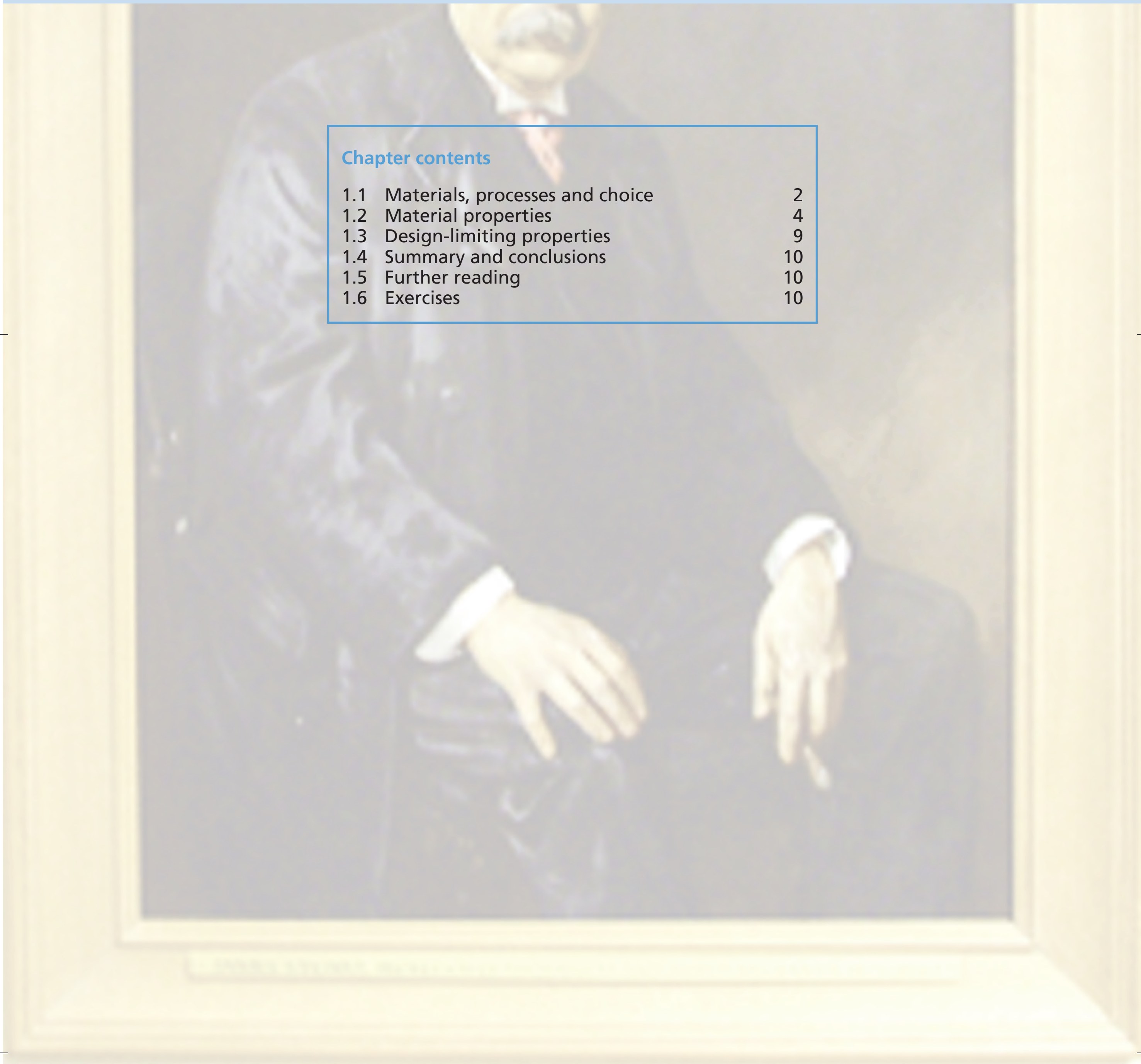
Chapter 1

Introduction: materials—history and character



Chapter contents

1.1 Materials, processes and choice

Engineers *make* things. They make them out of *materials*, and they shape, join and finish them using *processes*. The materials have to support loads, to insulate or conduct heat and electricity, to accept or reject magnetic flux, to transmit or reflect light, to survive in often-hostile surroundings, and to do all this without damage to the environment or costing too much.

And there is the partner in all this. To *make* something you also need a process. Not just any process—the one you choose has to be compatible with the material you plan to use. Sometimes it is the process that is the dominant partner and a material-mate must be found that is compatible with it. It is a marriage. Compatibility is not easily found—many marriages fail—and material failure can be catastrophic, with issues of liability and compensation. This sounds like food for lawyers, and sometimes it is: some specialists make their living as expert witnesses in court cases involving failed materials. But our aim here is not contention; rather, it is to give you a vision of the materials universe (since, even on the remotest planets you will find the same elements) and of the universe of processes, and to provide methods and tools for choosing them to ensure a happy, durable union.

But, you may say, engineers have been making things out of materials for centuries, and successfully so—think of Isambard Kingdom Brunel, Thomas Telford, Gustave Eiffel, Henry Ford, Karl Benz and Gottlieb Daimler, the Wright brothers. Why do we need new ways to choose them? A little history helps here. Glance at the portrait with which this chapter starts: it shows James Stuart, the first Professor of Engineering at Cambridge University from 1875 to 1890 (note the cigar). In his day the number of materials available to engineers was small—a few hundred at most. There were no synthetic polymers—there are now over 45 000 of them. There were no light alloys (aluminum was first established as an engineering material only in the 20th century)—now there are thousands. There were no high-performance composites—now there are hundreds of them. The history is developed further in Figure 1.1, the time-axis of which spans 10 000 years. It shows roughly when each of the main classes of materials first evolved. The time-scale is nonlinear—almost all the materials we use today were developed in the last 100 years. And this number is enormous: over 160 000 materials are available to today's engineer, presenting us with a problem that Professor Stuart did not have: that of optimally selecting from this huge menu. With the ever-increasing drive for performance, economy and efficiency, and the imperative to avoid damage to the environment, making the right choice becomes very important. Innovative design means the imaginative exploitation of the properties offered by materials.

These properties, today, are largely known and documented in handbooks; one such—the *ASM Materials Handbook*—runs to 22 fat volumes, and it is one of many. How are we to deal with this vast body of information? Fortunately another thing has changed since Prof. Stuart's day: we now have digital information storage and manipulation. Computer-aided design is now a standard part

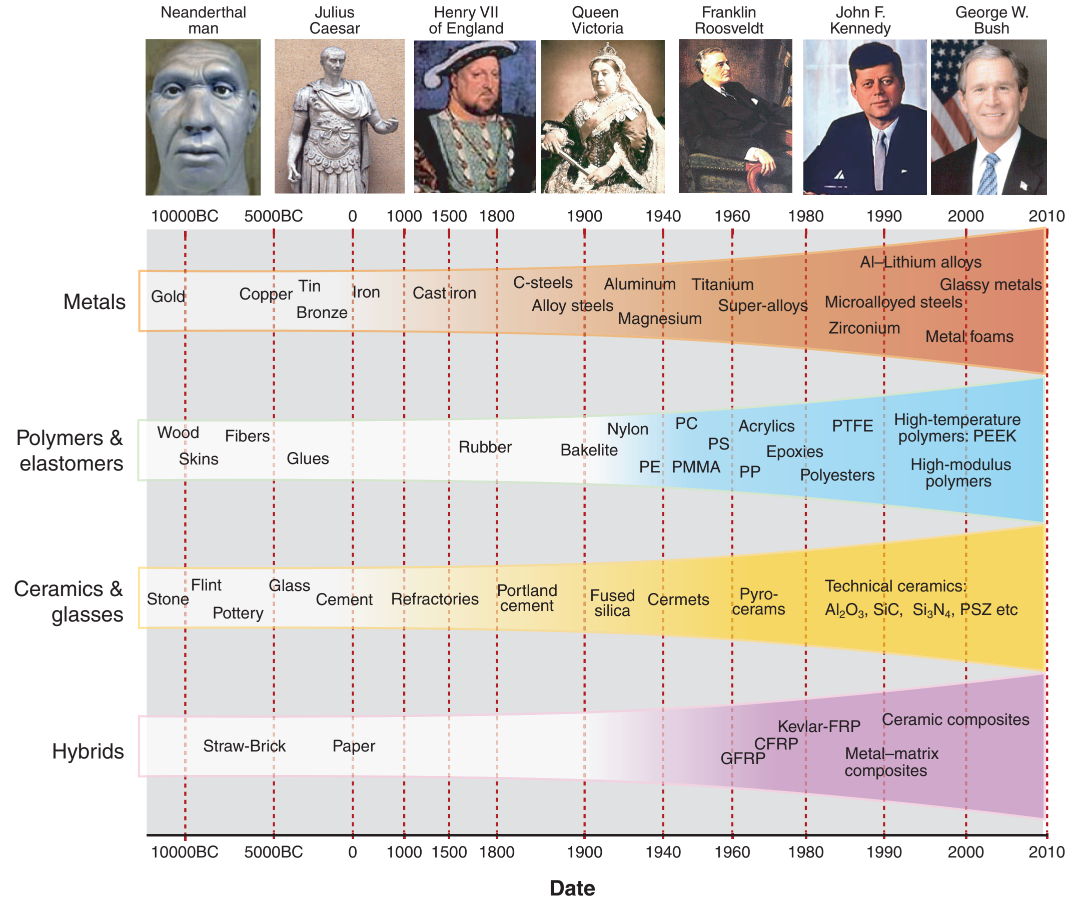


Figure 1.1 The development of materials over time. The materials of pre-history, on the left, all occur naturally; the challenge for the engineers of that era was one of shaping them. The development of thermochemistry and (later) of polymer chemistry enabled man-made materials, shown in the colored zones. Three—stone, bronze and iron—were of such importance that the era of their dominance is named after them.

of an engineer's training, and it is backed up by widely available packages for solid modeling, finite-element analysis, optimization, and for material and process selection. Software for the last of these—the selection of materials and processes—draws on databases of the attributes of materials and processes, documenting their mutual compatibility, and allows them to be searched and displayed in ways that enable selections that best meet the requirements of a design.

If you travel by foot, bicycle or car, you take a map. The materials landscape, like the terrestrial one, can be complex and confusing; maps, here, are also a good idea. This text presents a design-led approach to materials and manufacturing processes that makes use of maps: novel graphics to display the world of materials and processes in easily accessible ways. They present the properties of materials in ways that give a global view, that reveal relationships between properties and that enable selection.

1.2 Material properties

So what are these properties? Some, like density (mass per unit volume) and price (the cost per unit volume or weight) are familiar enough, but others are not, and getting them straight is essential. Think first of those that have to do with carrying load safely—the *mechanical properties*.

Mechanical properties

A steel ruler is easy to be bend *elastically*—'elastic' means that it springs back when released. Its elastic stiffness (here, resistance to bending) is set partly by its shape—thin strips are easy to bend—and partly by a property of the steel itself: its *elastic modulus*, E. Materials with high E, like steel, are intrinsically stiff; those with low E, like polyethylene, are not. Figure 1.2(b) illustrates the consequences of inadequate stiffness.

The steel ruler bends elastically, but if it is a good one, it is hard to give it a permanent bend. Permanent deformation has to do with *strength*, not stiffness. The ease with which a ruler can be permanently bent depends, again, on its shape and on a different property of the steel—its *yield strength*, σ_y. Materials with large σ_y, like titanium alloys, are hard to deform permanently even though their stiffness, coming from E, may not be high; those with low σ_y, like lead, can be deformed with ease. When metals deform, they generally get stronger (this is called 'work hardening'), but there is an ultimate limit, called the *tensile strength*, σ_{ts}, beyond which the material fails (the amount it stretches before it breaks is called the *ductility*). Figure 1.2(c) gives an idea of the consequences of inadequate strength.

So far so good. One more. If the ruler were made not of steel but of glass or of PMMA (Plexiglas, Perspex), as transparent rulers are, it is not possible to bend it permanently at all. The ruler will fracture suddenly, without warning, before it acquires a permanent bend. We think of materials that break in this way as brittle, and materials that do not as tough. There is no permanent deformation here, so σ_y is not the right property. The resistance of materials to cracking and fracture is measured instead by the *fracture toughness*, K_{1c}. Steels are tough—well, most are (steels *can* be made brittle)—they have a high K_{1c}. Glass epitomizes brittleness; it has a very low K_{1c}. Figure 1.2(d) suggests consequences of inadequate fracture and toughness.

We started with the material property *density*, mass per unit volume, symbol ρ. Density, in a ruler, is irrelevant. But for almost anything that moves, weight carries a fuel penalty, modest for automobiles, greater for trucks and trains, greater still for aircraft, and enormous in space vehicles. Minimizing weight has

CH001 11/28/06 7:56 PM Page 5

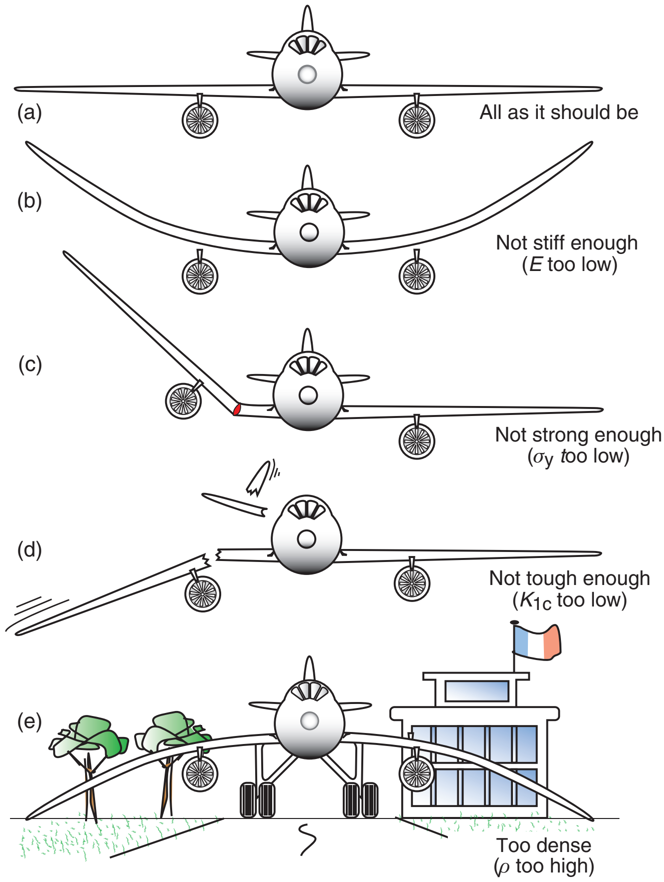


Figure 1.2 Mechanical properties.

much to do with clever design—we will get to that later—but equally to choice of material. Aluminum has a low density, lead a high one. If our little aircraft were made of lead, it would never get off the ground at all (Figure 1.2(e)).

These are not the only mechanical properties, but they are the most important ones. We will meet them, and the others, in Chapters 4–11.

Thermal properties

The properties of a material change with temperature, usually for the worse. Its strength falls, it starts to 'creep' (to sag slowly over time), it may oxidize, degrade or decompose (Figure 1.3(a)). This means that there is a limiting temperature called the *maximum service temperature*, T_{max}, above which its use is impractical. Stainless steel has a high T_{max}—it can be used up to 800°C; most polymers have a low T_{max} and are seldom used above 150°C.

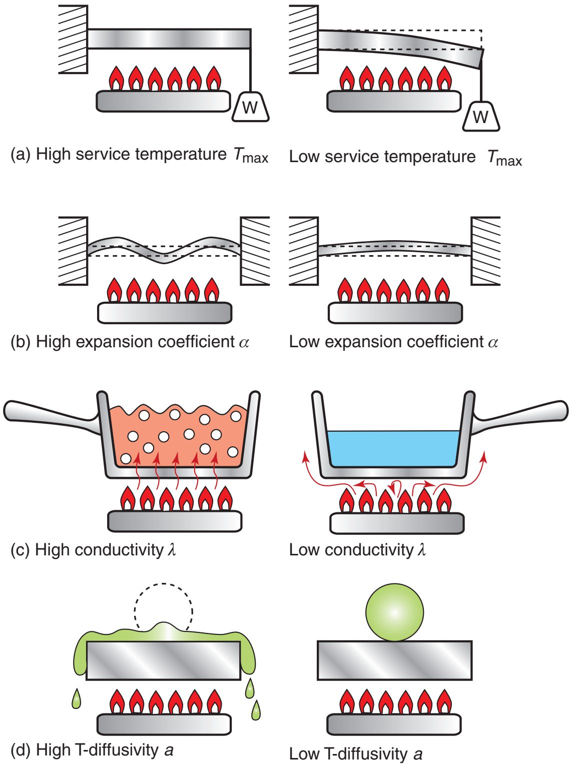


Figure 1.3 Thermal properties.

Most materials expand when they are heated, but by differing amounts depending on their thermal expansion coefficient, α. The expansion is small, but its consequences can be large. If, for instance, a rod is constrained, as in Figure 1.3(b), and then heated, expansion forces the rod against the constraints, causing it to buckle. Railroad track buckles in this way if provision is not made to cope with it.

Some materials—metals, for instance—feel cold; others—like woods—feel warm. This feel has to do with two thermal properties of the material: *thermal conductivity* and *heat capacity*. The first, thermal conductivity, λ, measures the rate at which heat flows through the material when one side is hot and the other cold. Materials with high λ are what you want if you wish to conduct heat from one place to another, as in cooking pans, radiators and heat exchangers; Figure 1.3(c) suggests consequences of high and low λ for the cooking vessel. But low λ is useful too—low λ materials insulate homes, reduce the energy consumption of refrigerators and freezers, and enable space vehicles to re-enter the earth's atmosphere.

These applications have to do with long-time, steady, heat flow. When time is limited, that other property—*heat capacity*, C_p—matters. It measures the amount of heat that it takes to make the temperature of material rise by a given amount. High heat capacity materials—copper, for instance—require a lot of heat to change their temperature; low heat capacity materials, like polymer foams, take much less. Steady heat flow has, as we have said, to do with thermal conductivity. There is a subtler property that describes what happens when [AU] heat is first applied. Think of lighting the gas under a cold slab of material with a bole of ice-cream on top (here, lime ice-cream) as in Figure 1.3(d). An instant after ignition, the bottom surface is hot but the rest is cold. After a while, the middle gets hot, then later still, the top begins to warm up and the ice-cream first starts to melt. How long does this take? For a given thickness of slab, the time is inversely proportional to the *thermal diffusivity, a,* of the material of the slab. It differs from the conductivity because materials differ in their heat capacity—in fact, it is proportional to λ/C_p.

There are other thermal properties—we'll meet them in Chapters 12 and 17—but this is enough for now. We turn now to matters electrical, magnetic and optical.

Electrical, magnetic and optical properties

We start with electrical conduction and insulation (Figure 1.4(a)). Without electrical conduction we would lack the easy access to light, heat, power, control and communication that—today—we take for granted. Metals conduct well—copper and aluminum are the best of those that are affordable. But conduction is not always a good thing. Fuse boxes, switch casings, the suspensions for transmission lines all require insulators, and in addition those that can carry some load, tolerate some heat and survive a spark if there were one. Here the property we want is *resistivity*, ρ_e, the inverse of electrical conductivity κ_e. Most plastics and glass have high resistivity (Figure 1.4(a))—they are used as insulators—though, by special treatment, they can be made to conduct a little.

Figure 1.4(b) suggests further electrical properties: the ability to allow the passage of microwave radiation, as in the radome, or to reflect them, as in the passive reflector of the boat. Both have to do with *dielectric* properties, particularly the *dielectric constant* ε_D. Materials with high ε_D respond to an electric field by shifting their electrons about, even reorienting their molecules; those with low ε_D are immune to the field and do not respond. We explore this and other electrical properties in Chapter 13.

Electricity and magnetism are closely linked. Electric currents induce magnetic fields; a moving magnet induces, in any nearby conductor, an electric current. The response of most materials to magnetic fields is too small to be of practical value. But a few—called ferromagnets and ferrimagnets—have the capacity to trap a magnetic field permanently. These are called 'hard' magnetic materials because, once magnetized, they are hard to demagnetize. They are used as permanent magnets in headphones, motors and dynamos. Here the key property is the *remanence*, a measure of the intensity of the retained magnetism. A few others—'soft'

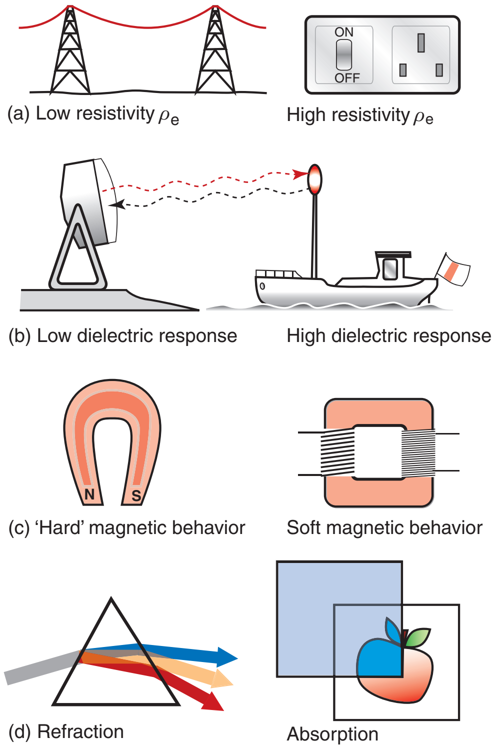


Figure 1.4 Electrical, magnetic and optical properties.

magnet materials—are easy to magnetize and demagnetize. They are the materials of transformer cores and the deflection coils of a TV tube. They have the capacity to conduct a magnetic field, but not retain it permanently (Figure 1.4(c)). For these a key property is the *saturation magnetization*, which measures how large a field the material can conduct. These we meet again in Chapter 14.

Materials respond to light as well as to electricity and magnetism—hardly surprising, since light itself is an electromagnetic wave. Materials that are opaque *reflect* light; those that are transparent *refract* it, and some have the ability to *absorb* some wavelengths (colors) while allowing others to pass freely (Figure 1.4(d)). These are explored in more depth in Chapter 15.

Chemical properties

Products often have to function in hostile environments, exposed to corrosive fluids, to hot gases or to radiation. Damp air is corrosive, so is water; the sweat of your hand is particularly corrosive, and of course there are far more aggressive environments than these. If the product is to survive for its design life it must be made of materials—or at least coated with materials—that can tolerate the surroundings in which they operate. Figure 1.5 illustrates some of the commonest of these: fresh and salt water, acids and alkalis, organic solvents, oxidizing flames

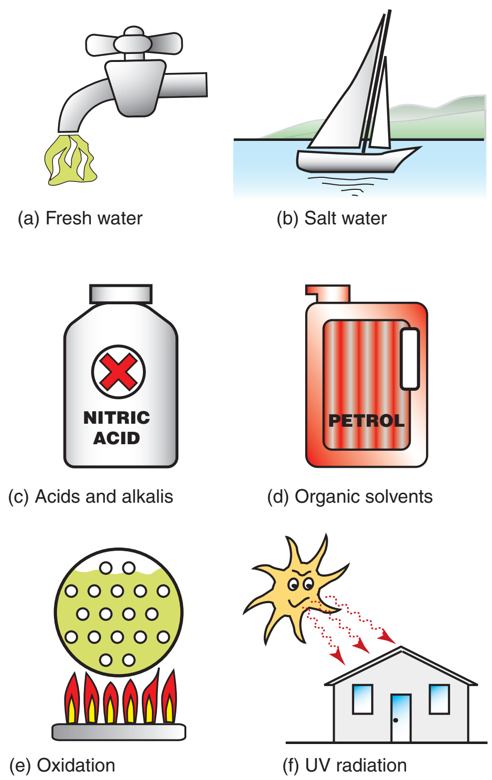


Figure 1.5 Chemical properties: resistance to water, acids, alkalis, organic solvents, oxidation and radiation.

and ultraviolet radiation. We regard the intrinsic resistance of a material to each of these as material properties, measured on a scale of 1 (very poor) to 5 (very good). Chapter 16 deals with the material durability.

1.3 Design-limiting properties

The performance of a component is limited by certain of the properties of the materials of which it is made. This means that, to achieve a desired level of performance, the values of the design-limiting properties must meet certain targets—those that fail to do so are not suitable. In the cartoon of Figure 1.2, stiffness, strength and toughness are design limiting—if any one of them were too low, the plane won't fly. In the design of power transmission lines electrical resistivity is design limiting; in the design of a camera lens, it is optical quality and refractive index.

Materials are chosen by identifying the design-limiting properties and applying limits to them, screening out those that do not meet the limits (Chapter 3).

Processes, too, have properties, although we have not met them yet. These too can be design limiting, leading to a parallel scheme for choosing viable processes (Chapters 18 and 19).

1.4 Summary and conclusions

Engineering design depends on *materials* that are shaped, joined and finished by *processes*. Design requirements define the performance required of the materials, expressed as target values for certain *design-limiting properties*. A material is chosen because it has properties that meet these targets and is compatible with the processes required to shape, join and finish it.

This chapter introduced some of the design-limiting properties (*physical properties* like density, *mechanical properties* like modulus and yield strength) and *functional properties* (those describing the thermal, electrical, magnetic and optical behavior). We examine all of these in more depth in the chapters that follow, but those just introduced are enough to be going on with. We turn now to the materials themselves: the families, the classes and the members.

1.5 Further reading

The history and evolution of materials

A History of Technology (1954–2001) (21 volumes), edited by Singer, C., Holmyard, E.J., Hall, A.R., Williams, T.I. and Hollister-Short, G. Oxford University Press, Oxford, UK. ISSN 0307-5451. (*A compilation of essays on aspects of technology, including materials.*)

Delmonte, J. (1985) *Origins of Materials and Processes*, Technomic Publishing Company, Pennsylvania, USA. ISBN 87762-420-8. (*A compendium of information about materials in engineering, documenting the history.*)

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

1.6 Exercises

Exercise E1.1 Use Google to research the history and uses of one of the following materials:

- Tin
- Glass
- Cement

- Titanium
- Carbon fiber.

Present the result as a short report of about 100–200 words (roughly half a page).

Exercise E1.2 What is meant by the *design-limiting properties* of a material in a given application?

Exercise E1.3 There have been many attempts to manufacture and market plastic bicycles. All have been too flexible. Which design-limiting property is insufficiently large?

Exercise E1.4 What, in your judgement, are the design-limiting properties for the material for the blade of a knife that will be used to gut fish?

Exercise E1.5 What, in your judgement, are the design-limiting properties for the material of an oven glove?

Exercise E1.6 What, in your judgement, are the design-limiting properties for the material of an electric lamp filament?

Exercise E1.7 A material is needed for a flexible tube to carry fuel from the fuel tank to the carburetor of a motor mower. The design requires that the tube be flexible and transparent. List what you would think to be the design-limiting properties.

Exercise E1.8 A material is required as the magnet for a magnetic soap holder. Soap is mildly alkaline. List what you would judge to be the design-limiting properties.

Exercise E1.9 The cases in which most CDs are sold have an irritating way of cracking and breaking. Which design-limiting property has been neglected in selecting the material of which they are made?

Exercise E1.10 List three applications that, in your judgement, need high stiffness and low weight.

Exercise E1.11 List three applications that, in your judgement, need optical quality glass.