Chapter 1 Introduction: materials-history and character

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 support loads, they insulate or conduct heat and electricity, and they channel or reject magnetic flux, transmit or reflect light, and tolerate hostile surroundings. Ideally, they do all this without damage to the environment or costing too much. To make something, you also need a *process*, one that is compatible with the material you plan to use. Sometimes it is the process that is the dominant partner, and a material match must be found. Compatibility with viable processing conditions is not always easy to find, and material failure can be catastrophic, with issues of liability and compensation. But our aim here is not contention; rather, it is to give a vision of the universe of materials (universe, since even on the remotest planets you will find the same elements) and of the universe of processes, and to provide methods for choosing them to ensure a durable, compatible 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. The portrait with which this chapter starts shows James Stuart, the first professor of engineering at Cambridge University. 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 (aluminium was first used in engineering only in the 20th century) — now there are thousands. There were no high-performance composites — now there are hundreds to choose from. The history is developed further in Figure 1.1, the time axis of which spans 10,000 years. The timescale is non-linear — 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 the best one. 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: digital information storage and manipulation. Computer-aided design is now a standard part of an engineer's training, and it is backed up by widely available packages for solid modelling, finiteelement analysis, optimisation and for material and process selection. Soft- ware 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 re- quirements 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, revealing relationships between properties and enabling selection.

1.2 Material properties

What are 'material properties'? Some, like density ɵ mass per unit volume ɵ and price ɵ the cost per unit volume or weight ɵ are familiar enough, but others are not, and getting them straight is essential. Think first of those that relate to the safe carrying of loads ɵ the *me- chanical properties*.

Mechanical Properties. A steel ruler is easy to bend *elastically* ɵ 'elastic' means that it springs back when released. Its elastic stiffness (here, resistance to bending) is set partly by its shape ɵ thin strips are easier to bend than thick ones ɵ 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 relates to *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 ɵ its *yield strength*, S_y. Materials with large S_y, like titanium alloys, are hard to deform permanently, even though their stiffness, coming from *E*, may not be high. Those with low S_y, like lead, can be deformed with ease. When metals deform, they generally get stronger (it is called 'work hardening'), but there is an ultimate limit, called the *tensile strength*, S_{ts}, beyond which the material fails (and the amount it stretches before it breaks is called the *ductility)*. The hardness, *H*, is related to the strength, S_y. High hardness gives scratch resistance and resistance to wear. Figure 1.2(c) gives an idea of the consequences of inade- quate strength.

So far so good. There is one more property, and it is a tricky one. If the ruler were made not of steel but of glass or of PMMA (Plexiglass, Perspex), as transparent rulers are, it is not possible to bend it permanently at all. The ruler will fracture suddenly before it acquires a permanent bend. We think of materials that break in this way as brittle, and materials that deform and resist fracture as tough. If there is no permanent deformation, then s_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 ɵ well, most are (steels *can* be made brittle) ɵ they have a high K_{1c}. Glass epitomises brittleness; it has a very low K_{1c}. Figure 1.2(d) suggests the consequences of inadequate fracture toughness.

We started with the material property *density*, symbol r. 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. Minimising weight has much to do with clever design ɵ we will get to that later ɵ but equally, to the choice of material. Aluminium has a low density, lead a high one. If our airplane 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 4ɵ11.

Thermal Properties. The properties of a material change with temperature, usually for the worse. Its strength falls, it starts to *creep* ɵ to sag slowly over time ɵ it may oxidise, 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} ɵ it can be used up to 800 C; most polymers have a low T_{max} and are seldom used above 150 C.

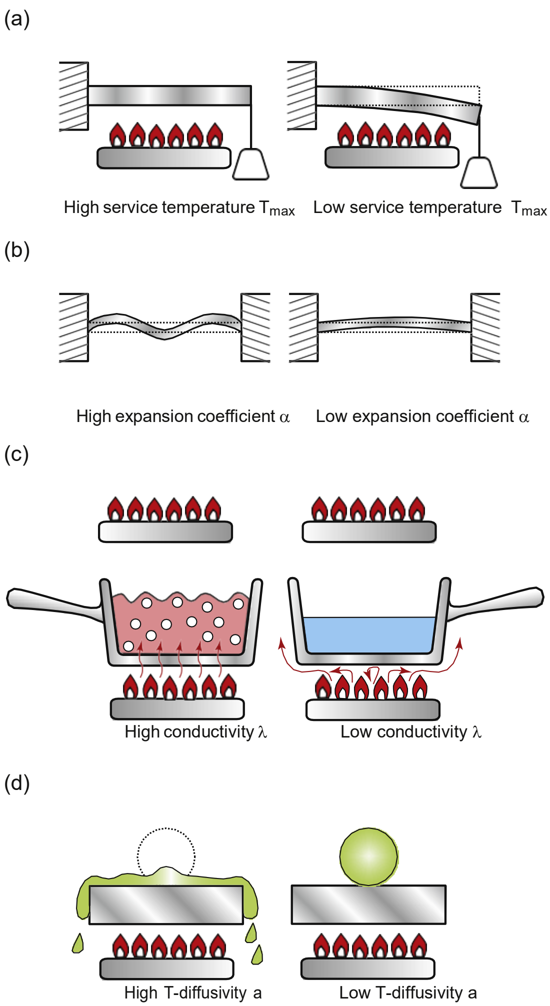

Figure 1.3 Thermal properties.

Most materials expand when they are heated, but by differing amounts depending on their thermal expansion coefficient, a. The expansion is small, but its consequences can be large. If, for instance, a rod is constrained and then heated, as in Figure 1.3(b), 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. Bridges have expansion joints for the same reason.

Metals feel cold; woods feel warm. This feel has to do with two thermal properties: *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 a 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 — enters the picture. It measures the amount of heat required to make the temperature of a 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 heat is first applied. Think of lighting the gas under a cold slab of material with a scoop of ice cream on top, as in Figure 1.3(d). An instant after ignition, the bottom surface is hot, but the rest is cold. After a time, the middle gets hot; then later still, the top begins to warm up, and only then does the ice cream start 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, a is proportional to l/C_p.

Chemical properties. Products often encounter hostile environments and are exposed to corrosive fluids or hot gases or 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 it operates. Figure 1.4 illustrates some of the commonest of these: fresh and salt water, acids and alkalis, organic solvents, oxidising flames and ultra-violet 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 14 deals with material durability.

Figure 1.4 Chemical properties: resistance to water, acids, alkalis, organic solvents, oxidation and radiation.

Electrical, magnetic and optical properties. Without electrical conduction, we would lack the easy access to light, heat, power, control and communication that we take for granted. Metals conduct well ⊖ copper and aluminium are the best of those that are affordable. But conduction is not always a good thing. Fuse boxes, switch casings, and the suspensions

for transmission lines all require insulators that must also carry some load, tolerate some heat, and survive a spark if there is one. Here the property we want is *resistivity*, r_e, the inverse of electrical conductivity, k_e. Most plastics and glass have high resistivity (Figure 1.5(a)) ⊖ they are used as insulators ⊖ though, by special treatment, they can be made to conduct a little.

Figure 1.5 Electrical, magnetic and optical properties.

Figure 1.5(b) suggests further electrical properties: the ability to allow the passage of microwave radiation, as in the radome, or to reflect it, 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 re-orienting 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 15.

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 ⊖ ferro-magnets and ferri-magnets ⊖ 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. In contrast, the 'soft' magnetic materials are easy to magnetise ⊖ they are the materials of transformer cores. They have the capacity to conduct a magnetic field, but not retain it permanently (Figure 1.5(c)). For these, a key property is the *saturation magnetisation*, which measures how large a field the material can conduct. These materials and properties we meet again in Chapter 16.

Materials respond to light as well as to electricity and magnetism ⊖ hardly surprising, since light itself is an electro-magnetic wave. Materials that are opaque *reflect* light; those that are transparent *refract* it. Some are opaque to all wavelengths (colours); others *absorb* specific wavelengths while allowing others to pass freely (Figure 1.5(d)). These are explored in more depth in Chapter 17.

Environmental properties. Making, shaping, joining and finishing materials consumes nearly one-third of global energy demand. The associated emissions are already a cause for international concern, and demand for material extraction and processing is likely to double in the next 40 years. It's important, therefore, to understand the envi- ronmental properties of materials and to seek ways to use them more sustainably than

we do now. Chapter 20 introduces the key ideas of material life-cycle analysis, material efficiency and sustainability, all of which are central to the way we will use materials in the future.

Three quantities describe the environmental character of a material (Figure 1.6):

embodied energy ⊖ the energy required to produce 1 kg of the material, including that used to mine and refine the feedstocks, and that required to refine or synthesise these into usable material stock;
carbon footprint ⊖ the mass of carbon released due to the production of 1 kg of the material (or, strictly, the carbon-equivalent release ⊖ a way of including the global warming effect of all the gaseous emissions);
water demand ⊖ the volume of water that is drawn from usable sources and not returned to them during the production of 1 kg of material.

The performance of a component is limited by the properties of the materials of which it is made. 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 wouldn't fly. In the design of power transmission lines, electrical resistivity is design-limiting; in the design of a camera lens, it is optical qualities that constrain the design.
Materials are chosen by identifying the design-limiting properties and applying limits to them and screening out materials 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 target values for the *design-limiting properties*. A material is chosen because it has properties that meet these targets and is compatible with the processes that will be used 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; *functional properties*: those describing the thermal, electrical, magnetic and optical behaviour; *chemical properties*: those determining how the material reacts with its environment; and *eco-properties*: those that relate to the impact the production of the material has on the world around it. We examine these in more depth in the chapters that follow, but turn next to the materials themselves: the families, the classes and the members

Chapter 2

Family trees: organising materials and processes

2.1 Introduction and synopsis

A successful product ɘ one that performs well, gives pleasure to the user, and is good value for money ɘ uses the best materials for the job and fully exploits their potential and characteristics. The families of materials ɘ metals, polymers, ceramics and so forth ɘ are introduced in Section 2.2. But it is not, in the end, a *material* that we seek in design; it is a certain *profile of properties* ɘ the one that best meets the needs of the design. The members of each family have characteristics in common ɘ a sort of 'family likeness' ɘ which is useful when deciding which family offers the best starting point for a given design. Section 2.2 explains how this enables a classification scheme for materials, allowing information about them to be organised.

Choosing a material is only half the story. The other half is the choice of a process route to shape, join and finish it. Section 2.3 introduces process families and their attributes. Choice of material and process are tightly coupled: a given material can be processed in some ways but not others, and a given process works with some materials but not with others. On top of that, the act of processing can change, even create, the properties of the material (Section 2.4). Process families, too, exhibit family likenesses ɘ commonality in the materials that members of a family can handle, or the shapes they can make. Section 2.3 introduces a classification for processes that parallels that for materials.

Family likenesses are most strikingly seen in *material property charts*, which are a central feature of this book (Section 2.5). These are charts with material properties as axes showing the location of the families and their members. Materials have many properties. They can be thought of as the axes of a 'materialɘproperty' space ɘ each chart is a two-dimensional slice through this space. Each material family occupies a discrete part of this space, distinct from the other families. The charts give an overview of materials and their properties; they reveal aspects of the science underlying the properties, and they provide a powerful tool for materials selection. Process attributes can be treated in a similar way to create process attribute charts. We leave these for Chapter 18.

The classification systems of Sections 2.2 and 2.3 provide a structure for computer-based information management, which is introduced in Section 2.6. In common with the rest of the book, the chapter ends with a summary, further reading and exercises.

2.2 Organising materials: the materials tree

Classifying materials. It is conventional to classify the materials of engineering into the six broad families shown in Figure 2.1: metals, polymers, elastomers, ceramics, glasses and hybrids ɘ composite materials made by combining two or more of the others. There is sense in this: the members of a family have certain features in common ɘ similar properties, similar processing routes and, often, similar applications.

Figure 2.2 illustrates how the families are expanded to show classes, sub-classes and members, each of which is characterised by a set of *attributes*: its properties. As an example, the Materials Universe contains the family *Metals*, which in turn contains the class *Aluminium alloys*, which contains the sub-class the *6000 series*, within which we find the particular member *Alloy 6061*. It, and every other member of the Universe, is char- acterised by a set of attributes that include not only the properties mentioned in Chapter 1, but also its processing characteristics and its typical applications. We call this its *property profile*.

As already mentioned, the members of one family have certain characteristics in common. Here, briefly, are some of them. *Metals* have relatively high stiffness, measured by the elastic modulus *E*. Most, when pure, are soft and easily deformed, meaning that the yield strength S_y is low. They can be made stronger by alloying and by mechanical and heat treatment, increasing S_y, but they remain ductile, allowing them to be formed by deformation processes like rolling or forging. And, broadly speaking, they are tough, with a usefully high fracture toughness, K_{1c}. They are good electrical and thermal conductors. But metals have weaknesses too: they are reactive, and most corrode rapidly if not protected.

Ceramics are non-metallic, inorganic solids, like porcelain or alumina ⊖ the material of the insulator casing of the spark plug in a petrol engine. They have many attractive features: they are stiff, hard and abrasion resistant; they retain their strength at high temperatures; and they resist corrosion well. Most are good electrical insulators. They, too, have their weaknesses: unlike metals, they are brittle, with low K_{1c}. giving ceramics a low tolerance for stress con- centrations (like holes or cracks) or for high contact stresses (at clamping points, for instance). *Glasses* are non-crystalline ('amorphous') solids, a term explained more fully in Chapter 4. The commonest are the soda-lime and boro-silicate glasses familiar as bottles and Pyrex ovenware, but there are many more. The lack of crystal structure suppresses plasticity, so, like ceramics, glasses are hard and remarkably corrosion resistant. They are excellent electrical insulators, and of course, they are transparent to light. But like ceramics, they are brittle and vulnerable to stress concentrations.

Polymers are organic solids based on long-chain molecules of carbon atoms (or, in a few, silicon). Polymers are light ⊖ their densities ρ are less than those of the lightest metals. Compared with other families, they are floppy, with moduli *E* that are roughly 50 times less than those of metals. But they can be strong, and because of their low density, their strength per unit weight is comparable to that of metals. Their properties depend on temperature, so a polymer that is tough and flexible at room temperature may be brittle at the 4°C of a household freezer, yet turn rubbery at the 100°C of boiling water. Few have useful strength above 150°C. If these aspects are allowed for in the design, the many advantages of polymers can be exploited. They are easy to shape (which is why they are called 'plastics'). Complicated parts performing several functions can be moulded from a polymer in a single operation. Their properties are well suited for components that snap together, making assembly fast and cheap. And by accurately sizing the mould and pre-colouring the polymer, no finishing operations are needed. Good design exploits these properties.

Elastomers, the material of rubber bands and running shoes, are polymers with the unique property that their stiffness, measured by *E*, is extremely low ⊖ 500 to 5000 times less than those of metals ⊖ and they can be stretched to many times their starting length yet recover their initial shape when released. Despite their low stiffness, they can be strong and tough ⊖ think of car tires.

Hybrids are combinations of two (or more) materials in an attempt to get the best of both. Glass- and carbon-fibre reinforced polymers (GFRP and CFRP) are hybrids; so, too, are sandwich structures, foams and laminates. And almost all the materials of nature ⊖ wood, bone, skin, leaf ⊖ are hybrids. Bone, for instance, is a mix of collagen (a polymer) with hy- droxyapatite (a mineral). 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, light weight and fuel efficiency provide increasing drivers for their use.

2.3 Organising processes: the process tree

A *process* is a method of shaping, joining or finishing a material. *Casting, injection moulding*, *fusion welding* and *electro-polishing* are all processes, and there are hundreds of them to choose from (Figures 2.3 and 2.4). It is important to select the right process route at an early stage in the design before the cost penalty of making changes becomes large. The choice for a given component depends on the material of which it is to be made; on its shape, dimensions and precision; and on how many are to be made ⊖ in short, on the *design requirements*.

The choice of material limits the choice of process. Polymers can be moulded; other mate- rials cannot. Ductile materials can be forged, rolled and drawn, but those that are brittle must be shaped in other ways. Materials that melt at modest temperatures to low-viscosity liquids can be cast; those that do not have to be processed by other routes. Shape, too, influences the

choice of process. Slender shapes can be made easily by rolling or drawing but not by casting. Hollow shapes cannot be made by forging, but they can by casting or moulding.

Classifying processes Manufacturing processes are organised under the headings shown in Figure 2.3. *Primary processes* create shapes. The first row lists six primary forming processes: casting, moulding, deformation, powder methods, methods for forming composites, and special methods including additive manufacture. *Secondary processes* modify shapes or properties; here they are shown as *machining*, which adds features to an already shaped body, and *heat treatment*, which enhances bulk properties. Below these come *joining*, and, finally, *surface treatment.* Figure 2.4 illustrates some of these; it is organised in the same way as Figure 2.3. The figure is a sort of flow chart: a progression through a manufacturing route. It should not be treated too literally; the order of the steps can be varied to suit the needs of the design.

Information about processes can be arranged in a hierarchical classification like that used for materials, giving each process a place. Figure 2.5 shows part of the hierarchy. The Process Universe has three families: *shaping, joining* and *surface treatment*. In this figure, the shaping family is expanded to show classes: casting, deformation, moulding and so on. One of these, *moulding*, is again expanded to show its members: rotation moulding, blow moulding, in- jection moulding and so forth. Each process is characterised by a set of *attributes*: the materials it can handle, the shapes it can make, their size, precision and an economic batch size (the number of units that it can make most economically).

The other two families are partly expanded in Figure 2.6. There are three broad classes of joining process: adhesives, welding and fasteners. In this figure, one of them, *welding*, is expanded to show its members. As before, each member has attributes. The first is the material

or materials that the process can join. After that, the attribute list differs from that for shaping. Here the geometry of the joint and the way it will be loaded are important, as are requirements that the joint can or cannot be disassembled, be watertight or be electrically conducting.

The lower part of the figure expands the family of surface treatment processes. Some of the classes it contains are shown; one, *coating*, is expanded to show some of its members. Finishing adds cost; the only justification for applying a finishing process is that it hardens, protects or decorates the surface in ways that add value.

We will return to process selection in Chapter 18, exploring how far a database of processes and their attributes can take us in design.

2.4 Process⊖property interaction

Processing can change properties. If you deform a metal, it gets harder ('work hardening'); if you then heat it up, it gets softer again ('annealing'). If polyethylene (PE) ⊖ the stuff of plastic bags ⊖ is drawn to a fibre, its strength is increased by a factor of five because the polymer chains are drawn into alignment. Soft, stretchy rubber is made hard and brittle by vulcanising. Glass can be chemically and thermally treated to give it the impact resistance to withstand a projectile ('bulletproof glass'). And composites like carbon fibre-reinforced epoxy have no useful properties at all until processed ⊖ prior to processing, they are just a soup of resin and a sheaf of fibres.

Joining, too, changes properties. Fusion welding involves the local melting and re-solidifying of the faces of the parts to be joined. As you might expect, the weld zone has properties that differ from those of the material far from the weld ⊖ usually worse. Surface treatments, by contrast, are generally chosen to improve properties: electroplating to improve corrosion resistance, or carburising to improve wear.

We return to process⊖property interactions in depth in Chapter 19, but many examples of the effect of processing on properties will be encountered on the way.

2.5 Material property charts

Data sheets for materials list their properties, but they give no perspective and present no comparisons. The way to achieve these is to plot *material property charts*. They are of two types: bar charts and bubble charts.

A *bar chart* is simply a plot of one property for all the materials of the Universe, or a subset of them. Figure 2.7 shows an example: it is a bar chart for modulus *E*. The largest is more than 10 million times greater than the smallest ⊖ many other properties have similarly large ranges ⊖ so it makes sense to plot them on logarithmic[1], not linear scales, as here. The length of each bar shows the range of the property for each material, here segregated by family. The differences between the families now become apparent. Metals and ceramics have high moduli. Those of polymers are smaller, by a factor of about 50, than those of metals, while those of elastomers are some 500 times smaller still.

More information is packed into the picture if two properties are plotted to give a *bubble chart*, as in Figure 2.8, here showing modulus *E* and density r. As before, the scales are logarithmic. Now the families are more distinctly separated: all metals lie in the reddish zone near the top right; all polymers lie in the dark-blue envelope in the centre, elastomers in the

lighter blue envelope below, ceramics in the yellow envelope at the top. Each family occupies a distinct, characteristic field. Within these fields, individual materials appear as smaller ellipses.

Material property charts like these are a core tool used throughout this book:
They give an overview of the physical, mechanical and functional properties of materials, presenting the information about them in a compact way.
They reveal aspects of the physical origins of properties, a help in understanding the underlying science.
They become a tool for optimised selection of materials to meet given design requirements, and they help us understand the use of materials in existing products.

2.7 Summary and conclusions

Classification is the first step in creating an information management system for materials and processes. In it the records for the members of each Universe are indexed, so to speak, by their position in the tree-like hierarchies of Figures 2.2, 2.5 and 2.6. Each record has a unique place, making retrieval easy.

There are six broad families of materials for mechanical design: metals, ceramics, glasses, polymers, elastomers, and hybrids that combine the properties of two or more of the others. Processes, similarly, can be grouped into families: those that create shape, those that join, and those that modify the surface to enhance its properties or to protect or decorate it. This structure forms the basis of computer-based materials selection systems, now widely available. Property charts are a unique and powerful way of presenting data for materials ⊖ two examples appeared in this chapter. They become one of the central features of the chapters that follow.