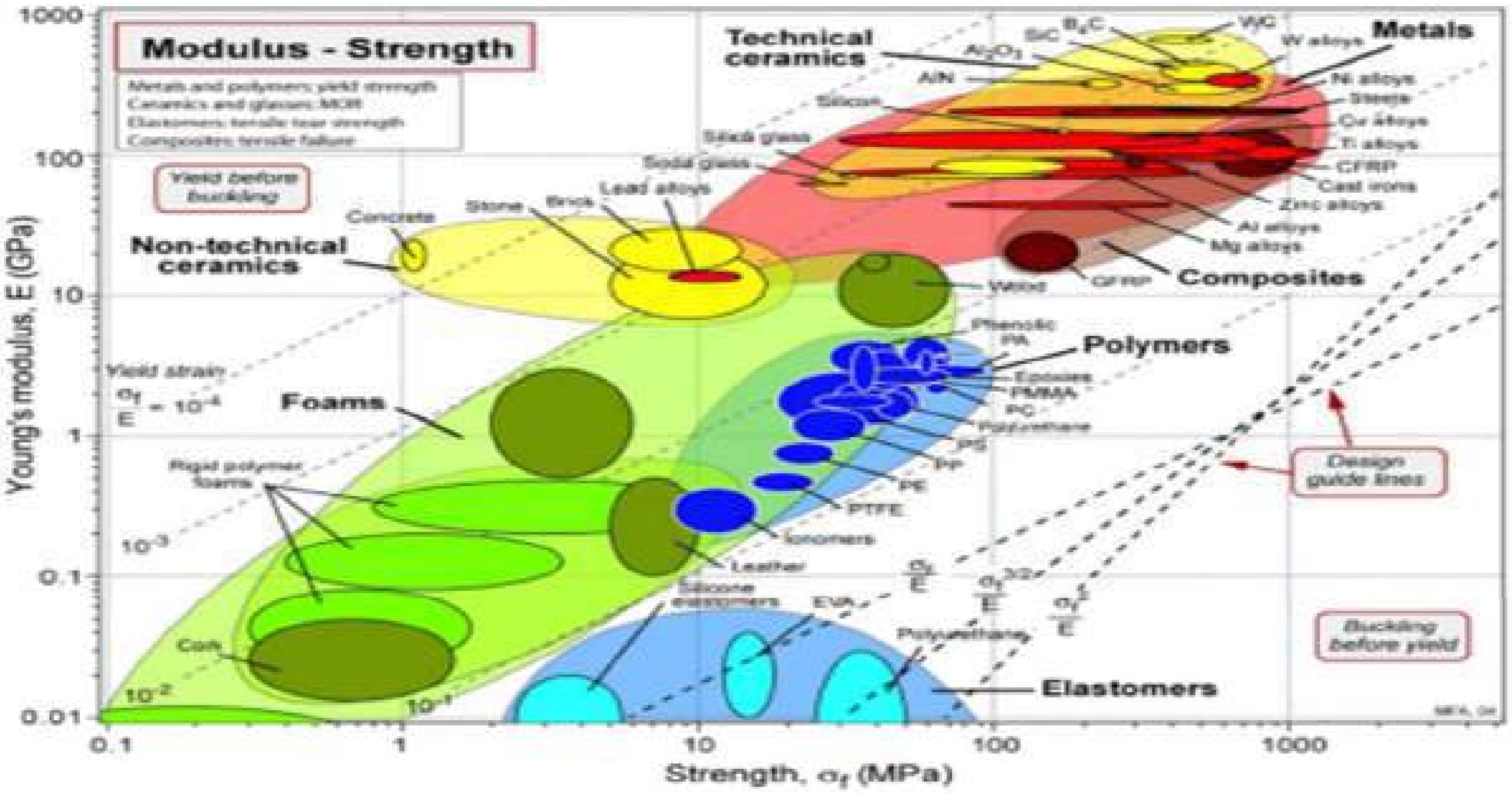


Figure 4.5 Young's modulus, E, plotted against strength, σf. The design guidelines help with the selection of materials for springs, pivots, knife-edges, diaphragms and hinges.

The chart shows that, for some polymers, the failure strain approaches this value. For most solids it is less, for two reasons. First, non-localized bonds (those in which the cohesive energy derives from the interaction of one atom with large number of others, not just with its nearest neighbors) are not broken when the structure is sheared. The metallic bond, and the ionic bond for certain directions of shear, are like this; very pure metals, for example, yield at stresses as low as E/10,000, and strengthening mechanisms are needed to make them useful in engineering. The covalent bond is localized; and covalent solids do, for this reason, have yield strength that, at low temperatures, are as high as E/10. It is hard to measure them (though it can sometimes be done by indentation) because of the second reason for weakness: they generally contain defects concentrators of stress from which shear fracture can propagate, at stresses well below the ‘‘ideal’’ E/10. Elastomers are anomalous (they have strengths of about E) because the modulus does not derive from bond-stretching, but from the change in entropy of the tangled molecular chains when the material is deformed.

Materials with high strength and low modulus lie towards the bottom right. Such materials tend to buckle before they yield when loaded as panels or columns. Those near the top left have high modulus and low strength: they end to yield before buckling. This has not yet explained how to choose good materials to make springs. This involves the design guidelines shown on the chart. The way to use them is described in Chapter 4.

3.4.5. The specific stiffness–specific strength chart :

Many designs, particularly those for things that move, call for stiffness and strength at minimum weight. To help with this, the data of the previous chart are replotted in Figure 4.6 after dividing, for each material, by the density; it shows E/ρ plotted against $\sigma f/\rho$. Composites, particularly CFRP, emerge as the material class with the most attractive specific properties, one of the reasons for their increasing use in aerospace. Ceramics have exceptionally high stiffness per unit weight, and the strength per unit weight is as good as metals. Metals are penalized because of their relatively high densities. Polymers, because their densities are low, do better on this chart than on the last one. The chart has application in selecting materials for light springs and energy-storage devices.

3.4.6. The fracture toughness–modulus chart:

Increasing the strength of a material is useful only as long as it remains plastic and does not fail by fast fracture. The resistance to the propagation of a crack is measured by the fracture toughness, K1C. It is plotted against modulus E in Figure 4.7. The range is large: from less than 0.01 to over 100 MPa.m1/2. At the lower end of this range are brittle materials, which, when loaded, remain elastic until they fracture. For these, linear-elastic fracture mechanics works well, and the fracture toughness itself is a well-defined property. At the upper end lie the super-tough materials, all of which show substantial plasticity before they break. For these the values of K1C are approximate, derived from critical J-integral (Jc) and critical crack-opening displacement (c) measurements (by writing K1C ¼ (EJc) 1/2, for instance). They are helpful in providing a ranking of materials. The figure shows one reason for the dominance of metals in engineering; they almost all have values of

K1C above 20 MPa.m1/2, a value often quoted as a minimum for conventional design

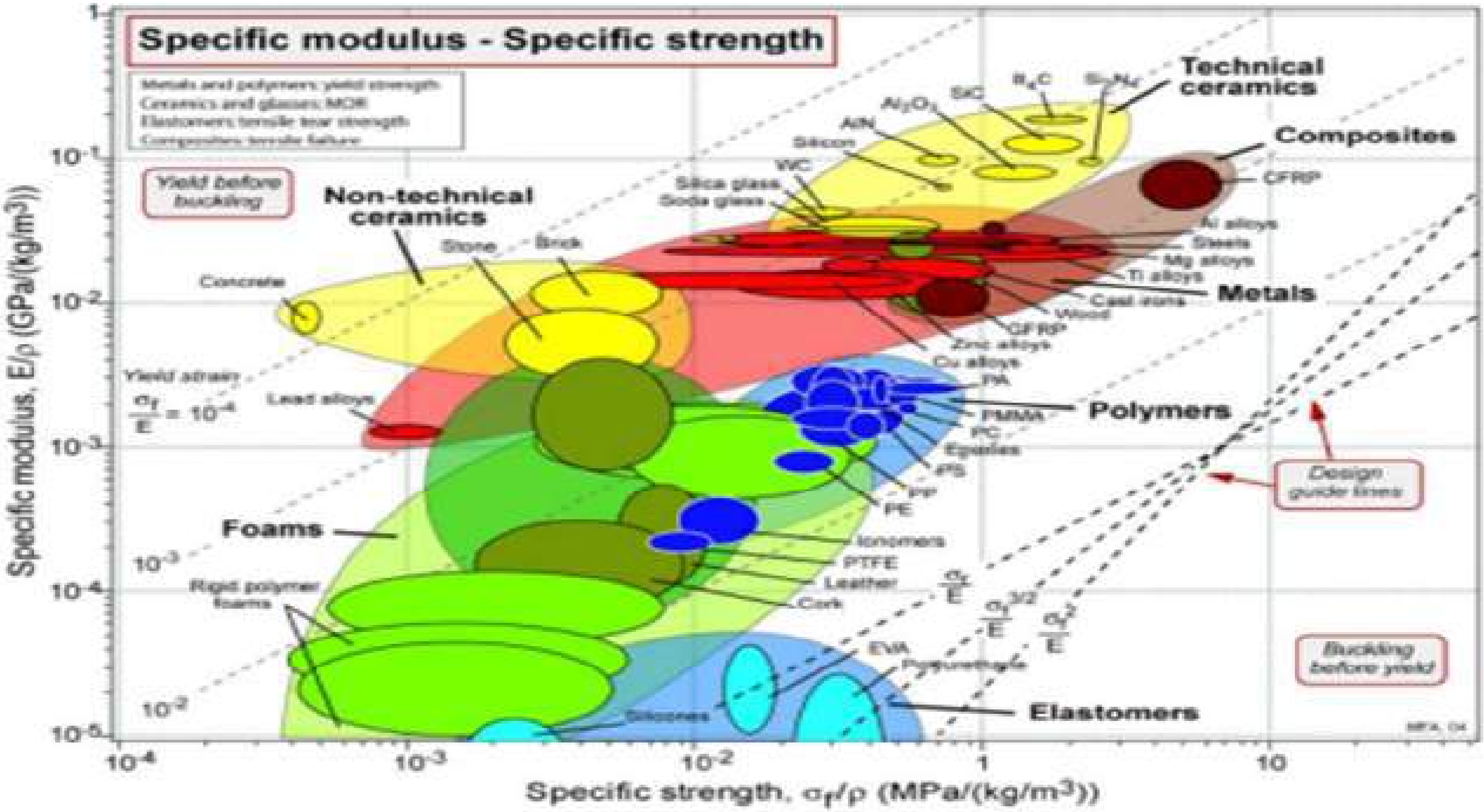


Figure 4.6 Specific modulus, E/ρ plotted against specific strength σf /ρ. The design guidelines help with the selection of materials for light-weight springs and energy-storage systems

As a general rule, the fracture toughness of polymers is less than that of ceramics. Yet polymers are widely used in engineering structures; ceramics, because they are ‘‘brittle’’, are treated with much more caution. Figure 4.7 helps resolve this apparent contradiction. Consider first the question of the necessary condition for fracture. It is that sufficient external work be done, or elastic energy released, to supply the surface energy, per unit area, of the two new surfaces that are created. We write this

$$G \geq 2\%$$

where G is the energy release-rate. Using the standard relation $K = (EG)^{1/2}$ between G and stress intensity K, we find

$$K \geq (2E\gamma)^{1/2}$$

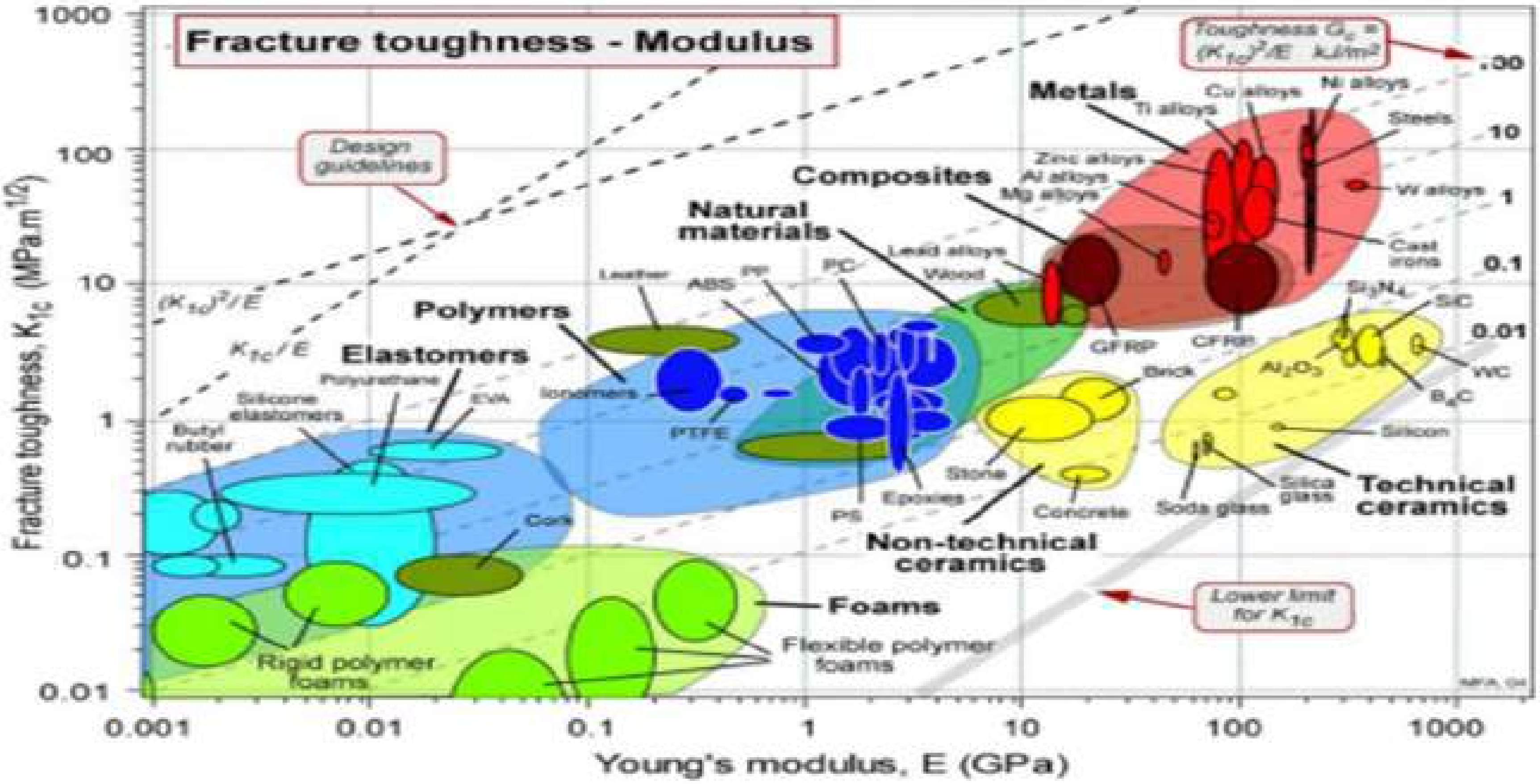


Figure 4.7   Fracture toughness, KIC, plotted against Young's modulus, E. The family of lines are of constant K2 IC=E (approximately GIC, the fracture energy or toughness). These, and the guideline of constant KIC/E, help in design against fracture. The shaded band shows the ''necessary condition'' for fracture. Fracture can, in fact, occur below this limit under conditions of corrosion, or cyclic loading

Now the surface energies, γ, of solid materials scale as their moduli; to an adequate approximation $y \approx Er_0/20$ where r_0 is the atom size, giving

$$K \geq E\left(\frac{r_0}{20}\right)^{1/2}$$

We identify the right-hand side of this equation with a lower-limiting value of $K_{1C,}$ when, taking as 2×10^{-10} m,

$$\frac{(K_{1C})_{\text{mia}}}{E} = \left(\frac{r_0}{20}\right)^{1/2} \approx 3 \times 10^{-6}\ \text{m}^{1/2}$$

This criterion is plotted on the chart as a shaded, diagonal band near the lower right corner. It defines a lower limit for K_1c. The fracture toughness cannor be less than this unless some other source of energy such as a chemical reaction, or the release of elastic energy stored in the special dislocation structures caused by fatigue loading, is available, when it is given a new symbol such as (K1)scc meaning ''the critical value of K1 for stress-corrosion cracking'' or (K1)threshold meaning ''the minimum range of K1 for fatigue-crack propagation''.

We note that the brittlest ceramics lie close to the threshold: when they fracture, the energy absorbed is only slightly more than the surface energy. When metals and polymers and composites fracture, the energy absorbed is vastly greater, usually because of plasticity associated with crack propagation. We come to this in a moment, with the next chart. Plotted on Figure 4.7 are contours of toughness, G1C, a measure of the apparent fracture surface-energy ðG1C K2 1C=EÞ. The true surface energies, of solids lie in the range 104 to 103 kJ/m2 .

The diagram shows that the values of the toughness start at 103 kJ/m2 and range through almost five decades to over 100 kJ/m2 . On this scale, ceramics (103 –101 kJ/m2) are much lower than polymers (101 –10 kJ/m2); and this is part of the reason polymers are more widely used in engineering than ceramics.

3.4.7. The fracture toughness–strength chart

The stress concentration at the tip of a crack generates a process-zone: a plastic zone in ductile solids, a zone of micro-cracking in ceramics, a zone of delamination, deboning and fiber pull-out in composites. Within the process zone, work is done against plastic and frictional forces; it is this that accounts for the difference between the measured fracture energy G1C and the true surface energy.

The amount of energy dissipated must scale roughly with the strength of the material within the process zone, and with its size, dy. This size is found by equating the stress field of the crack to the strength of the material. Figure 4.8 fracture toughness against strength shows that the size of the zone, dy (broken lines), varies enormously, from atomic dimensions for very brittle ceramics and glasses to almost 1 m for the most ductile of metals. At a constant zone size, fracture toughness tends to increase with strength (as expected): it is this that causes the data plotted in Figure 4.8 to be clustered around the diagonal of the chart. Materials towards the bottom right have high strength and low toughness; they fracture before they yield. Those towards the top left do the opposite: they yield before they fracture.

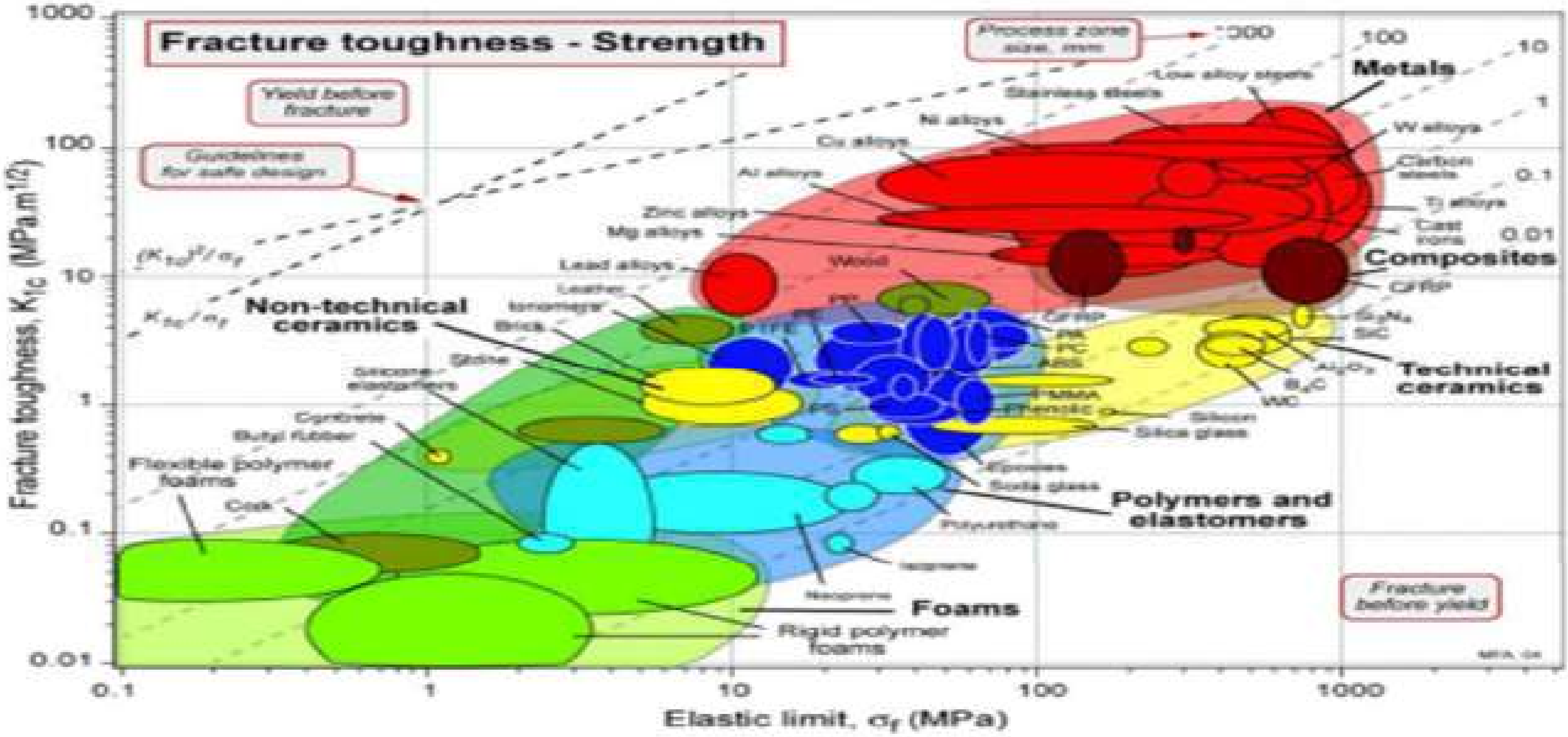


Figure 4.8 Fracture toughness, KIC, plotted against strength, σf. The contours show the value of K2 IC=$\pi\sigma$f — roughly, the diameter of the process-zone at a crack tip. The design guidelines are used in selecting materials for damage-tolerant design.

3.4.8. The loss coefficient–modulus chart:

Bells, traditionally, are made of bronze. They can be (and sometimes are) made of glass; and they could (if you could afford it) be made of silicon carbide. Metals, glasses and ceramics all, under the right circumstances, have low intrinsic damping or ‘‘internal friction’’, an important material property when structures vibrate. Intrinsic damping is measured by the loss coefficient, η, which is plotted in Figure 4.9. There are many mechanisms of intrinsic damping and hysteresis. Some (the ‘‘damping’’ mechanisms) are associated with a process that has a specific time constant; then the energy loss is centered about a characteristic frequency. Others (the ‘‘hysteresis’’ mechanisms) are associated with time-independent mechanisms; they absorb energy at all frequencies.

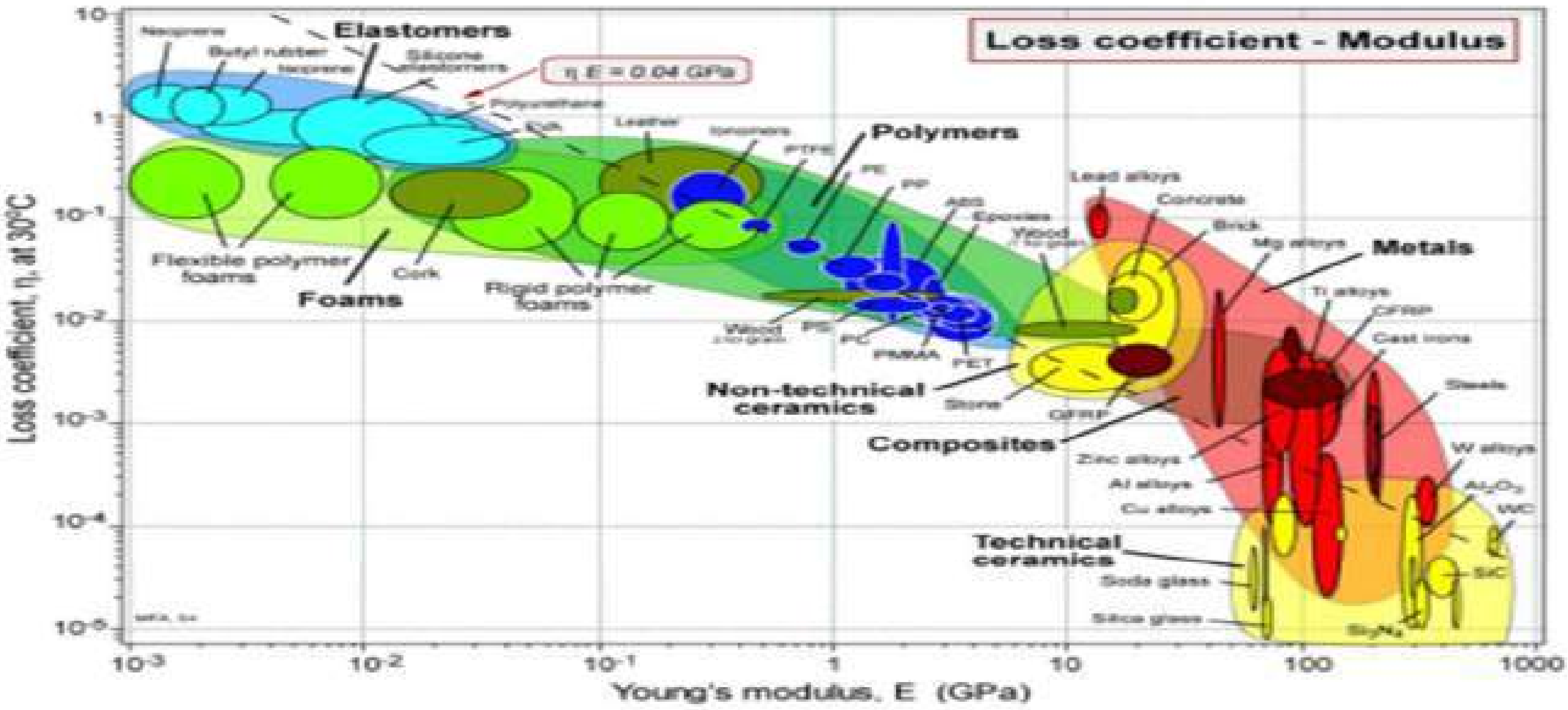


Figure 4.9 The loss coefficient, *p*, plotted against Young's modulus, E. The guideline corresponds to the condition ɲ=CE

In metals a large part of the loss is hysteretic, caused by dislocation movement: it is high in soft metals like lead and pure aluminum. Heavily alloyed metals like bronze and high-carbon steels have low loss because the solute pins the dislocations; these are the materials for bells. Exceptionally high loss is found in the Mn–Cu alloys, because of a strain-induced martensite transformation, and in magnesium, perhaps because of reversible twinning.

The elongated bubbles for metals span the large range made accessible by alloying and work hardening. Engineering ceramics have low damping because the enormous lattice resistance pins dislocations in place at room temperature. Porous ceramics, on the other hand, are filled with cracks, the surfaces of which rub, dissipating energy, when the material is loaded; the high damping of some cast irons has a similar origin. In polymers, chain segments slide against each other when loaded; the relative motion dissipates energy. The ease with which they slide depends on the ratio of the temperature T (in this case, room temperature) to the glass temperature, Tg, of the polymer. When T/Tg < 1, the secondary bonds are ‘‘frozen’’, the modulus is high and the damping is relatively low. When T/Tg>1, the secondary bonds have melted, allowing easy chain slippage; the modulus is low and the damping is high.

This accounts for the obvious inverse dependence of on E for polymers in Figure 4.9; indeed, to a first approximation,

$$\eta = \frac{4 \times 10^{-2}}{E}$$

(with E in GPa) for polymers, woods and polymer-matrix composites.

3.5. Summary and conclusions:

The engineering properties of materials are usefully displayed as material selection charts. The charts summarize the information in a compact, easily accessible way, they show the range of any given property accessible to the designer and they identify the material class associated with segments of that range. By choosing the axes in a sensible way, more information can be displayed: a chart of modulus E against density reveals the longitudinal wave velocity a plot of fracture toughness K1C against modulus E shows the toughness G1C; a diagram of thermal conductivity against diffusivity, a, also gives the volume specific heat Cv; strength, against modulus, E, shows the energy-storing capacity f =E, and there are many more. The most striking feature of the charts is the way in which members of a material class cluster together. Despite the wide range of modulus and density of metals (as an example), they occupy a field that is distinct from that of polymers, or that of ceramics, or that of composites.

The same is true of strength, toughness, thermal conductivity and the rest: the fields sometimes overlap, but they always have a characteristic place within the whole picture. The position of the fields and their relationship can be understood in simple physical terms: the nature of the bonding, the packing density, the lattice resistance and the vibrational modes of the structure (themselves a function of bonding and packing), and so forth. It may seem odd that so little mention has been made of micro-structure in determining properties. But the charts clearly show that the first-order difference between the properties of materials has its origins in the mass of the atoms, the nature of the inter-atomic forces and the geometry of packing. Alloying, heat treatment, and mechanical working all influence micro-structure, and through this, properties, giving the elongated bubbles shown on many of the charts;

but the magnitude of their effect is less, by factors of 10, than that of bonding and structure.

All the charts have one thing in common: parts of them are populated with materials and parts are not. Some parts are inaccessible for fundamental reasons that relate to the size of atoms and the nature of the forces that bind their atoms together. But other parts are empty even though, in principle, they are accessible. If they were accessed, the new materials that lay there could allow novel design possibilities. Ways of doing this are explored further in Chapters 4 and 5. The charts have numerous applications. One is the checking and validation of data.

3.6. Materials selection — the basics

3.6.1. Introduction and synopsis

This chapter sets out the basic procedure for selection, establishing the link between material and function (Figure 5.1). A material has attributes: its density, strength, cost, resistance to corrosion, and so forth. A design demands a certain profile of these: a low density, a high strength, a modest cost and resistance to sea water, perhaps. It is important to start with the full menu of materials in mind; failure to do so may mean a missed opportunity. If an innovative choice is to be made, it must be identified early in the design process. Later, too many decisions have been taken and commitments made to allow radical change: it is now or never. The task, restated in two lines, is that of

(1) identifying the desired attribute profile and then

(2) comparing it with those of real engineering materials to find the best match.

The first step in tackling it is that of translation, examining the design requirements to identify the constraints that they impose on material choice. The immensely wide choice is narrowed, first, by screening-out the materials that cannot meet the constraints. Further narrowing is achieved by ranking the candidates by their ability to maximize performance. Criteria for screening and ranking are derived from the design requirements for a component by an analysis of function, constraints, objectives, and free variables. This chapter explains how to do it. The materials property charts introduced in Chapter 4 are designed for use with these criteria. Property constraints and material indices can be plotted onto them, isolating the subset of materials that are the best choice for the design. The whole procedure can be implemented in software as a design tool, allowing computer-aided selection. The procedure is fast, and makes for lateral thinking.

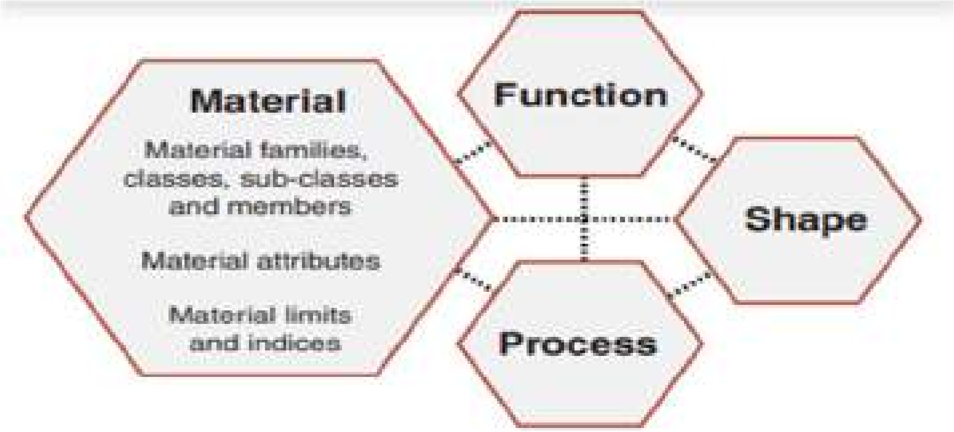


Figure 5.1 Material selection is determined by function. Shape sometimes influences the selection. This chapter and the next deal with materials selection when this is independent of shape.

3.7. The selection strategy

3.7.1. Material attributes

Figure 5.2 illustrates how the kingdom of materials is divided into families, classes, sub-classes, and members. Each member is characterized by a set of attributes: its properties. As an example, the materials kingdom contains the family ‘‘metals’’, which in turn contains the class ‘‘aluminum alloys’’, the subclass ‘‘6000 series’’ and finally the particular member ‘‘Alloy 6061’’. It, and every other member of the kingdom, is characterized by a set of attributes that include its mechanical, thermal, electrical, optical, and chemical properties, its processing characteristics, its cost and availability, and the environmental consequences of its use. We call this its property-profile. Selection involves seeking the best match between the property-profiles of the materials in the kingdom and that required by the design.

There are four main steps, which we here call translation, screening, ranking, and supporting information (Figure 5.3). The steps can be likened to those in selecting a candidate for a job. The job is first analyzed and advertised, identifying essential skills and experience required of the candidate (‘‘translation’’). Some of these are simple go/no go criteria like the requirement that the applicant ‘‘must have a valid driving license’’, or ‘‘a degree in computer science’’,

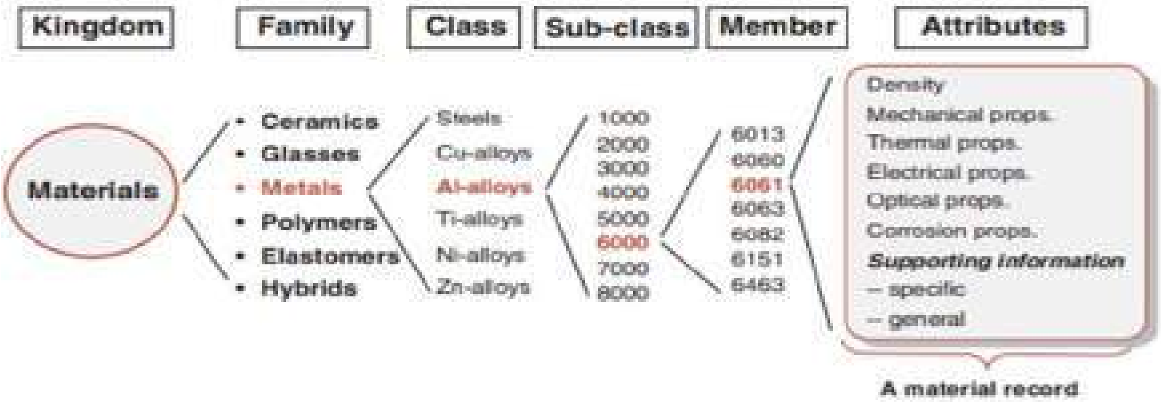
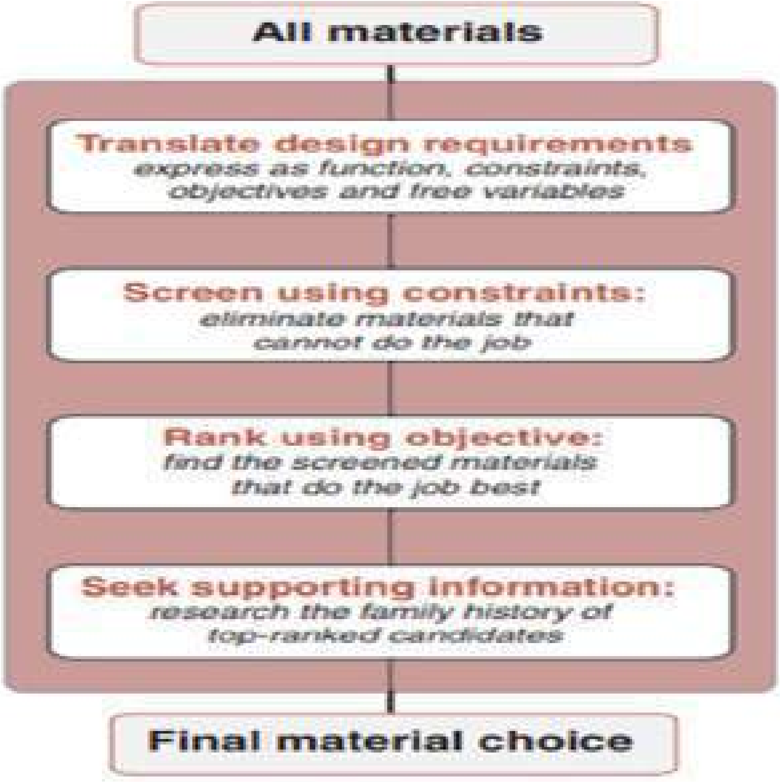


Figure 5.2 The taxonomy of the kingdom of materials and their attributes. Computer-based selection software stores data in a hierarchical structure like this



eliminating anyone who does not (‘‘screening’’). Others imply a criterion of excellence, such as ‘‘typing speed and accuracy are priorities’’, or ‘‘preference will be given to candidates with a substantial publication list’’, implying that applicants will be ranked by these criteria (‘‘ranking’’). Finally references and interviews are sought for the top ranked candidates, building a file of supporting information — an opportunity to probe deeply into character and potential.

3.7.2. Translation

How are the design requirements for a component (defining what it must do) translated into a prescription for a material? Any engineering component has one or more functions: to support a load, to contain a pressure, to transmit heat, and so forth. This must be achieved subject to constraints: that certain

Table 5.1 Function, constraints, objectives and free variables

Function	**What does component do?**
Constraints	**What non-negotiable conditions must be met?**
	What negotiable but desirable conditions...?
Objective	**What is to be maximized or minimized?**
Free variables	**What parameters of the problem is the designer free to change?**

"It is sometimes useful to distinguish between "hard" and "soft" constraints. Stiffness and strength might be absolute requirements (hard constraints); cost might be negotiable (a soft constraint).

dimensions are fixed, that the component must carry the design loads or pressures without failure, that it insulates or conducts, that it can function in a certain range of temperature and in a given environment, and many more. In designing the component, the designer has an objective: to make it as cheap as possible, perhaps, or as light, or as safe, or perhaps some combination of these. Certain parameters can be adjusted in order to optimize the objective — the designer is free to vary dimensions that have not been constrained by design requirements and, most importantly, free to choose the material for the component. We refer to these as free variables. Function and constraints, objective and free variables (Table 5.1) define the boundary conditions for selecting a material and — in the case of load-bearing components — a shape for its cross-section. The first step in relating design requirements to material properties is a clear statement of function, constraints, objective, and free variables.

3.7.3. Screening:

Attribute limits Unbiased selection requires that all materials are considered to be candidates until shown to be otherwise, using the steps in the boxes below ‘‘translate’’ in Figure 5.3. The first of these, screening, eliminates candidates that cannot do the job at all because one or more of their attributes lies outside the limits set by the constraints. As examples, the requirement that ‘‘the component must function in boiling water’’, or that ‘‘the component must be transparent’’ imposes obvious limits on the attributes of maximum service temperature and optical transparency that successful candidates must meet. We refer to these as attribute limits.

3.7.4. Ranking: material indices

Attribute limits do not, however, help with ordering the candidates that remain. To do this we need optimization criteria. They are found in the material indices, developed below, which measure how well a candidate that has passed the screening step can do the job. Performance is sometimes limited by a single property, sometimes by a combination of them. Thus the best materials for buoyancy are those with the lowest density; those best for thermal insulation the ones with the smallest values of the thermal conductivity. Here maximizing or minimizing a single property maximizes performance. But — as we shall see – the best materials for a light stiff tie-rod are those with the greatest value of the specific stiffness, where E is Young's modulus. The best materials for a spring are those with the greatest value of $\sigma 2$ f =E where σf is the failure stress.

The property or property-group that maximizes performance for a given design is called its material index. There are many such indices, each associated with maximizing some aspect of performance.1 They provide criteria of excellence that allow ranking of materials by their ability to perform well in the given application. To summarize: screening isolate candidates that are capable of doing the job; ranking identifies those among them that can do the job best

3.7.5. Supporting information

The outcome of the steps so far is a ranked short-list of candidates that meet the constraints and that maximize or minimize the criterion of excellence, whichever is required. You could just choose the top-ranked candidate, but what bad secrets might it hide? What are its strengths and weaknesses? Does it have a good reputation? What, in a word, is its credit-rating? To proceed further we seek a detailed profile of each: its supporting information (Figure 5.3, bottom). Supporting information differs greatly from the structured property data used for screening. Typically, it is descriptive, graphical or pictorial: case studies of previous uses of the material, details of its corrosion behavior in particular environments, information of availability and pricing, experience of its environmental impact. Such information is found in handbooks, suppliers' data sheets, CD-based data sources and the world-wide web. Supporting information helps narrow the short-list to a final choice, allowing a definitive match to be made between design requirements and material attributes. Why are all these steps necessary? Without screening and ranking, the candidate-pool is enormous and the volume of supporting information overwhelming. Dipping into it, hoping to stumble on a good material, gets you nowhere. But once a small number of potential candidates have been identified by the screening–ranking steps, detailed supporting information can be sought for these few alone, and the task becomes viable

3.7.6. Local conditions

The final choice between competing candidates will, often, depend on local conditions: on in-house expertise or equipment, on the availability of local suppliers, and so forth. A systematic procedure cannot help here — the decision must instead be based on local knowledge. This does not mean that the result of the systematic procedure is irrelevant. It is always important to know which material is best, even if, for local reasons, you decide not to use it. We will explore supporting information more fully in Chapter 15. Here we focus on the derivation of property limits and indices.

3.7.7.Example: Materials for overhead transmission lines.

Electrical power, today, is generated centrally and distributed by overhead or underground cables. Buried lines are costly so cheaper overhead transmission (Figure 5.6) is widely used. A large span is desirable because the towers are expensive, but so too is a low electrical resistance to minimize power losses. The span of cable between two towers must support the tension needed to limit its sag and to tolerate wind and ice loads. Consider the simple case in which the tower spacing L is fixed at a distance that requires a cable with a strength σf of at least 80 MPa (a constraint). The objective then becomes that of minimizing resistive losses, and that means seeking materials with the lowest possible resistivity, ρe, defining the material index for the problem. The translation step is summarized in Table 5.3. The prescription, then, is to screen on strength and rank on resistivity.

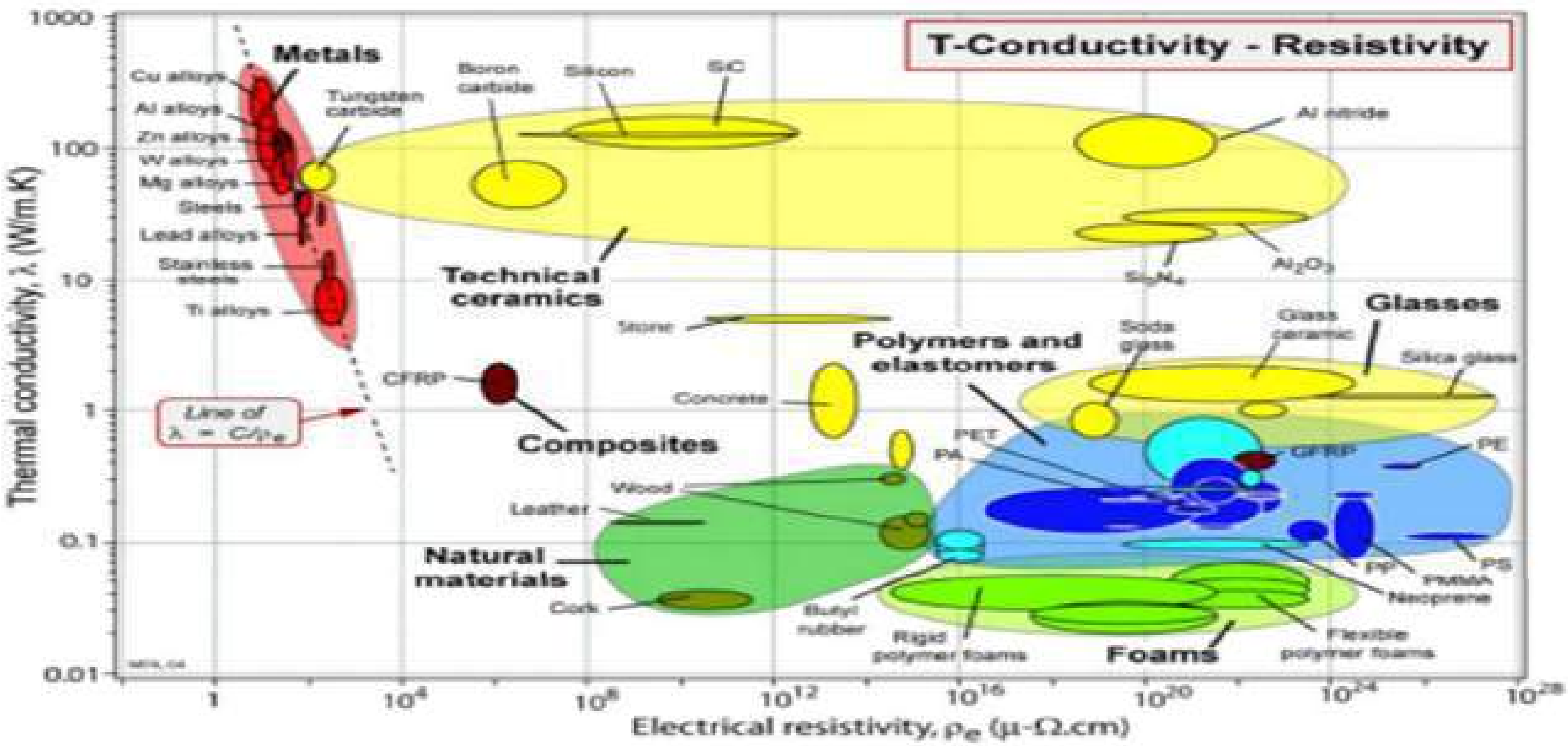


Figure 5.5 The λ-σe chart of Figure 4.10 with the attribute limit σe > 1019 and the index plotted on it. The selection is refined by raising the position of the selection line.

3.7.8. Material indicates when objectives are coupled to constraints

Think for a moment of the simplest of mechanical components, helped by Figure 5.7. The loading on a component can generally be decomposed into some combination of axial tension, bending, torsion, and compression. Almost always, one mode dominates. So common is this that the functional name given to the component describes the way it is loaded: ties carry tensile loads; beams carry bending moments; shafts carry torques; and columns carry compressive axial loads. The words ‘‘tie’’, ‘‘beam’’, ‘‘shaft’’, and ‘‘column’’ each imply a function. Many simple engineering functions can be described by single words or short phrases, saving the need to explain the function in detail. Here we explore property limits and material indices for some of these.

3.7.9. Example: Material index for a light, strong tie-rod.

A design calls for a cylindrical tie rod of specified length L to carry a tensile force F without failure; it is to be of minimum mass, as in the uppermost sketch in Figure 5.7. The length L is specified but the cross-section area A is not. Here, ‘‘maximizing performance’’ means ‘‘minimizing the mass while still carrying the load F safely’’. The design requirements, translated, are listed in Table 5.4. We first seek an equation describing the quantity to be maximized or minimized. Here it is the mass m of the tie, and it is a minimum that we seek. This equation, called the objective function, is m where A is the area of the cross-section and is the density of the material of which it is made. The length L and force F are specified and are there fore fixed; the cross-section A, is free. We can reduce the mass by reducing the cross-section, but there is a constraint: the section-area A must be sufficient to

- Table 5.4

  Design requirements for the light tie

  Function : Lengch L is specified

  Constraints : Tie must support axial tensile load F without failing Minimize the mass m of the tie

  Objective : Cross-section area, A

  Free variables : Choice of material

  Tie rod

- carry the tensile load F, requiring that

$$\frac{F}{A} \leq \sigma_{\mathrm{r}}$$

where σ_f is the failure strength. Eliminating A between these two equations give

$$m \geq (F)(L)\left(\frac{\rho}{\sigma_{\mathrm{f}}}\right)$$

Note the form of this result. The first bracket contains the specified load F. The second bracket contains the specified geometry (the length L of the tie). The last bracket contains the material properties. The lightest tie that will carry F

safely2 is that made of the material with the smallest value of ρ/σf. We could define this as the material index of the problem, seeking a minimum, but it is more usual, when dealing with specific properties, to express them in a form for which a maximum is sought. We therefore invert the material properties in equation (5.3) and define the material index M, as

$$M = \frac{\sigma_{\mathrm{I}}}{\rho}$$

The lightest tie-rod that will safely carry the load F without failing is that with the largest value of this index, the ‘‘specific strength’’, plotted in the chart of Figure 4.6. A similar calculation for a light stiff tie (one for which the stiffness S rather than the strength f is specified) leads to the index

$$M = \frac{E}{\rho}$$

where E is Young’s modulus. This time the index is the ‘‘specific stiffness’’, also shown in Figure 4.6. The material group (rather than just a single property) appears as the index in both cases because minimizing the mass m — the objective — was coupled to one of the constraints, that of carrying the load F without failing or deflecting too much. That was easy. Now for a slightly more difficult (and important) one.

3.7.10. Example: Material index for a light, stiff beam.

The mode of loading that most commonly dominates in engineering is not tension, but bending — think of floor joists, of wing spars, of golf-club shafts. Consider, then, a light beam of square section b and length L loaded in bending. It must meet a constraint on its stiffness S, meaning that it must not deflect more than under a load F (Figure 5.8). Table 5.5 translates the design requirements.The stiffness of beams is one of these. Turning to Section A3 we find an equation for the stiffness S of an elastic beam. The constraint requires that S ¼ F/ be greater than this:

$$S = \frac{F}{\delta} \geq \frac{C_1 EI}{L^3}$$

where E is Young’s modulus, C1 is a constant that depends on the distribution of load and I is the second moment of the area of the section, which, for a beam of square section (‘‘Useful Solutions’’, Appendix A, Section A.2), is

$$I = \frac{b^4}{12} = \frac{A^2}{12}$$

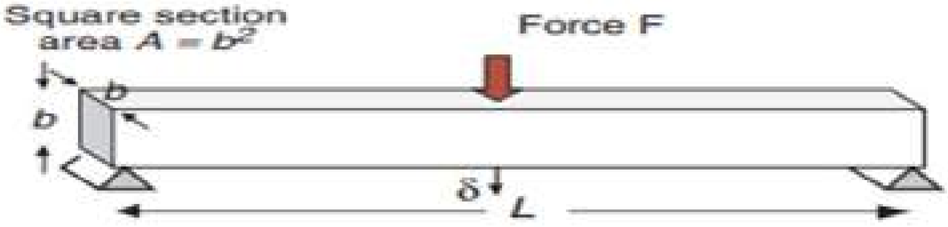


Figure 5.8 A beam of square section, loaded in bending. Its stiffness is S = F where F is the load and is the deflection.

Table 5.5 Design requirements for the light stiff beam

Function	**Beam**
Constraints	**Length *L* is specified**
	Beam must support a bending load *F* without deflecting too
	much, meaning that the bending stiffness *S* is specified
Objective	**Minimize the mass of the beam**
Free variables	**- Cross-section area, *A***
	- Choice of material

The stiffness S and the length L are specified; the section area A is free. We can reduce the mass of the beam by reducing A, but only so far that the stiffness constraint is still met. Using these two equations to eliminate A in equation (5.1) for the mass gives

$$m \geq \left(\frac{12S}{C_1 L}\right)^{1/2} (L^3) \left(\frac{\rho}{E^{1/2}}\right)$$

The brackets are ordered as before: functional requirement, geometry and material. The best materials for a light, stiff beam are those with the smallest values of $\rho/E^{1/2}$. As before, we will invert this, seeking instead large values of the material index

$$M = \frac{E^{1/2}}{\rho}$$

In deriving the index, we have assumed that the section of the beam remained square so that both edges changed in length when A changed. If one of the two dimensions is held fixed, the index changes. A panel is a flat plate with a given length L and width W; the only free variable (apart from material) is the thickness t. For this the index becomes (via an identical derivation)

$$M = \frac{E^{1/3}}{\rho}$$

Note the procedure. The length of the rod or beam is specified but we are free to choose the section area A. The objective is to minimize its mass, m. We write an equation for m: it is the objective function. But there is a constraint: the rod must carry the load F without yielding in tension (in the first example) or bending too much (in the second). Use this to eliminate the free variable A and read off the combination of properties, M, to be maximized. It sounds easy, and it is so long as you are clear from the start what the constraints are, what you are trying to maximize or minimize, which parameters are specified and which are free.

3.7.11. Deriving indices — how to do it

This is a good moment to describe the method in more general terms. Structural elements are components that perform a physical function: they carry loads, transmit heat, store energy, and so on: in short, they satisfy functional requirements. The functional requirements are specified by the design: a tie must carry a specified tensile load; a spring must provide a given restoring force or store a given energy, a heat exchanger must transmit heat a given heat flux, and so on. The performance of a structural element is determined by three things: the functional requirements, the geometry and the properties of the material of which it is made.3 The performance P of the element is described by an equation of the form

$$P=\left[\begin{pmatrix}\text{Functional}\\ \text{requirements, } F\end{pmatrix},\begin{pmatrix}\text{Geometric}\\ \text{parameters, } G\end{pmatrix},\begin{pmatrix}\text{Material}\\ \text{properties, } M\end{pmatrix}\right]$$

or

$$P=f(F,G,M)$$

where P, the performance metric, describes some aspect of the performance of the component: its mass, or volume, or cost, or life for example; and " f " means "a function of". Optimum design is the selection of the material and geometry that maximize or minimize P, according to its desirability or otherwise.

The three groups of parameters in equation (5.11) are said to be separable when the equation can be written

$$P = f_1(F) \cdot f_2(G) \cdot f_3(M)$$

where f_1, f_2, and f_3 are separate functions that are simply multiplied together. When the groups are separable, as they frequently are, the optimum choice of material becomes independent of the details of the design; it is the same for all geometries, G, and for all values of the function requirement, F. Then the optimum subset of materials can be identified without solving the complete design problem, or even knowing all the details of F and G. This enables

3.8. The selection procedure

We can now assemble the four steps into a systematic procedure:

3.8.1. Translation

Table 5.7 says it all. Simplified: identify the material attributes that are constrained by the design, decide what you will use as a criterion of excellence (to be minimized or maximized), substitute for any free variables using one of the constraints, and read off the combination of material properties that optimize the criterion of excellence.

3.8.2. Screening: applying attribute limits

Any design imposes certain non-negotiable demands (‘‘constraints’’) on the material of which it is made. We have explained how these are translated into attribute limits. Attribute limits plot as horizontal or vertical lines on material selection charts, illustrated in Figure 5.10. It shows a schematic E chart, in the manner of Chapter 4. We suppose that the design imposes limits on these of E > 10