INTRODUCTION TO MATERIALS

THE ELEMENTS

An element is a fundamental material like copper or zinc. All other materials are made from elements. Brass, for example, is an alloy or mixture of copper and zinc. Before our modern idea of elements, many different ideas existed about the true 'building blocks' of the world. One was that everything was created from Earth, Fire, Wind and Water.

However, as people used more of the Earth's materials, they spent more time trying to understand those materials and classify them into basic building blocks. During this process some new elements came and some old ones went as they were found to be simply combinations of other elements and so disappeared from the list. For many many years, all that was required for something to be regarded as an element was that the scientists could not break it down into more basic components.

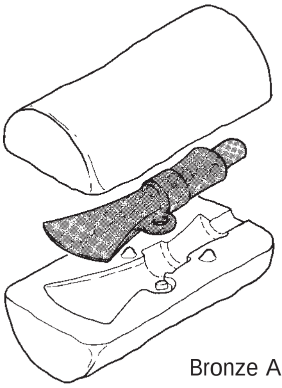
Eventually, scientists developed patterns or families of elements, suggesting that some members were missing, searched for these and found them.

In your working life, new elements may or may not appear but you can be absolutely certain that new materials will. These new materials will be built from the elements that scientists have known of for many years but will be used in ways not yet thought of.

Today, the age of 'designer' materials is upon us. First of all you say what your material must do and then you make it to order! A far cry from our ancestors who worked natural materials through no more than a few stages.

HISTORY NOTE

Early Stone Age manufacturers chipped stone to reshape it but Late Stone Age people made clay into pottery. Early metal age workers took metals that lay on the earth's surface and made jewellery from these but late metal age workers made metal from stone - metal ores - and then made metal objects from this.

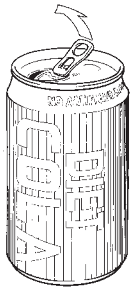


Bronze Age axe mould

Table 2.1 The Elements

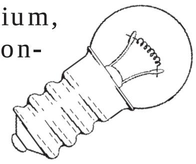
Ac	actinium
Al	aluminium
Am	americium
Sb	antimony
Ar	argon
As	arsenic
At	astatine
Ba	barium
Bk	berkelium
Be	beryllium
Bi	bismuth
B	boron
Br	bromine
Cd	cadmium
Cs	caesium
Ca	calcium
Cf	californium
C	carbon
Ce	cerium
Cl	chlorine
Cr	chromium
Co	cobalt
Cu	copper
Cm	curium
Dy	dysprosium
Es	einsteinium
Er	erbium
Eu	europium
Fm	fermium
F	fluorine
Fr	francium
Gd	gadolinium
Ga	gallium
Ge	germanium
Au	gold
Hf	hafnium
He	helium
Ho	holmium
H	hydrogen
In	indium
I	iodine
Ir	iridium
Fe	iron
Kr	krypton
La	lanthanum
Lr	lawrencium
Pb	lead
Li	lithium
Lu	lutetium
Mg	magnesium
Mn	manganese
Md	mendelevium
Hg	mercury
Mo	molybdenum
Nd	neodymium
Ne	neon
Np	neptunium
Ni	nickel
Nb	niobium
N	nitrogen
No	nobelium
Os	osmium
O	oxygen
Pd	palladium
P	phosphorus
Pt	platinum
Pu	plutonium
Po	polonium
K	potassium
Pr	praseodymium
Pm	promethium
Pa	protoactinium
Ra	radium
Rn	radon
Re	rhenium
Rh	rhodium
Rb	rubidium
Ru	ruthenium
Sm	samarium
Sc	scandium
Se	selenium
Si	silicon
Ag	silver
Na	sodium
Sr	strontium
S	sulphur
Ta	tantalum
Tc	technetium
Te	tellurium
Tb	terbium
Tl	thallium
Th	thorium
Tm	thulium
Sn	tin
Ti	titanium
W	tungsten
U	uranium
V	vanadium
Xe	xenon
Yb	ytterbium
Y	yttrium
Zn	zinc
Zr	zirconium

SOME USES OF THE ELEMENTS



Aluminium (Al) The most abundant element on the earth's surface, a white light metal. Widely used for: its light weight in aircraft, cars and lorries, it is about a third of the weight of steel and very malleable; its high electrical conductivity and ductility in electrical cables, particularly in high voltage power transmission; its high corrosion resistance in decorative and architectural metalwork, e.g. Eros.Widely used as alloys, principally with Cu in Dural.

Antimony (Sb) A low-melting point metal widely used in alloys such as pewter, woods metal.

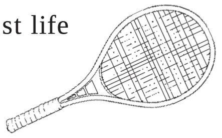


Argon (Ar) An inert (or noble) gas (along with Helium, Neon, Krypton, Xenon, and Radon) used in argon-arc welding where it inhibits oxidation of the joining surfaces and in argon lamps where it inhibits corrosion of the lamp element.

Beryllium (Be) A toxic metal used principally as an alloying element with copper to produce a 'springy' alloy for use as springs in electrical devices and clocks. Used in the internal coating of fluorescent tubes.

Cadmium (Cd) A toxic 'heavy' metal. Used to protect metal surfaces giving them a light greeny-yellow coating which protects against water. Involved in the Minemata disease occurrence.

Calcium (Ca) Occurs commonly as $CaCO_3$ (in shells) of which limestone and chalk are largely composed. Used as $CaCO_3$ to make cement, to smelt iron and in flue gas desulphurisation.



Carbon (C) A common element of which most life forms are largely composed. Important constituent in oil and gas and, hence, in most polymers.

Chlorine (Cl) A gas at room temperature which is highly toxic, kills bacteria, hence used as a disinfectant, particularly in the purification of water.

Cobalt (Co) A heavy metal, an important constituent in alloys used for electromagnets and also as a source of gamma rays in X-ray studies.

Copper (Cu) A pink metal used extensively for electrical conductors, domestic boilers, etc. Main constituent in bronze and brass alloys and was the principal 'new' material of the Calcolithic or Copper Age.

Fluorine (F) A highly-reactive gas. An essential element in the body, put into toothpaste as fluoride.

Gold (Au) A very stable metal, resists corrosion, used in jewellery and in electrical connections.

Helium (He) A light gas used in balloons and to make artificial ‘air’ for divers. The second-most common element in the universe.

Hydrogen (H) The lightest element in the universe and the most abundant. Used as a rocket fuel and was used in the Zeppelin balloons.

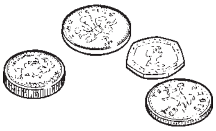
Iron (Fe) A malleable metal which has been used as wrought iron since the iron age but now rarely seen. Was used as cast iron since the middle ages. Its principal use is in the alloy ‘steel’ where it is combined with carbon and other materials.

Lead (Pb) A soft, heavy and toxic metal. Used since the bronze age in alloys such as bronze and pewter. Now used for batteries, in solder and as a shield against X-rays. Also used as an additive in leaded petrol which is being phased out in the UK.

Magnesium (Mg) A light metal which burns in air, used in castings in aircraft, etc.

Nickel (Ni) A metal used in ‘silver’ coins and in stainless steel. Commonly used as plating to protect other metals from corrosion.

Selenium (Se) A metal which develops an electric charge when illuminated by light, and is the basis for the development of photocopiers.



Silver (Ag) A decorative metal used in coinage, ornamental ware and (expensive) cuttlery. It has exceptionally high electrical and thermal conductivity. Some of its chemical compounds are affected by light and are used in photography.

Tin (Sn) A metal known since the bronze age, used in bronze. Now used to plate steel to protect from corrosion, also used in solder and pewter.

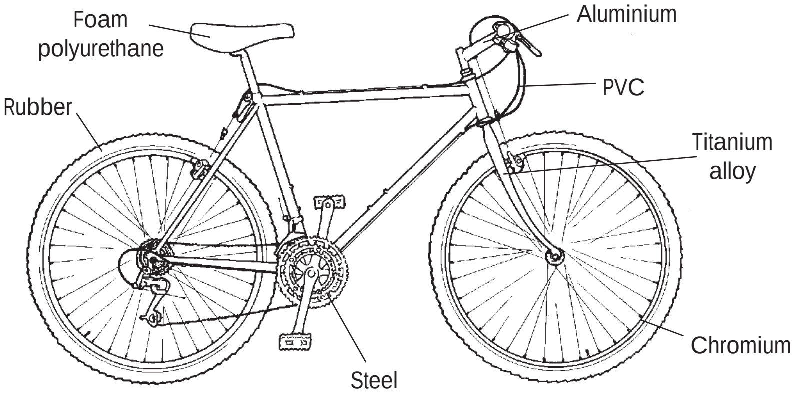
Titanium (Ti) A metal used for its strength and lightness in aircraft and for its resistance to corrosion in marine applications.

Zinc (Zn) A metal known since Roman times. Used in brass, for galvanising and, for its low melting point, in die castings.

Zirconium (Zr) A metal extensively used as an alloying element in a variety of alloys and as a cladding material for nuclear fuel since it absorbs neutrons only slightly.

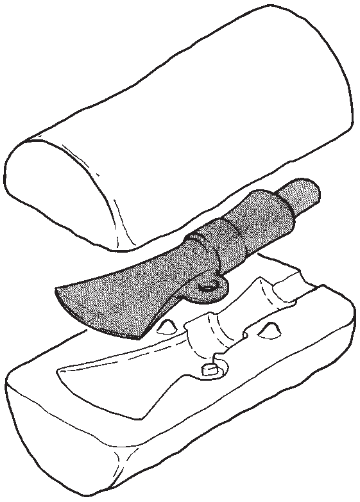
MATERIALS

Most materials used in technology are created by combining elements. These combinations may be of metals or non-metals. They may be composite materials which receive new characteristics from the various components which make them up. They may be polymers made from organic materials, such as oil, which are woven into complex structures to form the latest in 'designer' materials. A modern cycle with accessories may contain over 100 different types of material. A few are listed below.



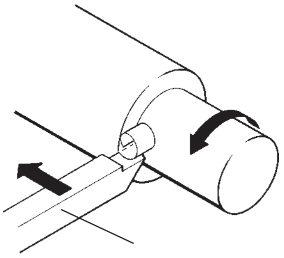
Alloys are mixtures of different metals and/or non-metals. They are not new! The Bronze Age was founded on bronze - an alloy of copper with either arsenic or tin. An alloy that offered considerable practical benefit over the copper that it replaced: it melted at a lower temperature and it produced a harder edge for cutting.

Alloys are used simply because they're better at doing some jobs than pure metals. They're often said to combine the properties of the things that make them but bronze is harder than either of the two parts that make it up. It does, however, melt at a temperature between the two.

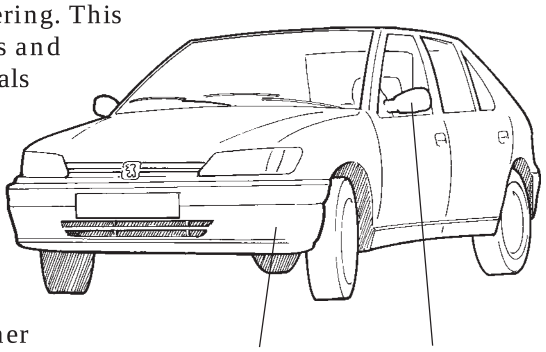


Bronze Age axe and mould. Tin / copper alloy

Probably the most used alloy of all is steel - a mixture of iron and carbon. However, a vast range of other materials, such as chromium, is now added to steels to form what are now known as 'alloy steels'. High speed steel (HSS) is a very hard alloy steel used in tool bits. It remains hard even at high temperatures.


Steel tool bit

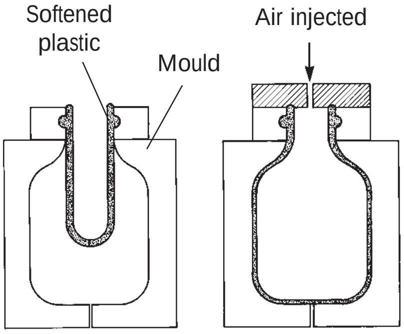
Polymers are another group of materials that find increasing application in engineering. This group includes plastics and rubber. Rubber materials are also called elastomers because of their elastic properties. Modern vehicles make use of a wide range of polymers and co-polymers. A co-polymer is a mixture of plastics that gives special characteristics.

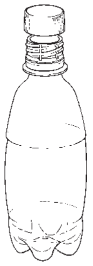

Impact resistant co-polymers

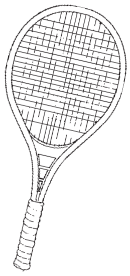
The range of plastics in the modern world is vast and grows day by day and it is the ability of chemists and chemical engineers to create 'designer plastics' that is increasing the rate at which they replace other materials.

Polymers have been made from a range of raw materials but the most important source today has to be crude oil. This single source of hydrogen and carbon is manipulated to form the enormous family of plastics. These are tailored for each application but also for the manufacturing process as some soften when heated and others harden and stay hard. The group that softens as they become hot can be pressed or blown into a desired shape once softened and are known as thermoplastic materials. The other group, however, hardens when heated and then stays hard so any working is done cold and then the finished product fired.

Plastic bottle being moulded

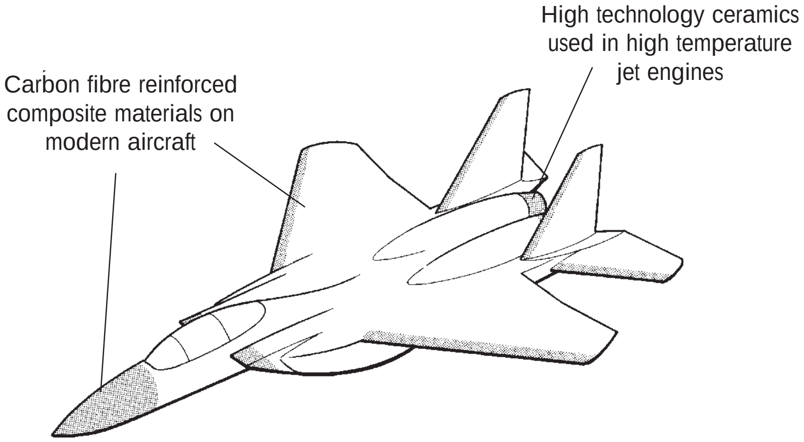



PET fizzy drinks bottle - PET stands for polyethelene teraphthalate, a co-polymer with high tensile strength



Composite materials have become important new additions to the range of materials available today. Perhaps the best known applications of these use carbon fibre, a relatively new product from a common material. When used with resins or plastic fillers, carbon fibre finds itself in products from aero engines to tennis rackets to bike frames to pressure vessels. Everywhere that its high tensile can be combined with the toughness of other material will be a place to find this combination. Many other combinations are emerging which enable the designer to tailor the composite material to the exact needs of the application.

Ceramic materials have long been an important source of raw material for manufacturing. During the Stone Age, pots were made for many uses and the technology was developed that led to the use of bricks and tiles, clay moulds for casting metals, as well as the ability to create temperatures high enough to melt metals. Ceramics are good insulators, very hard, can withstand high temperatures and today, ceramics are essential materials in many fields. Many electrical insulators are of ceramic and fireplaces, boilers and ovens all use them as thermal insulation, while manufacturing uses cutting tools made from a variety of ceramics.

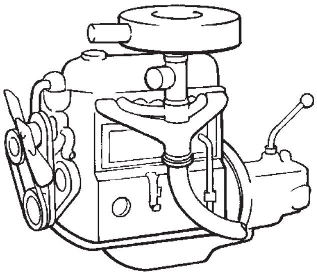


Because they too are designer materials, made up by mixing a variety of raw materials in the right proportions, ceramics find their way into applications both commonplace and exotic. They make the bricks that we live in and they coat the nose cone of the space shuttle - a much more exotic living space.

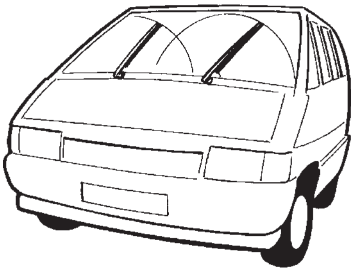
Natural materials still form an important part of raw materials in use, albeit a much less important part than in earlier times. Of these materials, wood must remain the most important, finding uses in all types of industrial and domestic products.

SOME PHYSICAL PROPERTIES OF MATERIALS

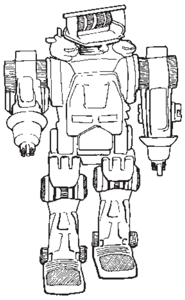
When choosing a material to do a particular job, many different properties need to be considered. Just what is important will depend very much on the application. It may be that cost is of greatest importance, it could be weight or perhaps the melting point of the material. In many cases, a number of properties need to be considered and carefully weighed up against each other. The products shown below contain many hundreds of different materials between them. Each material is carefully selected for good reasons.



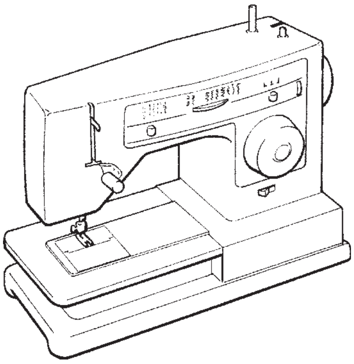
Car engine



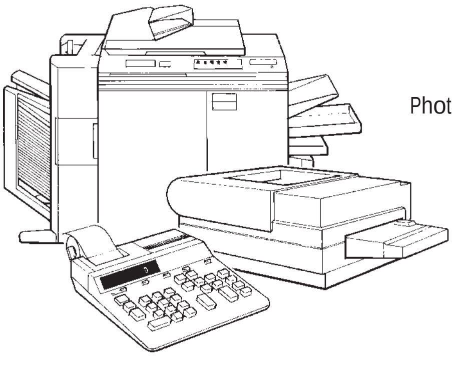
Other car components



Transformer toy



Sewing machine



Photocopier / printer / calculator

Fortunately, many properties of materials have been established by scientists and engineers and tabulated for ease of reference. These tables enable us to compare the properties of different materials and speed up the decision when setting out to choose the correct material. During the derivation of tables such as these, great care has to be taken to ensure that the experimental conditions are standardised. This means that the laboratory or equipment used must be maintained at a standard temperature and pressure (STP). The values derived must be repeatable anywhere on earth under similarly-standardised conditions. This is very important as many properties vary with temperature and/ or pressure.

The following tables list some of the important properties of materials. Not all of the information in these tables will be obvious to you, and a more advanced explanation of some of the properties appears after the tables.

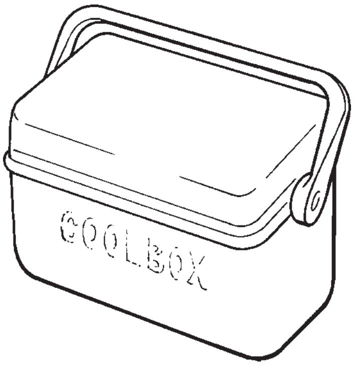
The tables are of two kinds:

- *tables that give precise numerical information to enable you, for example, to compare specific properties of materials such as hardness;*

- *tables that provide information without figures that has been reorganised for quick look-up purposes. The information on stiffness of sections (2.15) and special properties (2.16) are two examples.*

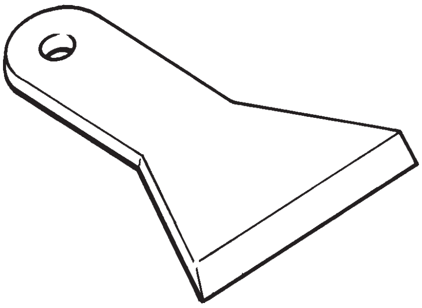
What can you learn from the tables and how will they assist you in designing and making things? When asked to produce a design specification, you need to state very clearly what your intended product has to do. You will almost certainly have to say something about its performance and this will lead you to think about suitable materials from which to make it. Here are some examples of how look-up information can help:

Example 1. The insulated container



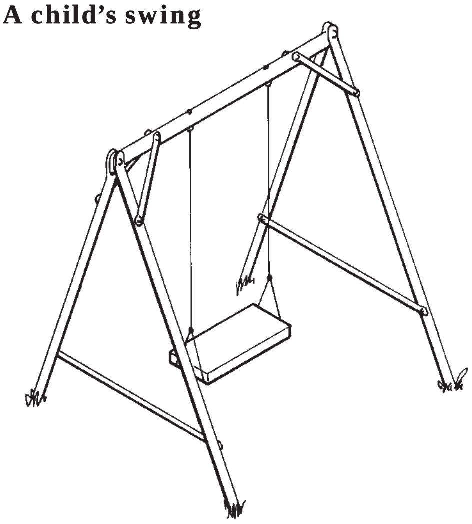
You are designing and making a small container to keep food and drink either hot or cold. What materials might be suitable for insulation ? Table 2.16 lists a number of materials that are especially good insulators. You can cross-check some of these by looking at table 2.4 which gives figures for thermal conductivity of different materials. A low figure in this table means that a material is a poor conductor of heat. We see, for example, that paper is a very poor conductor of heat and might be suitable as a cheap insulator - as it is for take-home fish and chips! It is especially good in layers because it also traps pockets of air which itself is a good insulator when not moving.

Example 2. The window scraper



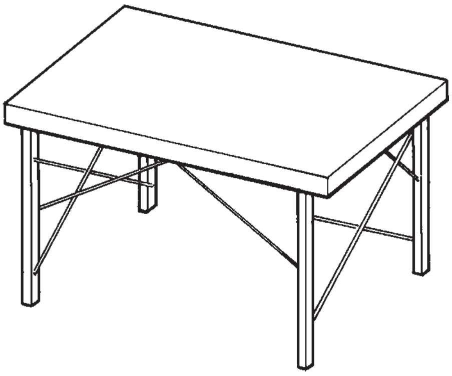
You are designing and making a small scraper to remove ice/frost from car windows and you want to make it in a single material. What will be strong enough and at the same time not scratch the window or paintwork ? Table 2.9 provides some hardness figures for metals and plastics. If the edge of the scraper is not to be worn away quickly we need a hard material but mild steel (BHN 130) is too hard because it will almost certainly scratch the paintwork. The plastics materials appear to be the most suitable ones on the list, but polythene will probably be too soft (BHN 2). Acrylic or polystyrene seem to be possibilities and you can cross-check these on table 2.14. Acrylic is the stronger material in terms of tensile strength but it is very poor for impact resistance. It will not stand up knocks and the edge will probably chip against hard ice. Polystyrene would seem a reasonable choice of material.

Example 3. A child's swing



You are designing and making a small child's swing with a tubular metal frame whose ends are to be closed flat, drilled and bolted together. Can you use any tube for the frame? Table 2.15 reveals that a tube of large diameter for a given cross-sectional area of material is stiffer than one with a smaller diameter. (The table also provides other options such as square tube.) It is also clear that the larger diameter tube has good torsional resistance - unlike the 'I' section at the very top of the table!

Example 4. A folding table



You are looking for a suitable timber to construct a small folding table. What is the best material available to you when judged against strength and weight ? If you compare density against strength in table 2.13, you will see that spruce, although not the strongest material in the table, *is the strongest for its weight*. In fact, weight for weight, spruce is as strong as mild steel and for this reason it is still used a material in light aircraft construction.

Further, more detailed, look-up information can be found in two standard reference books available in all reference libraries:

- Kempe's Engineers Year-Book
- Newne's Engineers Handbook

Table 2.2: Some Physical Properties of Metallic Elements

Element	Mass Density Specific Gravity Kg/litre	Melting point °C	Boiling point °C	Thermal Cond. W/m°C	Coeff of Expn 10^{-6}/°C	Elect. Restvty nΩm	Main uses
Aluminium	2.7	660	2400	205	23	27	Electric Wire
Copper	6.96	1083	2580	390	178	16.8	Electric Wire
Gold	19.3	1063	2660	310	14	23	Jewellery/Elec Contacts
Iron	7.9	1535	2900	76	12	97	Castings
Lead	11.3	327	1750	35	29	206	Pipes
Nickel	8.9	1453	2820	91	13	68	Plating
Platinum	21.5	1769	3800	69	9	106	Jewellery/Elec contacts
Silver	10.5	961	2180	418	19	16	Jewellery/Photographic emulsions
Tantalum	16.6	3000	5300	54	6	135	Capacitors
Tin	7.3	232	2500	64	23	120	Surface coating
Titanium	4.5	1680	3300	17	9	550	Aircraft parts
Tungsten	19.5	3380	6000	190	4.5	55	Light Bulb Elements
Zinc	7.1	420	907	113	31	59	Surface Coating

Table 2.3: Some Physical Properties of Alloys

Alloy	Mass Density Specific Gravity Kg/litre	Melting point °C	Thermal Cond. W/m°C	Coeff of Expn 10^{-6}/°C	Elect. Restvty nΩm	Main uses
Brass	8.45	927	120	20	69	marine fittings
Constantan(60/40)	8.9	1320	22	-	490	thermocouples
Dural (4.4% Cu)	2.8	640	150	23	52	cladding of vehicles, aircraft
Manganin (84% Cu)	8.5	-	22	-	440	castings
Nichrome (80/20)	8.36	-	13	12.5	1030	resistance wire
Phosphor-bronze	8.92	1050	75	18	115	marine parts, bearings
Steel (mild)	7.85	-	50	11	120	structures

Table 2.4: Some Physical Properties of Non-Metals

Material	Mass Density Specific Gravity Kg/litre	Melting point °C	Thermal Cond. W/m°C	Coeff of Expn 10^{-6}/°C	Elect. Restvty MΩm	Main uses
Alumina	3.9	2050	21	8	10^3-10^6	high temperature linings, etc.
Brick	14.4-2.2	-	0.4-0.8	3-9	1-2	structure & cladding in buildings
Concrete	2.4	-	1.0-1.5	10-14	-	structure & cladding in buildings
Dry ground	1.6	-	-	-	0.01-0.1	all sorts!
Glass	2.4 - 3.5	1100	0.4-1.1	3-10	5.10^3-10^6	containers, windows, insulation
Granite	2.7		2.4	6-9	-	decorative cladding, working surfaces
Mica	2.8		0.5		10^3-10^6	insulation, was used in small windows
Nylon	1.14	200-220	0.25-0.33	80-130	10^4-10^7	textiles, engineering components
Paper (dry)	1.0	-	0.06		10^4	newspapers, magazines, books
Perspex	1.2	85-115	0.19-0.23	50-80	-	models, experimental construction
Polystyrene	1.06	80-105	0.8-0.2	60-80	10^{10}	engineering components, packaging
Polythene	0.93	65-130	0.25-0.5	110-220	10^5	engineering components, packaging
PTFE	2.2	-	0.23-0.27	90-130	10^9	engineering components, non-stick surfaces
PVC (plasticised)	1.7	70-80	0.16-0.19	50-250	10^4-10^7	protection of components, clothing
Porcelain	2.4	1550	0.8-1.85	2.2	10^4-10^7	containers, insulation, heat & electrical
Quartz (crystal)	2.65	-	5-9	7.5-13.7	10^6-2×10^8	crystal oscilators
Rubber (natural)	1.1-1.2	125	0.15	200	10^7	tyres, insulation heat, electrical & vibration
Sandstone	2.4	-	1.1-2.3	5-12	-	structure & cladding in buildings
Timber (along grain)	0.4-0.8	-	0.15	3-5	-	all sorts!

Table 2.5 Some Mechanical Properties of Metals

E	Young's modulus (kN/mm^2) - (linear stress)/(linear strain)*
G	Shear modulus (kN/mm^2) - (shear stress)/(shear strain)*
ν	Poisson's ratio - (lateral strain)/(longitudinal strain)*
σ_y	Proof or yield stress (N/mm^2)
σ_f	Ultimate (failure) stress (N/mm^2)

*within the elastic limits

Values of σ_y and σ_f usually depend strongly on the preparation and condition of a material. The ranges given are typical but not necessarily exhaustive and, unless otherwise stated, those for metals refer to drawn or wrought rather than cast material of commercial purity.

	σ_f	σ_y	E	G	ν
Metallic elements					
Aluminium	60-160	30-140	70	26	0.34
Copper	200-350	47-320	124	46	0.35
Gold	110-230	0-210	80	28	0.42
Iron (wrought)	350	160	195	76	0.29
Iron (cast)	140-320		115	45	0.25
Lead	15-18		16	6	0.44
Nickel	480-730	140-660	205	79	0.31
Platinum	125-200	15-180	168	61	0.38
Silver	140-380	55-300	76	28	0.37
Tantalum	340-930		186		
Tin	15-200	9-14	47	17	0.36
Titanium	250-700	200-500	110	41	0.34
Tungsten	1000-4000		360	140	
Zinc	110-200		97	36	0.35

Table 2.6 Alloys

	σ_f	σ_y	E	G	ν
Alloys					
Brass (65/35)	330-530	62-430	105	38	0.35
Constantan (60/40)	400-570	200-440	163	61	0.33
Dural (4.4% Cu)	230-500	125-450	70	27	0.33
Manganin (84% Cu)	465		124	47	
Mumetal (77% Ni)	540-910		220		
Nichrome (80/20)	170-900		186		
Phosphor-bronze	330-750	110-670	100		0.38
Steel mild	480	240	210	81	0.30
Steel high yield	600	450	210	81	0.30

Table 2.7 Non-metals

	E	ν	$\sigma_{f\ (tension)}$	$\sigma_{f(compression)}$
Non-metals				
Alumina	200-400	0.24	140-200	1000-2500
Brick	10-50			69-140
Concrete	10-17	0.1-0.21		27-55
Glass	50-80	0.2-0.27	30-90	
Granite	40-70			90-235
Nylon 6	1-2.5		70-85	50-100
Perspex	2.7-3.5		50-75	80-140
Polystyrene	2.5-4.0		35-60	80-110
Polythene	0.1-1.0		7-38	15-20
PTFE	0.4-0.6		17-28	5-12
PVC (plasticized)	0.3		14-40	75-100
Rubber (natural)	0.001-1	0.46-0.49	14-40	
Sandstone	14-55			30-135
Timber (along grain)	8-13		20-110	50-100

Table 2.8 Comparative Tensile Strengths of Materials

This table gives approximate tensile strengths for a range of materials for purposes of comparison.

Material	MN/m^2
steel piano wire	3000
high tensile steel	1500
titanium alloys	700 - 1400
mild steel	400
aluminium alloys	140 - 550
traditional wrought iron	140 - 280
modern cast iron	140 - 280
copper	140
brasses	120 - 400
pure cast aluminium	70
flax	700
cotton	350
silk	350
spider's thread	240
bone	140
wood (along grain)	100
tendon (muscle)	100
hemp rope	80
leather	40
glass window or wine glass	30-170
ordinary brick	5
cement and concrete	4
wood (across grain)	3

2.9 Typical Brinell hardness numbers (BHN) for metals and plastics

Material	**BHN**
Soft brass	60
Mild steel	130
Annealed chisel steel	235
White cast iron	415
Nitrided surface	750
PVC rigid	20
Polystyrene	25
Acrylic (Perspex)	34
Polythene (high density)	2
Epoxy resin (glass filled)	38

2.10 Comparison of hardness numbers

Rockwell *C* scale	Vickers pyramid	Brinell hardness number	Rockwell *C* scale	Vickers pyramid	Brinell hardness number	Rockwell *C* scale	Vickers pyramid	Brinell hardness number
68	1030	–	49	515	468	30	299	286
67	975	–	48	500	458	29	291	279
66	935	–	47	485	447	28	284	272
65	895	–	46	470	436	27	277	266
64	860	–	45	456	426	26	271	260
63	830	–	44	442	416	25	265	255
62	800	–	43	430	406	24	260	250
61	770	–	42	418	396	23	255	245
60	740	–	41	406	386	22	250	240
59	715	609	40	395	376	21	245	235
58	690	594	39	385	366	20	240	230
57	670	579	38	375	356	–	220	210
56	650	564	37	365	346	–	200	190
55	630	549	36	355	337	–	180	171
54	610	534	35	345	328	–	160	152
53	590	519	34	335	319	–	140	133
52	570	504	33	325	310	–	120	114
51	550	492	32	315	302	–	100	95
50	532	480	31	307	294	–	–	–

2.11 Density of materials

In this table densities (ρ) are given for normal pressure and temperature.

Metals				Wood (15% moisture)	
Metal	ρ (kg m^{-3})	Metal	ρ (kg m^{-3})	Wood	ρ (kg m^{-3})
Aluminium	2700	Monel	18900	Ash	660
Aluminium bronze (90%Cu, 10%Al)	7700	Nickel	8900	Balsa	100-390
Antimony	6690	Nimonic (average)	8100	Beech	740
Beryllium	1829	Palladium	12160	Birch	720
Bismuth	9750	Phosphor bronze (typical)	8900	Elm: English	560
Brass (60%Cu/40%Zn)	8520	Platinum	21370	Dutch	560
Cadmium	8650	Sodium	971	wych	690
Chromium	7190	Steel: mild	7830	Fir, Douglas	480-550
Cobalt	8900	stainless	8000	Mahogany	545
Constantan	8920	Tin: grey	5750	Pine: Parana	550
Copper	8930	rhombic	6550	pitch	640
Gold	19320	tetragonal	7310	Scots	530
Inconel	8510	Titanium	4540	Spruce, Norway	430
Iron: pure	7870	Tungsten	19300	Teak	660
cast	7270	Uranium	18680		
Lead	11350	Vanadium	5960		
Magnesium	1740	Zinc	7140		
Manganese	7430				
Mercury	13546				
Molybdenum	10200				

2.12 Safe stresses in structural timbers (N mm^{-2})

Timber	Bending			Compression			
	Stress in extreme fibre		Horizontal shear stress	Stress parallel to grain		Stress perpendicular to grain	
	Outside location	Dry location	All locations	Outside location	Dry location	Outside location	Dry location
Oak	8.3	9.7	0.9	6.0	6.9	1.6	3.5
Douglas fir	7.6	9.0	0.6	6.0	6.9	1.6	2.1
Norway spruce	6.9	7.6	0.6	5.5	5.5	1.2	2.1

2.13 Mechanical properties of some timbers

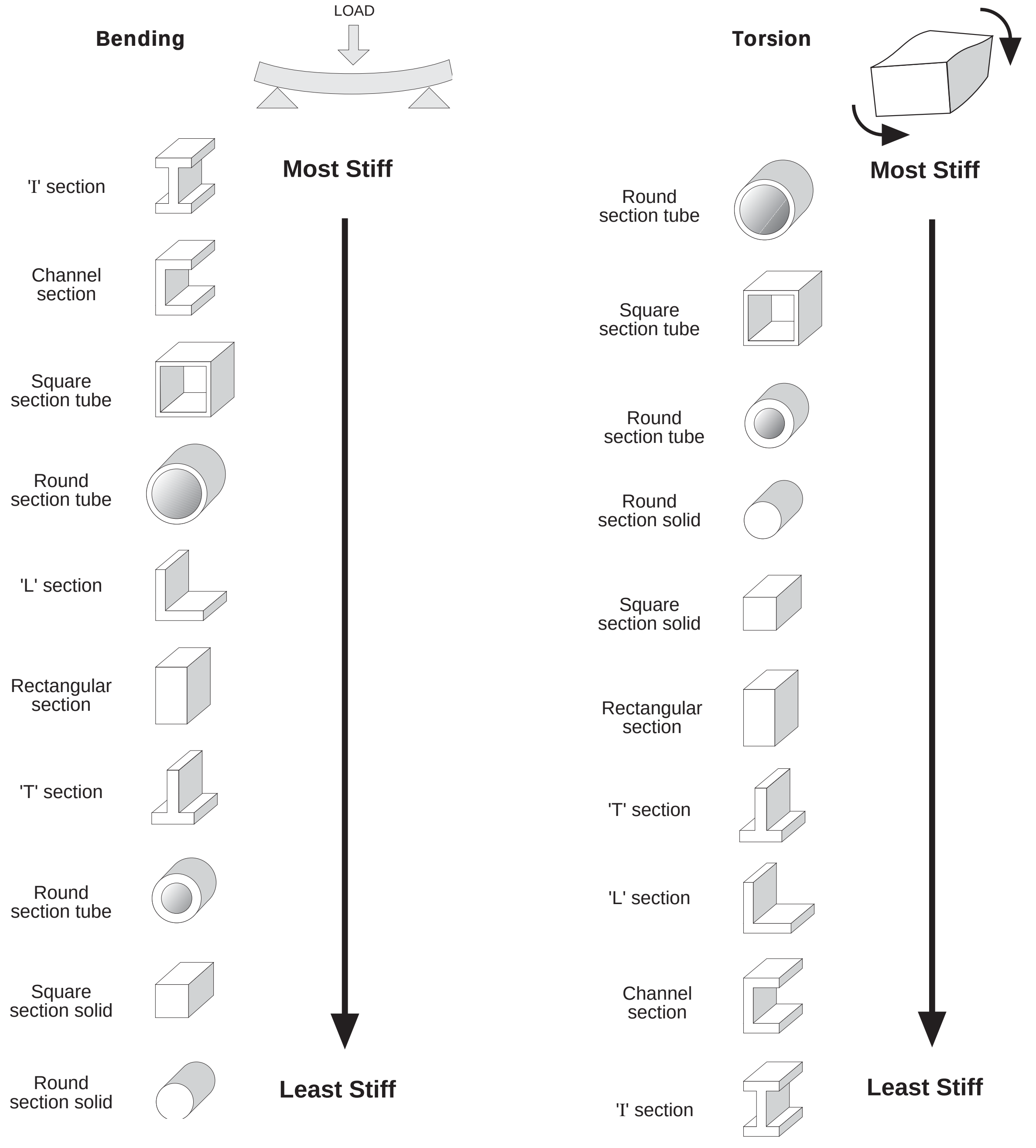
Wood	Moisture (%)	Density, ρ (kg m^{-3})	Fibre stress at elastic limit (N mm^{-2})	Modulus of elasticity E (N mm^{-2})	Modulus of rupture (N mm^{-2})	Compressive strength parallel to grain (N mm^{-2})	shear strength (N mm^{-2})
Ash	15	657	60	10070	103	48	10
Beech	–	740	60-110	10350	–	27-54	8.3-14
Birch	9-10	710	85-90	15170	130-135	67-74	13-18.5
English elm	–	560	40-54	11790	–	17-32	8-11.3
Fir, Douglas	6-9	530	45-73	10340-15170	71-97	49-74	7.4-8.8
Mahogany	15	545	60	8690	80	45	6.0
Oak	–	740	56-87	14550	–	27-50	8-12
Scots pine	–	530	41-83	8550-10340	–	21-42	5.2-9.7
Poplar	–	450	40-43	7240	–	20	4.8
Spruce	–	430	36-62	7380-8620	–	18-39	4.3-8
Sycamore	–	625	62-106	8970-13450	–	26-46	8.8-15

2.14 Physical properties of some plastics

Properties of plastic	ρ (kg m^{-3})	Tensile strength (N mm^{-2})	Elongation (%)	*E* (GN m^{-2})	Impact resistance	BHN	Machinability
Thermoplastics							
PVC rigid	1330	48	200	3.4	Good	20	Very good
Polystyrene	1300	48	3	3.4	Average	25	Average
PTFE	2100	13	100	0.3	V.good	–	Very good
Polypropylene	1200	27	200-700	1.3	V.good	10	Very good
Nylon	1160	60	90	2.4	Good	10	Very good
Cellulose nitrate	1350	48	40	1.4	Average	10	Very good
Cellulose acetate	1300	40	10-60	1.4	Average	12	Very good
Acrylic (Perspex)	1190	74	6	3.0	Poor	34	Very good
Polythene (high density)	1450	20-30	20-100	0.7	Average	2	Very good
Thermosetting plastics							
Epoxy resin (glass filled)	1600-2000	68-200	4	20	V.good	38	Good
Melamine formaldehyde (fabric filled)	1800-2000	60-90	–	7	V.good	38	Average
Urea formaldehyde (cellulose filled)	1500	38-90	1	7-10	V.good	51	Average
Phenol formaldehyde (mica filled)	1600-1900	38-50	0.5	17-35	V.good	36	Good
Acetals (glass filled)	1600	58-75	2-7	7	V.good	27	Good

BHN = Brinell hardness number, ρ = density, *E* = Young's modulas

Table 2.15 Stiffness of sections



Bending	Torsion
Most Stiff	Most Stiff
'I' section	Round section tube
Channel section	Square section tube
Square section tube	Round section tube
Round section tube	Round section solid
'L' section	Square section solid
Rectangular section	Rectangular section
'T' section	'T' section
Round section tube	'L' section
Square section solid	Channel section
Round section solid	'I' section
Least Stiff	Least Stiff

2.16 Special properties

Some high temperature metals

Chromium
Heat-resisting alloy steels
High speed steel
Nichrome
Nimonic alloys
Stainless steel
Stellite
Tantalum
Titanium
Tungsten
Vanadium

Corrosion resistant metals

Cupronickel
Lead
Monel metal
Nickel
Pure aluminium
Stainless steel
Tin
Titanium and alloys

Coating metals

Brass
Bronze
Cadmium
Chromium
Copper
Gold
Lead
Nickel
Platinum
Silver
Tin
Zinc

Good conductors of heat

Aluminium
Bronze
Copper
Duralumin
Silver
Zinc

Good conductors of electricity

Aluminium
Beryllium copper
Brass
Copper
Gold
Magnesium
Phosphor bronze
Silver

Good electrical insulators

Ceramics
Ebonite
Gases
Glass
Insulating papers
Mica
Shellac
Silicone rubber
Soft natural and synthetic rubber
Thermoplastics
Thermosetting plastics
Tufnol

Good heat insulators

Cork
Cotton wool
Expanded polystyrene
Felt
Glass fibre and foam
Glass wool
Hardboard
Insulating wallboard
Mineral wool
Plywood
Polyurethane foam
Rubber
Sawdust
Urea formaldehyde foam
Wood

High strength to weight ratio materials

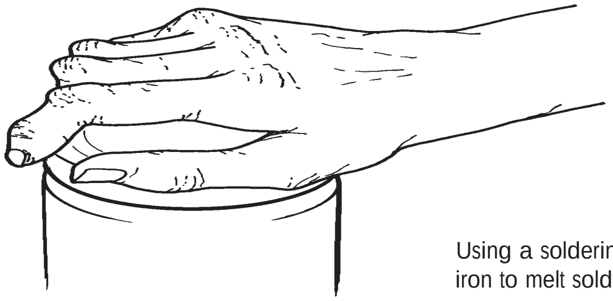
Carbon fibre reinforced plastics
Duralumin
Glass reinforced plastics
Magnesium alloys
Nylon
Polycarbonate
Some aluminium alloys
Spruce
Titanium
Titanium alloys

ADVANCED EXAMPLES TO EXPLAIN THE TABLES

- **Melting Point (*in °C*)**

(Tables 2.2, 2.3, 2.4, column 2)

This tells us about the temperature needed to change a solid metal into a molten one. It tells us, therefore, what materials may be used at high temperature and, conversely, what materials we can cast at low temperature. We must use this figure carefully, however, as materials will go through a phase of softening at temperature and may become unusable long before their melting temperature is reached. Nevertheless, the melting temperature will provide a guide to the performance of a material at elevated temperatures.

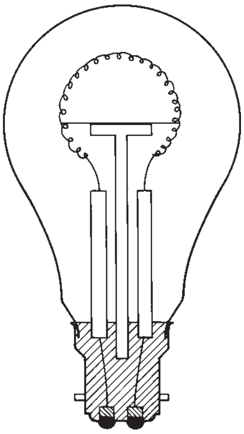


Using a soldering iron to melt solder

Another aspect of temperature that must be considered is the potential for a material to catch fire. For instance, although magnesium melts at 649°C and aluminium at 660°C, only 11°C higher, magnesium burns at a much lower temperature than aluminium. A strip of magnesium, for instance, can be ignited readily with a match and would burn with an intense flame. A similar strip of aluminium would do little other than oxidise - and that's if the flame's held there long enough.

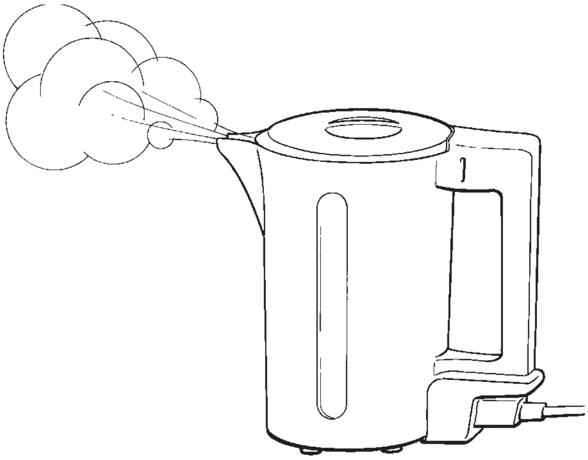
Where melting point is of vital importance is in the process of casting. When a molten metal is poured into a cavity, the lining of that cavity must be able to stand the temperature of the molten metal. Thus, while a large range of materials would be able to withstand the temperature of molten tin at 232°C, few would hold together when faced with molten tungsten at 3380.°C. So, in processes like die casting, where the mould is made of metal, low melting point materials such as zinc will be chosen to give an acceptable die life.

On the other hand, some devices such as a light bulb call for a high melting point material. In this a tungsten filament is heated to white heat, giving off light. At the temperature which the bulb's filament attains, most metals would have vaporised.



- **Boiling Point** ***(℃)***

(Table 2.2 column 3)
This tells us about the temperature at which a liquid changes phase to become a vapour. A good example of the process is seen with water at 100°C (212°F). At this temperature, it bubbles vigorously as molecules change into a vapour. These molecules expand as they change phase, as steam has a volume 1300 times greater than the corresponding volume of water. As they expand, their density falls and they rise to the surface of the liquid and escape from this into the atmosphere above the surface of the liquid.



Molten metals behave in the same way as they pass from the liquid to the vapour state. The values at which the change of state occurs in metals is shown in column 3 of Table 2.2.

In the case of alloys this temperature is not so significant as the alloy is likely to break down into its constituent parts before the theoretical boiling point is reached. When this happens, the different parts of the alloy are likely to behave differently. This is readily seen with brass, in which the zinc content has much lower melting and boiling points. When this is heated even only mildly above the alloy's melting point, the zinc evaporates from the molten alloy. Thus, while casting brass, care has to be taken to control the gas emitted from the molten alloy. If correctly controlled, the gas can be collected and condensed to recover the zinc.

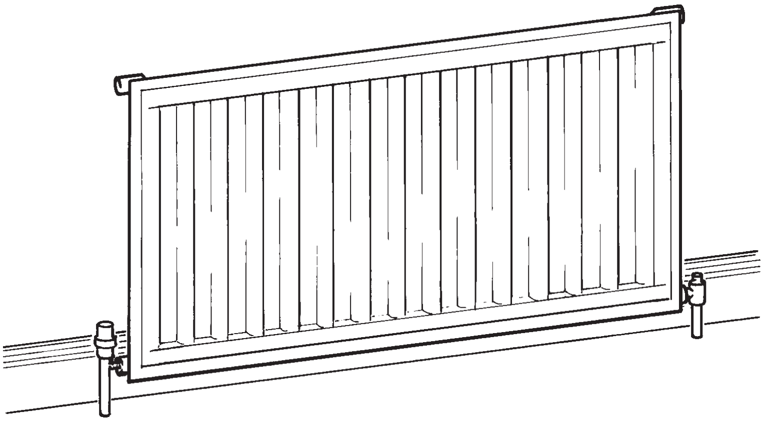
The effect can be seen in another way when brass is stored under poor conditions. In time, the zinc will evaporate from the surface, leaving the brass looking like copper.

In the case of Table 2.4, no figures are given for the non-metallic materials. This is for a variety of reasons. In some cases, these materials are complex mixtures, such as paper and these will burn long before they evaporate. In other cases, the boiling points are very high and have little significance in practical terms.

- **Thermal conductivity at or near 0°C *(in W/m °C)* (Tables 2.2, 2.3, 2.4, column 4)**

This tells us about the rate at which heat can flow through the material. In general, metals enable heat to flow quite readily as you can tell when you grasp the metal handle of a hot saucepan.

This phenomenon is used in devices such as radiators where the heat from hot water is transferred through to the metal outside of the radiator itself. In industrial heat exchangers, copper tubes are used to carry steam and to allow the heat in this to be transferred through to other media such as water or air. The old steam trains had a mass of copper tubes which passed through the firebox, allowing the coal fire to convert water into steam. A domestic refrigerator has a heat exchanger to transfer heat from the cooling circuit to the atmosphere.



In spite of the fact that metals have, in general, good thermal conductivity, there still remains a remarkable difference between the 205 W/m °C of aluminium and the 17 w/m k of titanium.

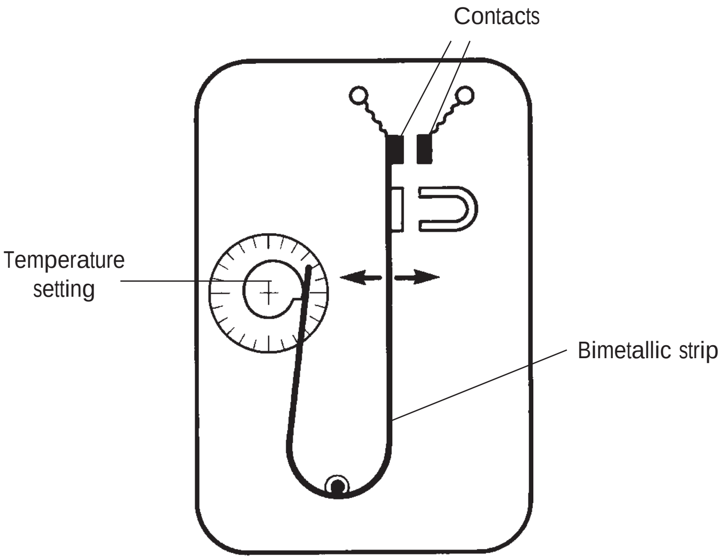
The values for thermal conductivity are determined by measuring the rate at which heat flows along a material, from its hot to its cold end.

- **Coefficient of Linear Expansion** ***(in 10^{-6}/°C)***
(Tables 2.2, 2.3, 2.4, column 5)

This tells us how much a material expands when it is heated. It is important to know this figure if we are fastening together two different metals and these are going to be subjected to heat. If one is going to expand more than the other then this could lead to problems as one tries to stretch the other. The forces generated could well lead to the failure of a joint.

However, the differences in expansion can also be put to good use in measuring temperature. If two strips of different metals are fastened together, one of which expands at a higher rate than the other, these will distort when heated. The strip with the higher rate of expansion will extend more than the other strip and will cause the combined strip to curve. This phenomenon is used in thermostats, where a bimetallic strip is used to switch the heater off and on in order to maintain the system at a steady temperature. This bimetallic strip is frequently made into a coil and the winding and unwinding of this carries out the switching action.

The values for the coefficient of linear expansion are determined by measuring the length of the material at different temperatures and calculating how much it expands for each step of 1°C (or °K).



Thermostat

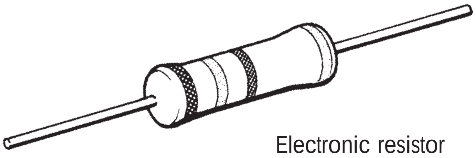
- **Electrical Resistivity** ***(in Ωm)***

(Tables 2.2, 2.3, 2.4, column 6)
This is a measure of how easily electrical current flows through a material. It is, of course, most interesting in electrical devices and, most importantly, when making electrical wire.

The low resistivity of copper makes it one of the most commonly used materials for electric wire but aluminium comes a close second. You'd look long and hard in the house to find aluminium wire because it is used mainly for high voltage power transmission. Even when strengthened with a steel core it is much lighter than copper and enables pylons to be spaced well apart, saving considerably in the process of getting electricity from the power station to the home.

Other applications call for low resistance wires but make greater demands, particularly in terms of temperature. It is here where gold and platinum come into their own, providing wires for sensors and microchips. Gold, Silver and platinum offer the added advantage that they do not readily oxidise and, thus, offer the attraction of very low resistance joints. Contrast that with aluminium which has a great affinity for oxygen and is almost always covered with a thin film of oxide. Hence its relegation to industrial use where specialist care can be applied in creating joints.

At the other end of the scale metals can be prized for their high resistance. In an electric fire element, for instance, the high resistance to electrical current gives rise to the heating effect that makes the fire work. In electronics too, materials are needed which allow current to flow but offer resistance. These are used to make resistors of various types.



Electronic resistor

Electrical resistivity is derived by measuring the flow of current through a wire of a set size and then using Ohm's law to calculate the resistance. The resistivity is then calculated from the relationship:

$$\text{resistance} = \frac{\text{resistivity} \times \text{length}}{\text{area}}$$

The resisitivity is usually referred to by the Greek character rho (ρ) but also occasionally as 's' (for specific resistivity). Thus, the relationship becomes:

$$r = \frac{\rho l}{a} \quad \textit{OR} \quad r = \frac{sl}{a}$$

Thus, if a piece of copper wire of length 1 metre and diameter of 1mm is found to have a resistance of $21.4 \times 10^{-3}\Omega$, what is the resistivity of the copper?

From:

$$\text{resistance} = \frac{\text{resistivity} \times \text{length}}{\text{area}}$$

$$\text{resistivity} = \frac{\text{resistance} \times \text{area}}{\text{length}}$$

i.e.,

$$\text{the area of the wire} = \frac{\pi d^2}{4} = \frac{\pi \times (1 \times 10^{-3})^2}{4}$$

$$= \underline{0.785 \times 10^{-6}}$$

$$\text{i.e., resistivity} = \frac{21.4 \times 10^{-3} \times 0.785 \times 10^{-6}}{1.0}$$

$$= \underline{16.8 \times 10 \text{ n}\Omega\text{m}}$$

- **Alloys**

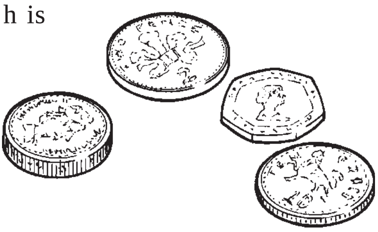
Table 2.3 lists some common alloys and provides data about their physical properties and use.

Alloys have been in use pretty well as long as metals. This is because the rocks from which metals are extracted contain not just single metals but whole suites of different metals. Thus, many of the early alloys could be described as 'natural' alloys, all their elements coming from the same ore.

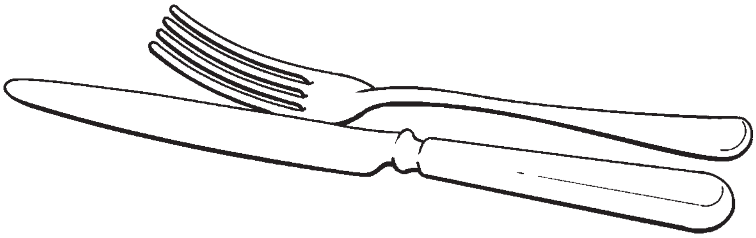
However, there were few sources of tin known to the ancient world and yet the copper tin alloy 'bronze' was in almost universal use at one time. Clearly, alloys do offer an advantage over pure metals.

The main alloys of ancient times were based on iron and copper and this remains largely so at the present time. Only aluminium has entered the fray in a serious way since then. Copper still features strongly in the bronzes which offer good corrosion resistance as well as providing excellent low friction bearing alloys. In these alloys, it is combined with tin and phosphorus.

When combined with nickel, copper produces the alloy constantan which is used in thermocouples. The same combination, but with only a smaller amount of nickel, produces the money alloys from which the British 'silver' coinage is now produced.



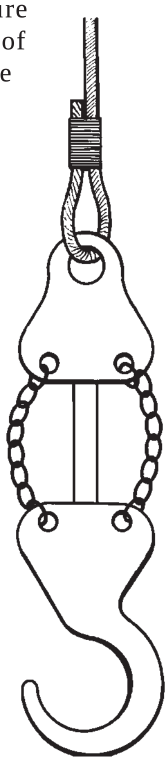
Iron still finds a use as cast iron but is most common when alloyed with carbon to form steel. The amount of carbon in the steel has a profound effect on its properties and is a subject in its own right. Probably the most profound development in the recent history of steel was the development of stainless steel.. When the relatively large amounts of 18% chromium and 8% of nickel are added to steel, a workable and non-corroding alloy is produced. Food production and preparation have been revolutionised, along with much of consumer design.



Aluminium came of age in the 20th century and a range of new alloys have extended its use in castings, in forgings and in wrought work. Perhaps the commonest element to be alloyed with aluminium is copper, the addition of 4% producing duralumin (or dural), an alloy which can be worked like aluminium but provides a harder and tougher sheet material.

- **Ultimate Tensile Strength (Table 2.5, Column 1)**

The ultimate tensile strength (UTS) of a material is its strength before failure occurs. It is an important figure that engineers use in calculations for the safe design of structures. The following example illustrates how the UTS figure can be applied to solve a simplified engineering design problem.



A crane has been designed that will allow a load of 10,000 N to be lifted. We know that if the user attempts to lift more than this the entire structure will be damaged. If we insert a pin, calculated to fail in tension at just under 10,000N between the steel hawser and the crane hook, the crane will never be able to lift more than the maximum permitted load before the pin fails. (If failure does occur, two safety chains connecting the steel hawser and crane hook will prevent a load falling or cable whiplash.)

How do we decide on the size of the pin?

Let's assume that we have decided to use an aluminium pin and that our tests show that its UTS is 100 N/mm². Thus, as the pin needs to withstand 10 000 N and each square mm can stand 100N we would need a pin area of:

$$\frac{10000}{100} = \underline{100\ \text{mm}^2}$$

i.e. if the diameter is d:

$$\frac{\pi d^2}{4} = 100$$

$$d^2 = \frac{100 \times 4}{\pi}$$

$$d = \underline{11.28\ \text{mm}}$$

Thus, the pin diameter would need to be 11.28 mm.

What if we had decided to use titanium and our tests had given a value of 600 N/mm² for its UTS?

Calculating this a different way:

$$\text{UTS} = \frac{\text{Load at failure}}{\text{area}}$$

$$\text{i.e. } 600 = \frac{10\ 000}{\text{area}}$$

Checking the units: $\frac{\text{N}}{\text{mm}^2} = \frac{\text{N}}{\text{mm}^2}$ OK

$$\text{area} = \frac{\pi d^2}{4}$$

$$\text{i.e., } 600 = \frac{10\ 000 \times 4}{\pi d^2} \qquad = 21.22$$

$$\text{i.e., } d^2 = \frac{10\ 000 \times 4}{\pi \times 600}$$

$$d = \sqrt{21.22}$$

$$\text{i.e. } d = \underline{4.61\text{mm}}$$

Failure pins are used in many mechanical devices to prevent damage, an example being on a lathe bed where the pin fails in shear if the tool post is fed into the chuck head.

- **The Proof or Yield Stress (Table 2.5, Column 2)**

When a material is loaded with a relatively low load, it will stretch, only to recover once the load is removed. If only half of the load is applied, the material will stretch only half the amount and we say that, under these conditions the material is behaving elastically. However, we do know that if we put enough load on the material it will break - and there's no return then. That's not elastic behaviour! So, at some stage the material ceases to behave elastically and begins to stretch permanently. This is referred to as plastic deformation and it actually begins some time before the metal breaks.

It's important to know when a material ceases to behave elastically and starts to stretch permanently as, once it has stretched, it's lost its original shape and could become somewhat unpredictable in its performance. This point where the changeover takes place is known as the elastic limit and the stress at this point as the proof or yield stress. Figure 2.4 shows a typical load/extension graph.

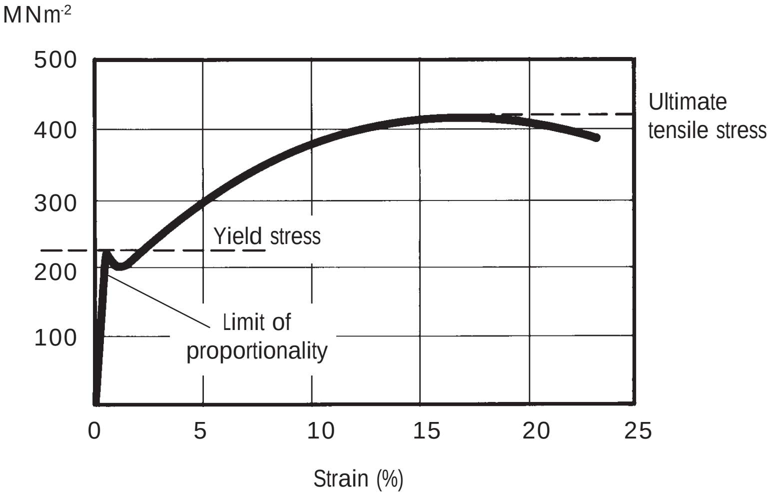


Figure 2.4: A typical load / extension graph for a low-carbon steel

What would happen to our failure pin were this to be loaded beyond its elastic limit?
Clearly, it would deform and might not even fit in its holdings any more. Because of this, failure pins are really only intended to detect sudden or shock loads.

Thus, we would expect the normal working load of the crane in our earlier example to work only up to the elastic limit of the failure pin if this is to remain effective. What, then, would this working load be?

Assume that our tests show the yield of the aluminium to be $50 N/mm^2$.

$$\text{Then, Yield Stress} = \frac{\text{Load at Yield}}{\text{area}}$$

$$50 = \frac{\text{Load}}{\pi d^2/4}$$

$$\text{i.e., Load} = \frac{50\pi(11.28)^2}{4}$$

$$= \underline{5\ 000N}$$

Of course, common sense might have told us that if we halve the allowable stress then we would halve the allowable load.

If we look at the two figures of UTS and proof stress for aluminium we see the following:

	Proof Stress	**UTS**	**Proof Stress/UTS**
minimum	60	30	0.50
maximum	160	140	0.88

What this chart tells us is that the lower strength aluminium stops behaving elastically when only half of the failure load has been applied. However, the higher strength material can take up to 88% of the failure load before it starts to behave elastically. Thus, the way a material is processed, or `worked', not only affects its strength but also its ability to behave elastically.

- **Young's Modulus, E (kN/mm^2)**

(Table 2.5, Column 3)

Frequently the designer needs to have rapid access to figures which tell just how elastic a material is and a way of expressing this was devised by the British physicist, Thomas Young. He worked out that a good measure of the characteristic was obtained when an applied stress was divided by the strain which it produced. This figure is now referred to as Young's Modulus of elasticity or simply Young's Modulus. Thus:

$$\text{Young's Modulus (E)} = \frac{\text{stress}}{\text{strain}}$$

Example:

Suppose that we wish to load a 500mm rod to a third of its yield stress and to know what the extension of this rod will be when this is done.

The material used is titanium with a Young's Modulus (E) of $90kNmm^{-2}$. and its yield or proof stress is $400Nmm^{-2}$.

We will carry out this calculation in Newtons and millimetres so you must be wary of Young's Modulus, as this is expressed in KNmm^{-2}, so as to keep the numbers in the tens and hundreds. Thus, the figure of 90kNmm^{-2} becomes 90 000 Nmm^{-2}.

The maximum allowable stress in the rod is: $\frac{400}{3} \left(\frac{N}{mm^2}\right)$

$$= \underline{133.3\ Nmm^{-2}}$$

$$\text{and} \qquad E = \frac{\text{stress}}{\text{strain}}$$

$$\text{i.e.,} \qquad 90\,000 = \frac{133.3}{\text{strain}}$$

$$\text{strain} = \frac{133.3}{90\,000} = \underline{0.00148}$$

$$\text{but} \qquad \text{strain} = \frac{\text{extension}}{\text{original length}}$$

$$\text{i.e.} \qquad 0.00148 = \frac{\text{extension}}{500}$$

$$\therefore \quad \text{extension} = 0.00148 \times 500$$

$$= \underline{0.74\ mm}$$

Suppose that the maximum allowable extension of the rod is 0.50mm. What would the maximum allowable stress be in the rod?

This time, we know the length of the rod and its maximum allowable extension, therefore, we can calculate the strain.

$$\text{strain} = \frac{\text{extension}}{\text{original length}}$$

$$= \frac{0.50}{500}$$

$$= \underline{0.001}$$

Note that strain has no units as it is calculated from mm/mm (millimetres divided by millimetres).

$$\text{But,} \qquad E = \frac{\text{stress}}{\text{strain}}$$

$$\text{i.e.,} \qquad 90\,000 = \frac{\text{stress}}{0.001}$$

$$\text{i.e.,} \qquad \text{stress} = 90\,000 \times 0.001 = \underline{90Nmm^{-2}}$$

Thus, the stress in the rod, if extended by 0.50mm, would be 90Nmm^{-2}

- **Shear Modulus (kN/mm^2) (Table 2.5, Column 4)**

This figure is very similar to Young's Modulus but uses the shear stress and shear strain rather than the linear stress and strain. What this means is that the stress value is obtained by twisting the sample rather than by stretching it.

Materials behave differently under shear than under tensile or stretching load and the shear modulus provides a measure of performance in the same way as Young's modulus does for tensile loading.

- **Poisson's Ratio (Table 2.5, Column 5)**

When an object is stressed and expands along its axis, it also contracts at right angles to this, i.e., it gets thinner. If the object is a circular rod, then expansion along its length is accompanied by contraction across its diameter.

For a given material, the ratio of contraction to expansion is constant. This was recognised by the French scientist Simeon-Denis Poisson and is named after him, the ratio being known as Poisson's Ratio.

$$\textbf{Poisson's ratio} = \frac{\textbf{lateral strain}}{\textbf{longitudinal strain}}$$

This ratio is used in design to calculate how a cross-sectional area of a component will vary as it is stressed along its axis.

FRICTION

When one surface moves against another, the resistance that opposes movement is called friction. If you push a pile of books over a table surface you can feel the friction between the table surface and the book in contact with it. Before the books start to move, there is a greater resistance. This is called *static* friction. When the books are moving, the resistance you feel is called *dynamic* (moving) friction.

If we divide the force just needed to move the books by their mass (in newtons) we get a figure called the coefficient of friction or 'μ'. This is expressed mathematically by saying:

$\mu = F/N$ (F = force, N = mass)

The coefficient of friction for any two materials sliding against one another tells us how easily they slip against one another. The smaller the number, the less friction there is. If you look at the table below, you will see that metal on ice has a very low value - which explains why ice skates work as well as they do. Rubber on a typical road surface has the highest coefficient. Why is this important for cyclists and motorists?

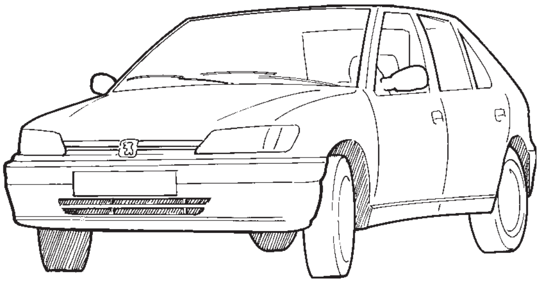


Table 2.17 Frictional characteristics of different materials

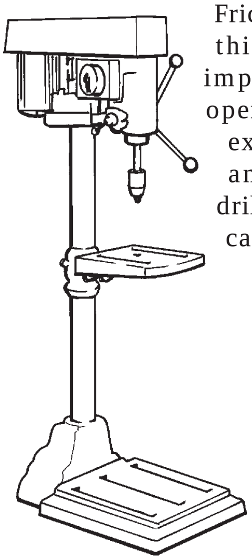
Materials	Lubrication	Approx. coefficient of friction (low pressure)
Metal on metal	none	0.20
Cast iron on hardwood	none	0.49
Cast iron on hardwood	some lubrication	0.19
Metal on hardwood	none	0.60
Metal on hardwood	some lubrication	0.20
Leather on metal	none	0.4
Rubber on metal	none	0.40
Rubber on road	none	0.90
Nylon on steel	none	0.3-0.5
Acrylic on steel	none	0.5
Teflon on steel	none	0.04
Metal on ice	–	0.02

Friction depends on:

- the force which keeps two surfaces in contact
- the roughness of their surfaces
- the materials in contact

Friction is a bad thing when it interferes with machines running. We try to reduce friction in machines such as car engines, cycles etc. We use special bearings and lubricate them well. Nevertheless, in the best machines some energy is still lost due to friction and it reappears as heat. (If a lubricated bearing dries out, it can get very hot and burn out or even melt.)

Friction is a good thing when we do not want things to slip against one another. Friction is important when we clamp things together or operate the brakes on a cycle. It is essential, for example, in transmitting power though pulleys and belts. Examples range from workshop drilling machines to the rubber belt drives in cassette players.



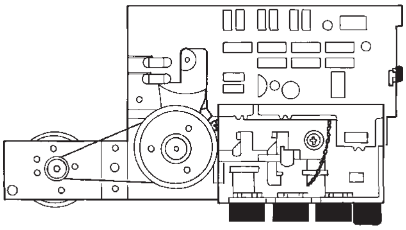


Table 2.18 gives coefficients of friction for different pairs of materials commonly used in clutches and brakes.

In any design work that you do, such tables can be used to help you decide which materials to use if you want either a lot of friction (e.g. a clamping device) or very little (e.g. a bearing). Larger engineers handbooks will give you many more combinations of materials if you need to look further.

Table 2.18 Clutches and brakes

Materials	Coefficient of friction wet	dry	Maximum temperature (°C)	Maximum pressure (bar)
Cast iron/steel	0.06	0.15-0.2	250	8-13
Hard steel/hard steel	0.05	–	250	7
Wood/cast iron or steel	0.16	0.2-0.35	150	6
Leather/cast iron or steel	0.12-0.15	0.3-0.5	100	2.5
Cork/cast iron or steel	0.15-0.25	0.3-0.5	100	1
Felt/cast iron or steel	0.18	0.22	140	0.6
Vulcanized paper or fibre/ cast iron or steel	–	0.3-0.5	100	3
Moulded asbestos/ cast iron or steel	0.08-0.12	0.2-0.5	250	1
Impregnated asbestos/ cast iron or steel	0.12	0.32	350	10
Asbestos in rubber/ cast iron or steel	–	0.3-0.40	100	6
Carbon graphite/steel	0.05-0.1	0.25	500	20
Moulded phenolic plastic with cloth base/ cast iron or steel	0.1-0.15	0.25	150	7