A. Metals

Chapter 1
Metals

Introduction

This first group of chapters looks at metals. There are so many different metals – literally hundreds of them – that it is impossible to remember them all. It isn't necessary – nearly all have evolved from a few "generic" metals and are simply tuned-up modifications of the basic recipes. If you know about the generic metals, you know most of what you need.

This chapter introduces the generic metals. But rather than bore you with a catalogue we introduce them through three real engineering examples. They allow us not only to find examples of the uses of the main generic metals but also to introduce the all-important business of how the characteristics of each metal determine how it is used in practice.

Metals for a model traction engine

Model-making has become big business. The testing of scale models provides a cheap way of getting critical design information for things from Olympic yacht hulls to tidal barrages. Architects sell their newest creations with the help of miniature versions correct to the nearest door-handle and garden shrub. And in an age of increasing leisure time, many people find an outlet for their energies in making models – perhaps putting together a miniature aircraft from a kit of plastic parts or, at the other extreme, building a fully working model of a steam engine from the basic raw materials in their own "garden-shed" machine shop.

Figure 1.1 shows a model of a nineteenth-century steam traction engine built in a home workshop from plans published in a well-known modellers' magazine. Everything works just as it did in the original – the boiler even burns the same type of coal to raise steam – and the model is capable of towing an automobile! But what interests us here is the large range of metals that were used in its construction, and the way in which their selection was dictated by the requirements of design. We begin by looking at metals based on *iron* (*ferrous* metals). Table 1.1 lists the generic iron-based metals.

How are these metals used in the traction engine? The design loads in components like the wheels and frames are sufficiently low that *mild steel*, with a yield strength σ_y of around 220 MPa, is more than strong enough. It is also easy to cut, bend or machine to shape. And last, but not least, it is cheap.

The stresses in the machinery – like the gear-wheel teeth or the drive shafts – are a good deal higher, and these parts are made from either *medium-carbon,*

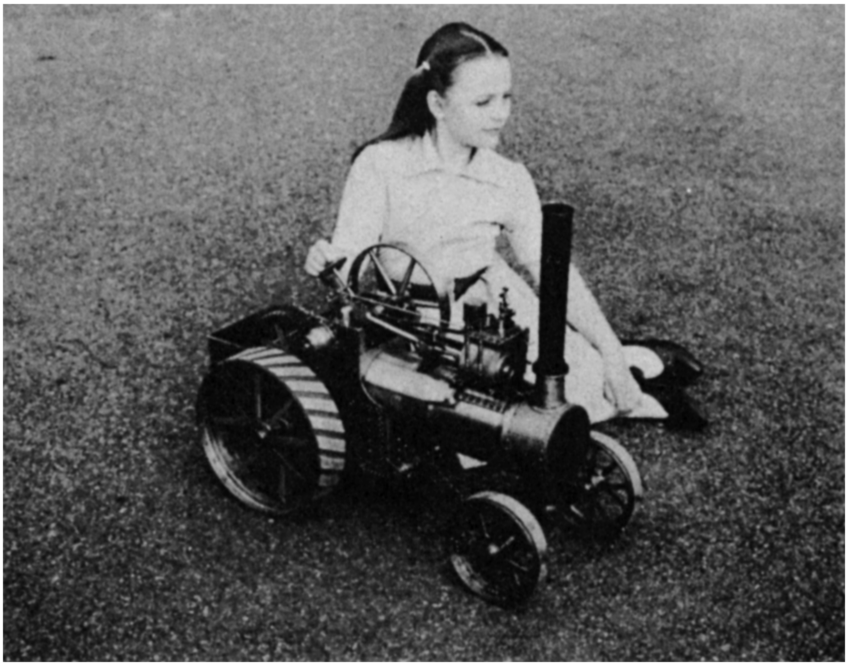

Figure 1.1 A fully working model, one-sixth full size, of a steam traction engine of the type used on many farms a hundred years ago. The model can pull an automobile on a few litres of water and a handful of coal. But it is also a nice example of materials selection and design.

Table 1.1 Generic iron-based metals

Metal	*Typical composition* (wt%)	*Typical uses*
Low-carbon ("mild") steel	Fe + 0.04 to 0.3 C (+ ≈ 0.8 Mn)	Low-stress uses. General constructional steel, suitable for welding.
Medium-carbon steel	Fe + 0.3 to 0.7 C (+ ≈ 0.8 Mn)	Medium-stress uses: machinery parts – nuts and bolts, shafts, gears.
High-carbon steel	Fe + 0.7 to 1.7 C (+ ≈ 0.8 Mn)	High-stress uses: springs, cutting tools, dies.
Low-alloy steel	Fe + 0.2 C 0.8 Mn 1 Cr 2 Ni	High-stress uses: pressure vessels, aircraft parts.
High-alloy ("stainless") steel	Fe + 0.1 C 0.5 Mn 18 Cr 8 Ni	High-temperature or anti-corrosion uses: chemical or steam plants.
Cast iron	Fe + 1.8 to 4 C (+ ≈ 0.8 Mn 2 Si)	Low-stress uses: cylinder blocks, drain pipes.

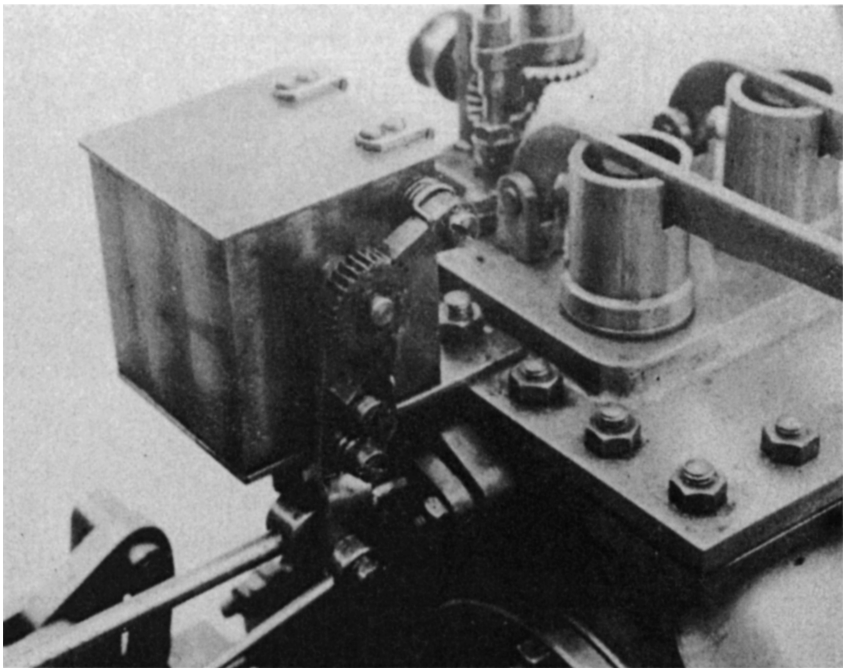

Figure 1.2 A close-up of the mechanical lubricator on the traction engine. Unless the bore of the steam cylinder is kept oiled it will become worn and scored. The lubricator pumps small metered quantities of steam oil into the cylinder to stop this happening. The drive is taken from the piston rod by the ratchet and pawl arrangement.

high-carbon or *low-alloy steels* to give extra strength. However, there are a few components where even the strength of high-carbon steels as delivered "off the shelf" ($\sigma_y \approx 400\,\text{MPa}$) is not enough. We can see a good example in the mechanical lubricator, shown in Fig. 1.2, which is essentially a high-pressure oil metering pump. This is driven by a ratchet and pawl. These have sharp teeth which would quickly wear if they were made of a soft alloy. But how do we raise the hardness above that of ordinary high-carbon steel? Well, medium- and high-carbon steels can be hardened to give a yield strength of up to 1000 MPa by heating them to bright red heat and then quenching them into cold water. Although the quench makes the hardened steel brittle, we can make it tough again (though still hard) by *tempering* it – a process that involves heating the steel again, but to a much lower temperature. And so the ratchet and pawls are made from a quenched and tempered high-carbon steel.

Stainless steel is used in several places. Figure 1.3 shows the fire grate – the metal bars which carry the burning coals inside the firebox. When the engine is working hard the coal is white hot; then, both oxidation and creep are problems. Mild steel bars can burn out in a season, but stainless steel bars last indefinitely.

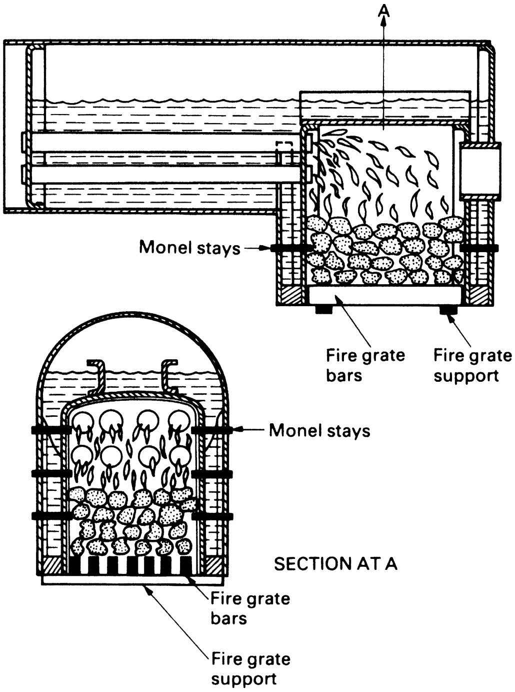

Figure 1.3 The fire grate, which carries the white-hot fire inside the firebox, must resist oxidation and creep. Stainless steel is best for this application. Note also the threaded monel stays which hold the firebox sides together against the internal pressure of the steam.

Finally, what about *cast iron*? Although this is rather brittle, it is fine for low-stressed components like the cylinder block. In fact, because cast iron has a lot of carbon it has several advantages over mild steel. Complicated components like the cylinder block are best produced by casting. Now cast iron melts much more easily than steel (adding carbon reduces the melting point in just the way that adding anti-freeze works with water) and this makes the pouring of the castings much easier. During casting, the carbon can be made to separate out as tiny particles of graphite, distributed throughout the iron, which make an ideal boundary lubricant. Cylinders and pistons made from cast iron wear very well; look inside the cylinders of your car engine next time the head has to come off, and you will be amazed by the polished, almost glazed look of the bores – and this after perhaps 10^8 piston strokes.

These, then, are the basic classes of ferrous alloys. Their compositions and uses are summarised in Table 1.1, and you will learn more about them in Chapters 11 and 12, but let us now look at the other generic alloy groups.

An important group of alloys are those based on copper (Table 1.2).

The most notable part of the traction engine made from copper is the boiler and its firetubes (see Fig. 1.1). In full size this would have been made from

Table 1.2 Generic copper-based metals

Metal	*Typical composition* (wt%)	*Typical uses*
Copper	100 Cu	Ductile, corrosion resistant and a good electrical conductor: water pipes, electrical wiring.
Brass	Zn	Stronger than copper, machinable, reasonable corrosion resistance: water fittings, screws, electrical components.
Bronze	Cu + 10–30 Sn	Good corrosion resistance: bearings, ships' propellers, bells.
Cupronickel	Cu + 30 Ni	Good corrosion resistance, coinage.

mild steel, and the use of copper in the model is a nice example of how the choice of material can depend on the *scale* of the structure. The boiler plates of the full-size engine are about 10 mm thick, of which perhaps only 6 mm is needed to stand the load from the pressurised steam safely – the other 4 mm is an allowance for corrosion. Although a model steel boiler would stand the pressure with plates only 1 mm thick, it would still need the same corrosion allowance of 4 mm, totalling 5 mm altogether. This would mean a very heavy boiler, and a lot of water space would be taken up by thick plates and firetubes. Because copper hardly corrodes in clean water, this is the obvious material to use. Although weaker than steel, copper plates 2.5 mm thick are strong enough to resist the working pressure, and there is no need for a separate corrosion allowance. Of course, copper is expensive – it would be prohibitive in full size – but this is balanced by its ductility (it is very easy to bend and flange to shape) and by its high thermal conductivity (which means that the boiler steams very freely).

Brass is stronger than copper, is much easier to machine, and is fairly corrosion-proof (although it can "dezincify" in water after a long time). A good example of its use in the engine is for steam valves and other boiler fittings (see Fig. 1.4). These are intricate, and must be easy to machine; dezincification is a long-term possibility, so occasional inspection is needed. Alternatively, corrosion can be avoided altogether by using the more expensive *bronzes*, although some are hard to machine.

Nickel and its alloys form another important class of non-ferrous metals (Table 1.3). The superb creep resistance of the nickel-based superalloys is a key factor in designing the modern gas-turbine aero-engine. But nickel alloys even appear in a model steam engine. The flat plates in the firebox must be stayed together to resist the internal steam pressure (see Fig. 1.3). Some model-builders make these stays from pieces of monel rod because it is much stronger than copper, takes threads much better and is very corrosion resistant.

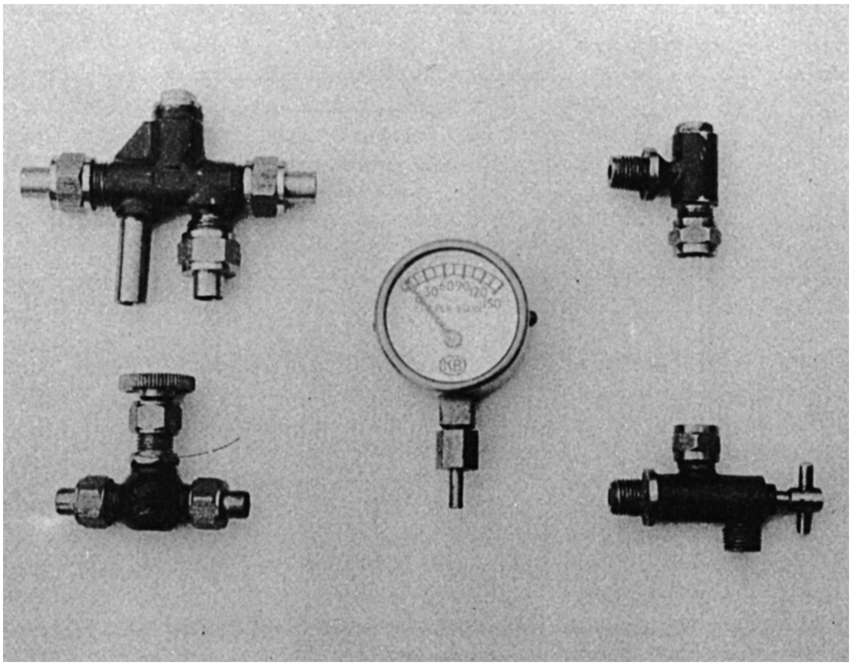

Figure 1.4 Miniature boiler fittings made from brass: a water-level gauge, a steam valve, a pressure gauge, and a feed-water injector. Brass is so easy to machine that it is good for intricate parts like these.

Table 1.3 Generic nickel-based metals

Metals	*Typical composition* (wt%)	*Typical uses*
Monels	Ni + 30 Cu 1Fe 1Mn	Strong, corrosion resistant: heat-exchanger tubes.
Superalloys	Ni + 30 Cr 30 Fe 0.5 Ti 0.5 Al	Creep and oxidation resistant: furnace parts.
	Ni + 10 Co 10 W 9 Cr 5 A12 Ti	Highly creep resistant: turbine blades and discs.

Metals for drinks cans

Few people would think that the humble drink can (Fig. 1.5) was anything special. But to a materials engineer it is high technology. Look at the requirements. As far as possible we want to avoid seams. The can must not leak, should use as little metal as possible and be recyclable. We have to choose a metal that is ductile to the point that it can be drawn into a single-piece can

Figure 1.5 The aluminium drink can is an innovative product. The body is made from a single slug of a 3000 series aluminium alloy. The can top is a separate pressing which is fastened to the body by a rolled seam once the can has been filled. There are limits to one-piece construction.

body from one small slug of metal. It must not corrode in beer or coke and, of course, it must be non-toxic. And it must be light and must cost almost nothing.

Aluminium-based metals are the obvious choice* (Table 1.4) – they are light, corrosion resistant and non-toxic. But it took several years to develop the process for forming the can and the alloy to go with it. The end product is a big advance from the days when drinks only came in glass bottles, and has created a new market for aluminium (now threatened, as we shall see in Chapter 21, by polymers). Because aluminium is lighter than most other metals it is also the obvious choice for transportation: aircraft, high-speed trains, cars, even. Most of the alloys listed in Table 1.4 are designed with these uses in mind. We will discuss the origin of their strength, and their uses, in more detail in Chapter 10.

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* One thinks of aluminium as a cheap material – aluminium spoons are so cheap that they are thrown away. It was not always so. Napoleon had a set of cutlery specially made from the then-new material. It cost him more than a set of solid silver.

Table 1.4 Generic aluminium-based metals

Metal	*Typical composition* (wt%)	*Typical uses*
1000 Series unalloyed Al	>99 Al	Weak but ductile and a good electrical conductor: power transmission lines, cooking foil.
2000 Series major additive Cu	$Al + 4\ Cu + Mg$, Si, Mn	Strong age-hardening alloy: aircraft skins, spars, forgings, rivets.
3000 Series major additive Mn	$Al + 1\ Mn$	Moderate strength, ductile, excellent corrosion resistance: roofing sheet, cooking pans, drinks can bodies.
5000 Series major additive Mg	$Al + 3\ Mg\ 0.5\ Mn$	Strong work-hardening weldable plate: pressure vessels, ship superstructures.
6000 Series major additives $Mg + Si$	$Al + 0.5\ Mg\ 0.5\ Si$	Moderate-strength age-hardening alloy: anodised extruded sections, e.g. window frames.
7000 Series major additives $Zn + Mg$	$Al + 6\ Zn + Mg$, Cu, Mn	Strong age-hardening alloy: aircraft forgings, spars, lightweight railway carriage shells.
Casting alloys	$Al + 11\ Si$	Sand and die castings.
Aluminium–lithium alloys	$Al + 3\ Li$	Low density and good strength: aircraft skins and spars.

Metals for artificial hip joints

As a last example we turn to the world of medicine. Osteo-arthritis is an illness that affects many people as they get older. The disease affects the joints between different bones in the body and makes it hard – and painful – to move them. The problem is caused by small lumps of bone which grow on the rubbing surfaces of the joints and which prevent them sliding properly. The problem can only be cured by removing the bad joints and putting artificial joints in their place. The first recorded hip-joint replacement was done as far back as 1897 – when it must have been a pretty hazardous business – but the operation is now a routine piece of orthopaedic surgery. In fact half a million hip joints are replaced world-wide every year.

Figure 1.6 shows the implant for a replacement hip joint. In the operation, the head of the femur is cut off and the soft marrow is taken out to make a hole down the centre of the bone. Into the hole is glued a long metal shank which carries the artificial head. This fits into a high-density polythene socket which in turn is glued into the old bone socket. The requirements of the implant are stringent. It has to take large loads without bending. Every time the joint is used ($\approx 10^6$ times a year) the load on it fluctuates, giving us a

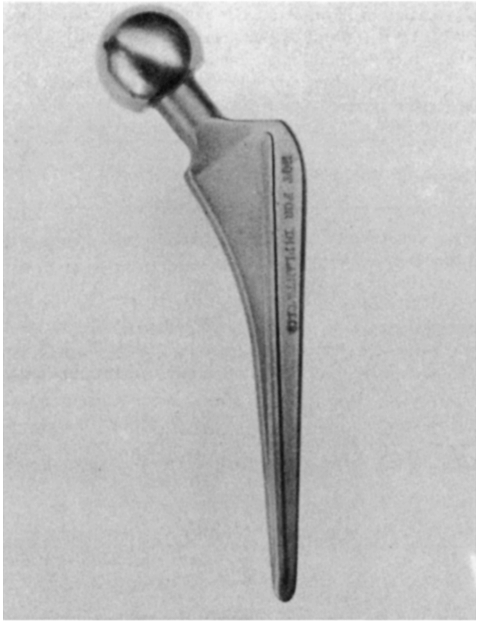

Figure 1.6 The titanium alloy implant for a replacement hip joint. The long shank is glued into the top of the femur. The spherical head engages in a high-density polythene socket which is glued into the pelvic socket.

high-cycle fatigue problem as well. Body fluids are as corrosive as sea water, so we must design against corrosion, stress corrosion and corrosion fatigue. The metal must be bio-compatible. And, ideally, it should be light as well.

The materials that best meet these tough requirements are based on *titanium*. The α–β alloy shown in Table 1.5 is as strong as a hardened and tempered high-carbon steel, is more corrosion resistant in body fluids than stainless steel, but is only half the weight. A disadvantage is that its modulus is only half that of steels, so that it tends to be "whippy" under load. But this can be overcome by using slightly stiffer sections. The same alloy is used in aircraft, both in the airframes and in the compressor stages of the gas turbines which drive them.

Table 1.5 Generic titanium-based metals

Metal	*Typical composition* (wt%)	*Typical uses*
α–β titanium alloy	Ti–6 Al4 V	Light, very strong, excellent corrosion resistance, high melting point, good creep resistance. The alloy workhorse: turbofans, airframes, chemical plant, surgical implants.

Table 1.6 Properties of the generic metals

Metal	*Cost* (UK£ (US$) tonne^{-1})	*Density* (Mg m^{-3})	*Young's modulus* (GPa)	*Yield strength* (MPa)	*Tensile strength* (MPa)	*Ductility*	*Fracture toughness* (MPa m$^{1/2}$)	*Melting Temperature* (K)	*Specific heat* (J kg^{-1}K^{-1})	*Thermal conductivity* (W m^{-1}K^{-1})	*Thermal expansion coefficient* (MK^{-1})
Iron	100 (140)	7.9	211	50	200	0.3	80	1809	456	78	12
Mild steel	200–230 (260–300)	7.9	210	220	430	0.21	140	1765	482	60	12
High-carbon steel	150 (200)	7.8	210	350–1600	650–2000	0.1–0.2	20–50	1570	460	40	12
Low-alloy steels	180–250 (230–330)	7.8	203	290–1600	420–2000	0.1–0.2	50–170	1750	460	40	12
High-alloy steels	1100–1400 (1400–1800)	7.8	215	170–1600	460–1700	0.1–0.5	50–170	1680	500	12–30	10–18
Cast irons	120 (160)	7.4	152	50–400	10–800	0–0.18	6–20	1403			
Copper	1020 (1330)	8.9	130	75	220	0.5–0.9	>100	1356	385	397	17
Brasses	750–1060 (980–1380)	8.4	105	200	350	0.5	30–100	1190		121	20
Bronzes	1500 (2000)	8.4	120	200	350	0.5	30–100	1120		85	19
Nickel	3200 (4200)	8.9	214	60	300	0.4	>100	1728	450	89	13
Monels	3000 (3900)	8.9	185	340	680	0.5	>100	1600	420	22	14
Superalloys	5000 (6500)	7.9	214	800	1300	0.2	>100	1550	450	11	12
Aluminium	910 (1180)	2.7	71	25–125	75–135	0.1–0.5	45	933	917	240	24
1000 Series	910 (1180)	2.7	71	28–165	75–180	0.1–0.45	45	915			24
2000 Series	1100 (1430)	2.8	71	200–500	300–600	0.1–0.25	10–50	860		180	24
5000 Series	1000 (1300)	2.7	71	40–300	120–430	0.1–0.35	30–40	890		130	22
7000 Series	1100 (1430)	2.8	71	350–600	500–670	0.1–0.17	20–70	890		150	24
Casting alloys	1100 (1430)	2.7	71	65–350	130–400	0.01–0.15	5–30	860		140	20
Titanium	4630 (6020)	4.5	120	170	240	0.25		1940	530	22	9
Ti–6 A14 V	5780 (7510)	4.4	115	800–900	900–1000	0.1–0.2	50–80	1920	610	6	8
Zinc	330 (430)	7.1	105		120	0.4		693	390	120	31
Lead–tin solder	2000 (2600)	9.4	40					456			
Diecasting alloy	800 (1040)	6.7	105		280–330	0.07–0.15		650	420	110	27

Data for metals

When you select a metal for any design application you need *data* for the properties. Table 1.6 gives you *approximate* property data for the main generic metals, useful for the first phase of a design project. When you have narrowed down your choice you should turn to the more exhaustive data compilations given in Appendix 3. Finally, before making final design decisions you should get detailed material specifications from the supplier who will provide the materials you intend to use. And if the component is a critical one (meaning that its failure could precipitate a catastrophe) you should arrange to test it yourself.

There are, of course, many more metals available than those listed here. It is useful to know that some properties depend very little on microstructure: the density, modulus, thermal expansion and specific heat of *any* steel are pretty close to those listed in the table. (Look at the table and you will see that the variations in these properties are seldom more than ±5%.) These are the "*structure-insensitive*" properties. Other properties, though, vary greatly with the heat treatment and mechanical treatment, and the detailed alloy composition. These are the "*structure-sensitive*" properties: yield and tensile strength, ductility, fracture toughness, and creep and fatigue strength. They cannot be guessed from data for other alloys, even when the composition is almost the same. For these it is *essential* to consult manufacturers' data sheets listing the properties of the alloy you intend to use, with the same mechanical and heat treatment.

Examples

1.1 Explain what is meant by the following terms:

(a) structure-sensitive property;
(b) structure-insensitive property.

List five different structure-sensitive properties.
List four different structure-insensitive properties.

Answers

Structure-sensitive properties: yield strength, hardness, tensile strength, ductility, fracture toughness, fatigue strength, creep strength, corrosion resistance, wear resistance, thermal conductivity, electrical conductivity. Structure-insensitive properties: elastic moduli, Poisson's ratio, density, thermal expansion coefficient, specific heat.

1.2 What are the five main generic classes of metals? For each generic class:

(a) give one example of a specific component made from that class;
(b) indicate why that class was selected for the component.