Chapter 1

Engineering materials and their properties

Chapter contents

1.1 Introduction

There are, it is said, more than 50,000 materials available to the engineer. In designing a structure or device, how is the engineer to choose from this vast menu the material which best suits the purpose? Mistakes can cause disasters. During World War II, one class of welded merchant ship suffered heavy losses, not by enemy attack, but by breaking in half at sea: the *fracture toughness* of the steel — and, particularly, of the welds was too low. More recently, three Comet aircraft were lost before it was realised that the design called for a *fatigue strength* that — given the design of the window frames — was greater than that possessed by the material. You yourself will be familiar with poorly designed appliances made of plastic: their excessive "give" is because the designer did not allow for the low *modulus* of the polymer. These bulk properties are listed in Table 1.1, along with other common classes of property that the designer must consider when choosing a material. Many of these

Table 1.1 Classes of property

Economic	Price and availability Recyclability
General Physical	Density
Mechanical	Modulus Yield and tensile strength Hardness Fracture toughness Fatigue strength Creep strength Damping
Thermal	Thermal conductivity Specific heat Thermal expansion coefficient
Electrical and Magnetic	Resistivity Dielectric constant Magnetic permeability
Environmental Interaction	Oxidation Corrosion Wear
Production	Ease of manufacture Joining Finishing
Aesthetic	Colour Texture Feel

properties will be unfamiliar to you — we will introduce them through examples in this chapter. They form the basis of this first course on materials.

In this first course, we shall also encounter the *classes of materials* shown in Table 1.2 and Figure 1.1. More engineering components are made of *metals and alloys* than of any other class of solid. But increasingly, *polymers* are replacing metals because they offer a combination of properties which are more attractive to the designer. And if you've been reading the newspaper, you will know that the new *ceramics,* at present under development world wide, are an emerging class of engineering material which may permit more efficient heat engines, sharper knives, and bearings with lower friction. The engineer can combine the best properties of these materials to make *composites* (the most familiar is fiberglass) which offer specially attractive packages of

Table 1.2 Classes of materials

Metals and alloys	Iron and steels Aluminium and its alloys Copper and its alloys Nickel and its alloys Titanium and its alloys
Polymers	Polyethylene (PE) Polymethylmethacrylate (Acrylic and PMMA) Nylon, alias Polyamide (PA) Polystyrene (PS) Polyurethane (PU) Polyvinylchloride (PVC) Polyethylene tetraphthalate (PET) Polyethylether Ketone (PEEK) Epoxies (EP) Elastomers, such as natural rubber (NR)
Ceramics and glasses*	Alumina (Al_2O_3, emery, sapphire) Magnesia (MgO) Silica (SiO_2) glasses and silicates Silicon carbide (SiC) Silicon nitride (Si_3N_4) Cement and concrete
Composites	Fiberglass (GFRP) Carbon-fiber reinforced polymers (CFRP) Filled polymers Cermets
Natural materials	Wood Leather Cotton/wool/silk Bone

* Ceramics are crystalline, inorganic, nonmetals. Glasses are noncrystalline (or *amorphous*) solids. Most engineering glasses are nonmetals, but a range of *metallic glasses* with useful properties is now available.

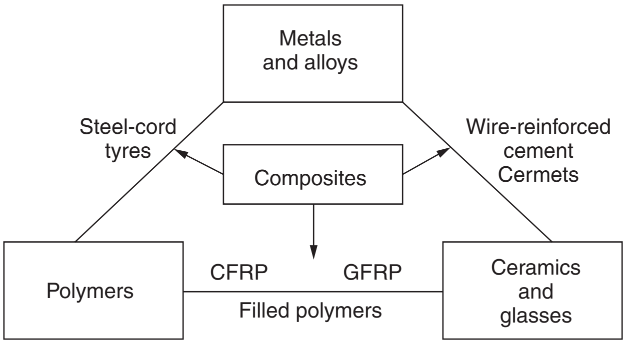

Figure 1.1 The classes of engineering materials from which articles are made.

AQ: Please provide Figures 1.2, 1.3 and 1.4

Figure 1.2 A typical screwdriver, with steel shaft and polymer (plastic) handle.

properties. And — finally — one should not ignore *natural materials* like wood and leather which have properties which — even with the innovations of today's materials scientists — are hard to beat.

In this chapter we illustrate, using a variety of examples, how the designer selects materials so that they provide him or her with the properties needed. As a first example, consider the selection of materials for a

1.2 Plastic-handled screwdriver

A typical screwdriver (Figure 1.2) has a shaft and blade made of carbon steel, a metal. Steel is chosen because its *modulus* is high. The modulus measures the resistance of the material to elastic deflection or bending. If you made the shaft out of a polymer like polyethylene instead, it would twist far too much. A high modulus is one criterion in the selection of a material for this application. But it is not the only one. The shaft must have a high *yield strength*. If it does not, it will bend or twist if you turn it hard (bad screwdrivers do). And the blade must have a high *hardness,* otherwise it will be damaged by the head of the screw. Finally, the material of the shaft and blade must not only do all these things, it must also resist fracture — glass, for instance, has a high modulus, yield strength, and hardness, but it would not be a good choice for this application because it is so brittle. More precisely, it has a very low *fracture toughness*. That of the steel is high, meaning that it gives a bit before it breaks.

The handle of the screwdriver is made of a polymer or plastic, in this instance polymethylmethacrylate, otherwise known as PMMA, plexiglass or perspex. The handle has a much larger section than the shaft, so its twisting, and thus its modulus, is less important. You could not make it satisfactorily out of a soft rubber (another polymer) because its modulus is much too low, although a thin skin of rubber might be useful because its *friction coefficient* is high, making it easy to grip. Traditionally, of course, tool handles were made of another natural polymer — wood — and, if you measure importance by the volume consumed per year, wood is still by far the most important polymer available to the engineer. Wood has been replaced by PMMA because PMMA becomes soft when hot and can be moulded quickly and easily to its final shape. Its *ease of fabrication* for this application is high. It is also chosen for aesthetic reasons: its *appearance,* and feel or *texture,* are right; and its *density* is low, so that the screwdriver is not unnecessarily heavy. Finally, PMMA is cheap, and this allows the product to be made at a reasonable *price*.

Figure 1.3 Cross-section through a typical turbofan aero-engine.

Now a second example (Figure 1.3), taking us from low technology to the advanced materials design involved in the turbofan aeroengines which power large planes. Air is propelled past (and into) the engine by the turbofan, providing aerodynamic thrust. The air is further compressed by the compressor blades, and is then mixed with fuel and burnt in the combustion chamber. The expanding gases drive the turbine blades, which provide power to the turbofan and the compressor blades, and finally pass out of the rear of the engine, adding to the thrust.

The *turbofan blades* are made from a titanium alloy, a metal. This has a sufficiently good modulus, yield strength, and fracture toughness. But the metal must also resist *fatigue* (due to rapidly fluctuating loads), *surface wear* (from striking everything from water droplets to large birds) and *corrosion* (important when taking off over the sea because salt spray enters the engine). Finally, *density* is extremely important for obvious reasons: the heavier the engine, the less the payload the plane can carry. In an effort to reduce weight even further, composite blades made of carbon-fiber reinforced polymers (CFRP) with density less than one-half of that of titanium, have been tried. But CFRP, by itself is simply not tough enough for turbofan blades—a "bird strike" demolishes a CFRP blade. The problem can be overcome by *cladding,* giving the CFRP a metallic leading edge.

Turning to the *turbine blades* (those in the hottest part of the engine) even more material requirements must be satisfied. For economy the fuel must be burnt at as high a temperature as possible. The first row of engine blades (the "HP1" blades) runs at metal temperatures of about 950°C, requiring resistance to *creep* and to *oxidation.* Nickel-based alloys of complicated chemistry and structure are used for this exceedingly stringent application; they are one pinnacle of advanced materials technology.

Figure 1.4 A petrol engine spark plug, with tungsten electrodes and ceramic body.

An example which brings in somewhat different requirements is the *spark plug* of an internal combustion engine (Figure 1.4). The *spark electrodes* must resist *thermal fatigue* (from rapidly fluctuating temperatures), *wear* (caused by spark erosion), and *oxidation and corrosion* from hot upper-cylinder gases containing nasty compounds of sulphur, and lead (from anti-knock additives). Tungsten alloys are used for the electrodes because they have the desired properties.

The *insulation* around the central electrode is an example of a nonmetallic material — in this case, alumina, a ceramic. This is chosen because of its electrical insulating properties and because it also has good thermal fatigue resistance and resistance to corrosion and oxidation (it is an oxide already).

The use of nonmetallic materials has grown most rapidly in the consumer industry. Our next example, a sailing cruiser (Figure 1.5), shows just how extensively polymers and manmade composites and fibers have replaced the "traditional" materials of steel, wood, and cotton. A typical cruiser has a *hull* made from GFRP, manufactured as a single moulding; GFRP has good

Figure 1.5 A sailing cruiser, with composite (GFRP) hull, aluminium alloy mast and sails made from synthetic polymer fibers.

appearance and, unlike steel or wood, does not rust or become eaten away by Terido worm. The *mast* is made from aluminium alloy, which is lighter for a given strength than wood; advanced masts are now being made by reinforcing the alloy with carbon or boron fibers (man-made composites). The sails, formerly of the natural material cotton, are now made from the polymers nylon, Terylene or Kevlar, and, in the running rigging, cotton ropes have been replaced by polymers also. Finally, polymers like PVC are extensively used for things like fenders, anoraks, buoyancy bags, and boat covers.

Three man-made composite materials have appeared in the items we have considered so far: GFRP; the much more expensive CFRP; and the still *more* expensive boron-fiber reinforced alloys (BFRP). The range of composites is a large and growing one (Figure 1.1); during the next decade composites will, increasingly, compete with steel and aluminium in many traditional uses of these metals.

So far we have introduced the mechanical and physical properties of engineering materials, but we have yet to discuss a consideration which is often of overriding importance: that of *price and availability*.

Table 1.3 shows a rough breakdown of material prices. Materials for large-scale structural use — wood, cement, and concrete, and structural steel — cost between UK£50 and UK£500 (US$90 and US$900) per tonne. There are many materials which have all the other properties required of a structural material — nickel or titanium, for example — but their use in this application is eliminated by their price.

The value that is added during light- and medium-engineering work is larger, and this usually means that the economic constraint on the choice of materials is less severe — a far greater proportion of the cost of the structure is that associated with labor or with production and fabrication. Stainless steels, most aluminum alloys and most polymers cost between UK£500 and UK£5000

Table 1.3 Breakdown of material prices

Class of use	*Material*	*Price per tonne*	
Basic construction	Wood, concrete, structural steel	UK£50–500	US$90–900
Medium and light engineering	Metals, alloys, and polymers for aircraft, automobiles, appliances, etc.	UK£500–5000	US$900–9000
Special materials	Turbine-blade alloys, advanced composites (CFRP, BFRP), etc.	UK£5000–50,000	US$9000–90,000
Precious metals, etc.	Sapphire bearings, silver contacts, gold microcircuits	UK£50,000–10m	US$90,000–18m
Industrial diamond	Cutting and polishing tools	> UK£10m	> US$18m

AQ: For the last 2 entries the price in the text is given as £100m where as here it is given as £10m.

(US$900 and US$9000) per tonne. It is in this sector of the market that the competition between materials is most intense, and the greatest scope for imaginative design exists. Here polymers and composites compete directly with metals, and new structural ceramics (silicon carbide and silicon nitride) may compete with both in certain applications.

Next there are the materials developed for high-performance applications, some of which we have mentioned already: nickel alloys (for turbine blades), tungsten (for spark-plug electrodes), and special composite materials such as CFRP. The price of these materials ranges between UK£5000 and UK£50,000 (US$9000 and US$90,000) per tonne. This the régime of high materials technology, actively under research, and in which major new advances are continuing to be made. Here, too, there is intense competition from new materials.

Finally, there are the so-called precious metals and gemstones, widely used in engineering gold for microcircuits, platinum for catalysts, sapphire for bearings, diamond for cutting tools. They range in price from UK£50,000 (US$90,000) to well over UK£100m (US$180m) per tonne.

As an example of how price and availability affect the choice of material for a particular job, consider how the materials used for building bridges in Cambridge have changed over the centuries. As our photograph of Queens' Bridge (Figure 1.6) suggests, until 150 years or so ago wood was commonly

Figure 1.6 The wooden bridge at Queens' College, a 1902 reconstruction of the original bridge built in 1749 to William Etheridge's design.

Figure 1.7 Clare Bridge, built in 1640, is Cambridge's oldest surviving bridge; it is reputed to have been an escape-route from the college in times of plague.

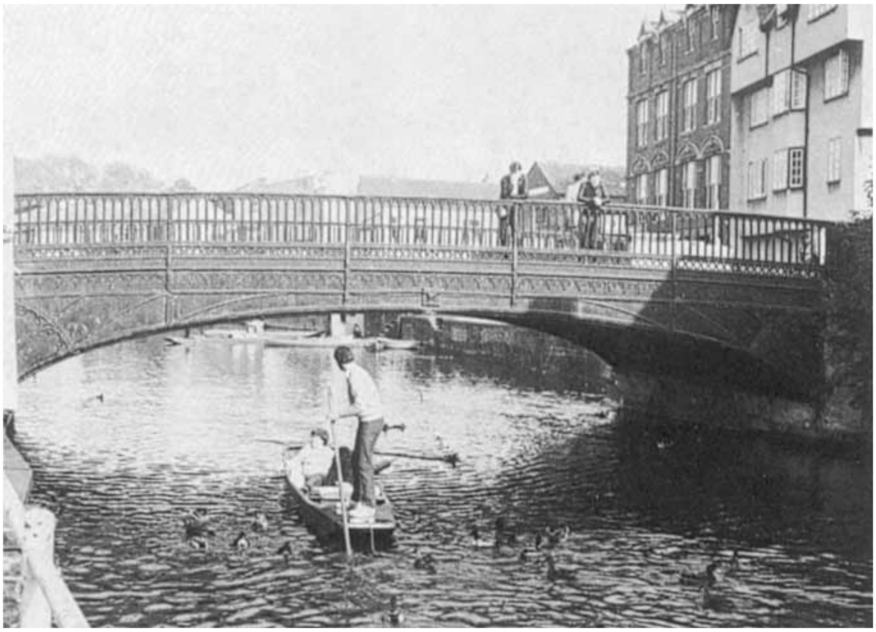

Figure 1.8 Magdalene Bridge built in 1823 on the site of the ancient Saxon bridge over the Cam. The present cast-iron arches carried, until recently, loads far in excess of those envisaged by the designers. Fortunately, the bridge has now undergone a well-earned restoration.

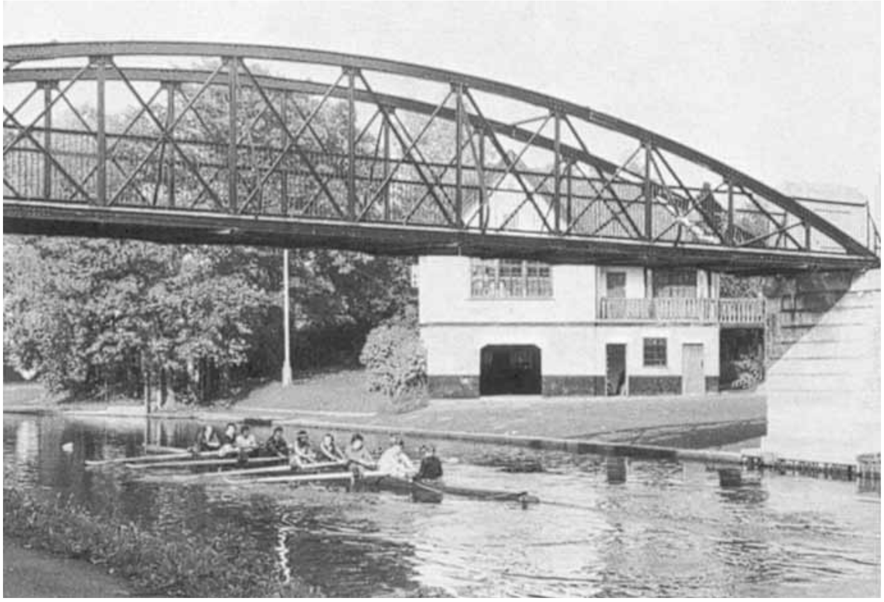

Figure 1.9 A typical twentieth-century mild-steel bridge; a convenient crossing to the Fort St George inn!

Figure 1.10 The reinforced concrete footbridge in Garret Hostel Lane. An inscription carved nearby reads: “This bridge was given in 1960 by the Trusted family members of Trinity Hall. It was designed by Timothy Guy MORGAN an undergraduate of Jesus College who died in that year.”

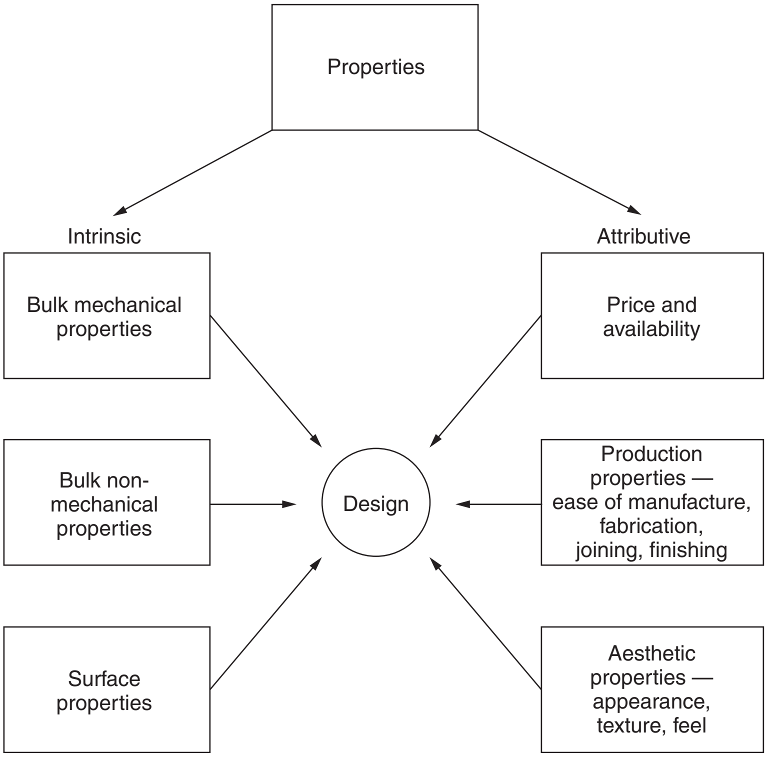

Figure 1.11 How the properties of engineering materials affect the way in which products are designed.

used for bridge building. It was cheap, and high-quality timber was still available in large sections from natural forests. Stone, too, as the picture of Clare Bridge (Figure 1.7) shows, was widely used. In the eighteenth century the ready availability of cast iron, with its relatively low assembly costs, led to many cast-iron bridges of the type exemplified by Magdalene Bridge (Figure 1.8). Metallurgical developments of the later nineteenth century allowed large mild-steel structures to be built (the Fort St. George Footbridge, Figure 1.9). Finally, the advent of cheap reinforced concrete led to graceful and durable structures like that of the Garret Hostel Lane bridge (Figure 1.10). This evolution clearly illustrates how availability influences the choice of materials. Nowadays, wood, steel, and reinforced concrete are often used interchangeably in structures, reflecting the relatively small *price* differences between them. The choice of which of the three materials to use is mainly dictated by the kind of structure the architect wishes to build: chunky and solid (stone), structurally efficient (steel), slender, and graceful (pre-stressed concrete).

Engineering design, then, involves many considerations (Figure 1.11). The choice of a material must meet certain criteria on bulk and surface properties (e.g. strength and corrosion resistance). But it must also be easy to fabricate; it must appeal to potential consumers; and it must compete economically with other alternative materials. In the next chapter we consider the economic aspects of this choice, returning in later chapters to a discussion of the other properties.