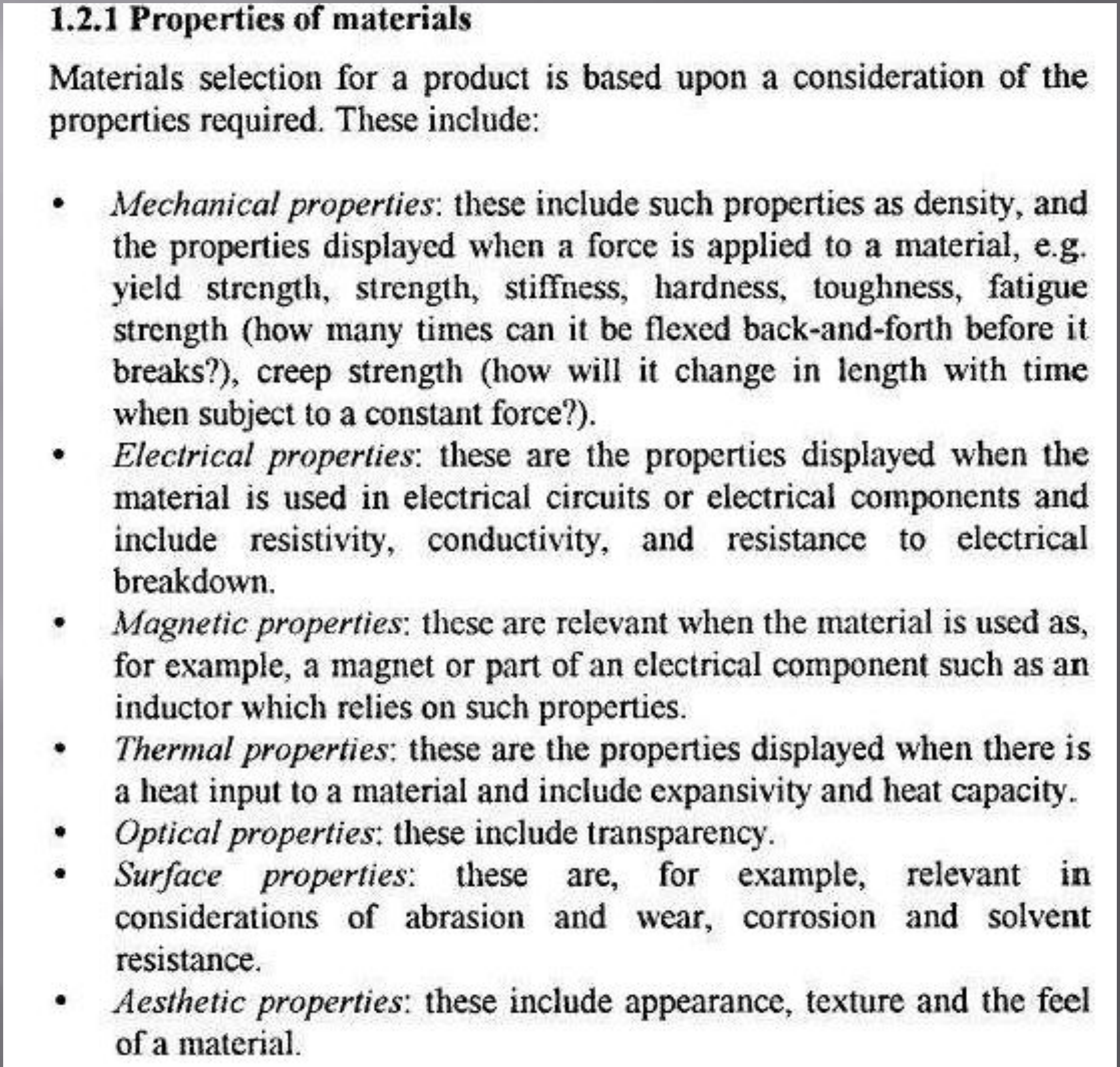
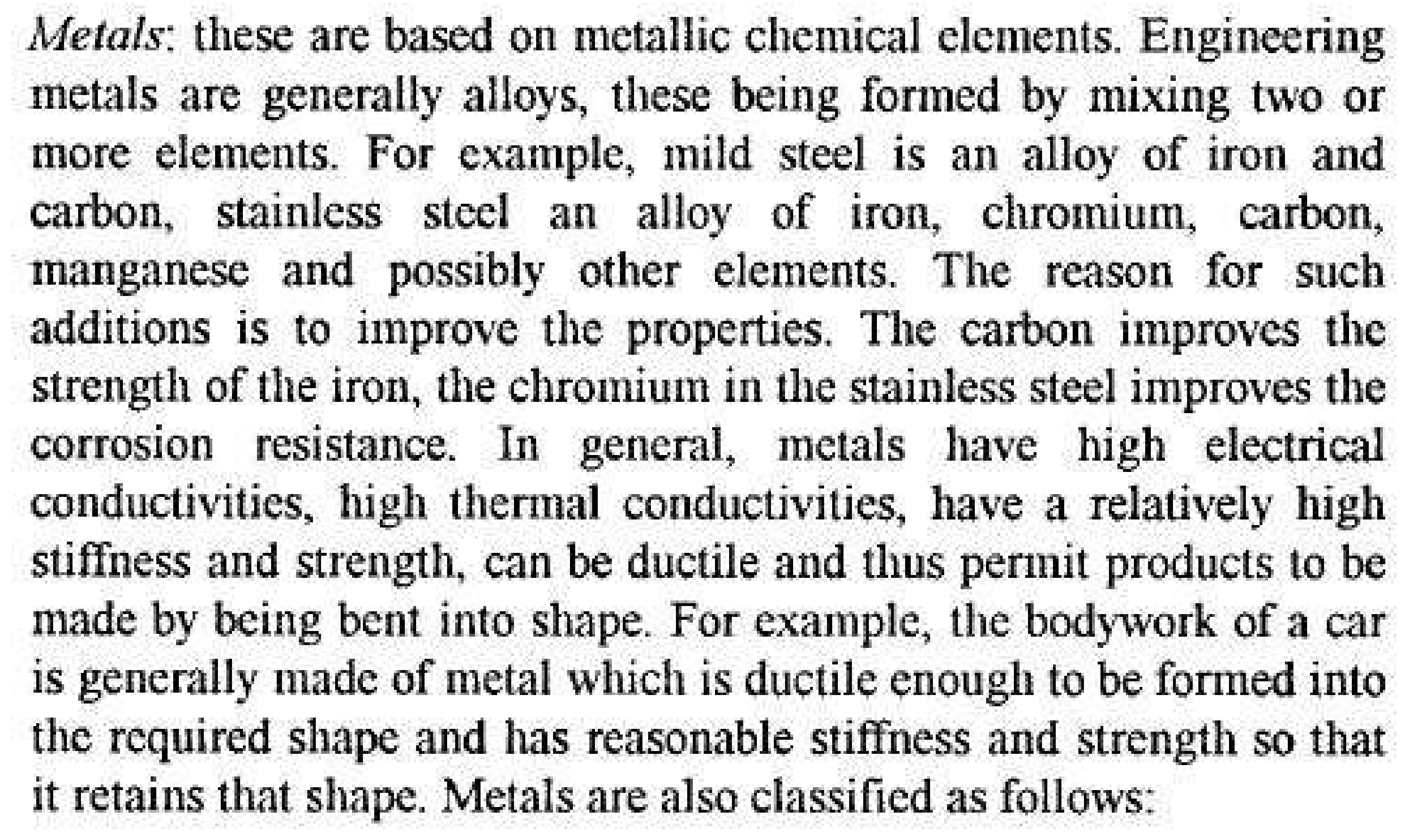


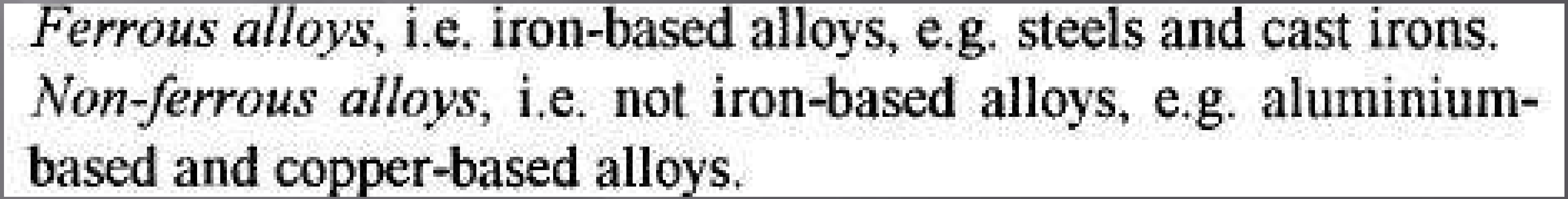
1.2.1 Properties of materials

Materials selection for a product is based upon a consideration of the properties required. These include:

- *Mechanical properties*: these include such properties as density, and the properties displayed when a force is applied to a material, e.g. yield strength, strength, stiffness, hardness, toughness, fatigue strength (how many times can it be flexed back-and-forth before it breaks?), creep strength (how will it change in length with time when subject to a constant force?).
- *Electrical properties*: these are the properties displayed when the material is used in electrical circuits or electrical components and include resistivity, conductivity, and resistance to electrical breakdown.
- *Magnetic properties*: these are relevant when the material is used as, for example, a magnet or part of an electrical component such as an inductor which relies on such properties.
- *Thermal properties*: these are the properties displayed when there is a heat input to a material and include expansivity and heat capacity.
- *Optical properties*: these include transparency.
- *Surface properties*: these are, for example, relevant in considerations of abrasion and wear, corrosion and solvent resistance.
- *Aesthetic properties*: these include appearance, texture and the feel of a material.

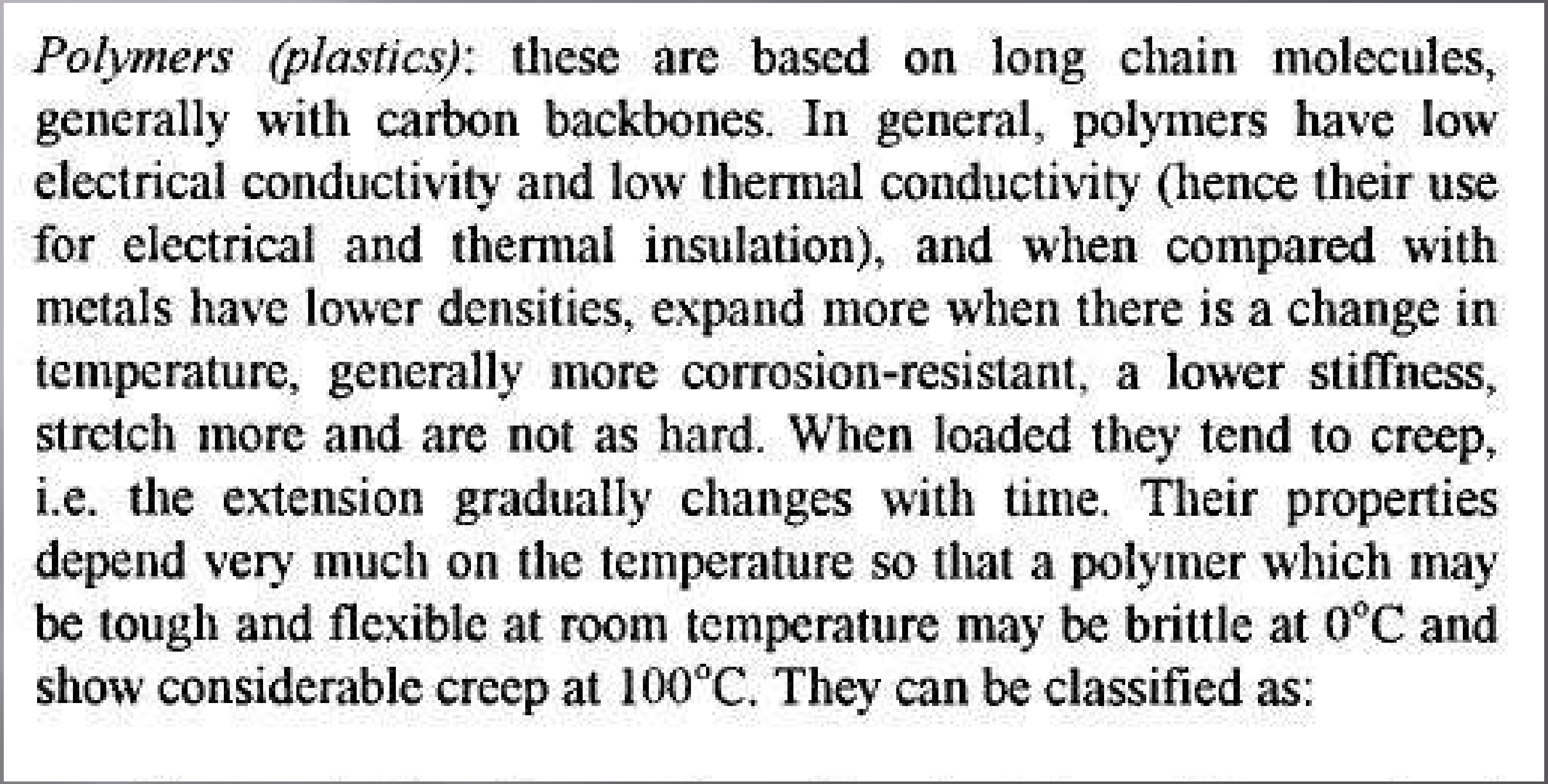


Metals: these are based on metallic chemical elements. Engineering metals are generally alloys, these being formed by mixing two or more elements. For example, mild steel is an alloy of iron and carbon, stainless steel an alloy of iron, chromium, carbon, manganese and possibly other elements. The reason for such additions is to improve the properties. The carbon improves the strength of the iron, the chromium in the stainless steel improves the corrosion resistance. In general, metals have high electrical conductivities, high thermal conductivities, have a relatively high stiffness and strength, can be ductile and thus permit products to be made by being bent into shape. For example, the bodywork of a car is generally made of metal which is ductile enough to be formed into the required shape and has reasonable stiffness and strength so that it retains that shape. Metals are also classified as follows:

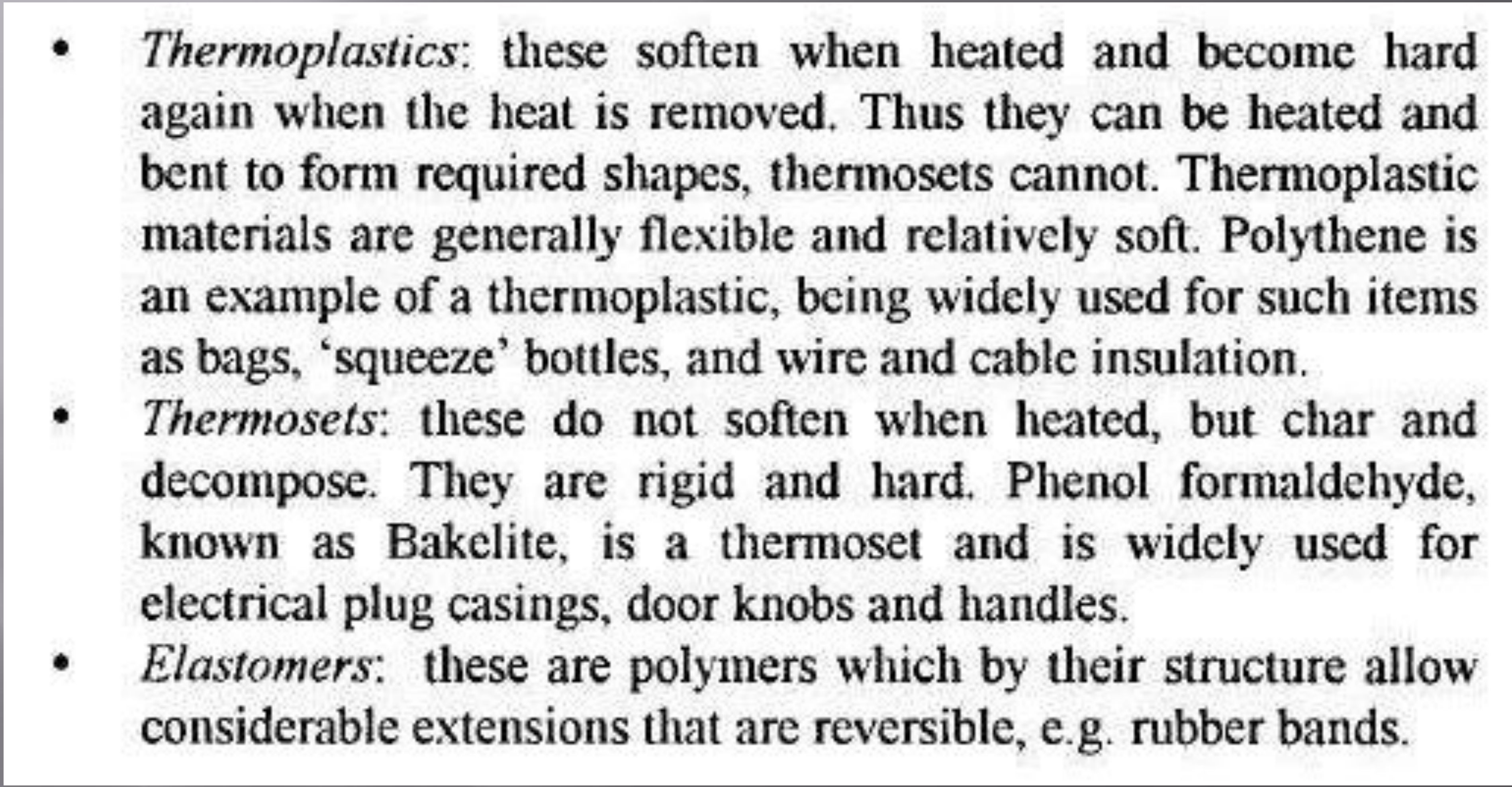


Ferrous alloys, i.e. iron-based alloys, e.g. steels and cast irons.

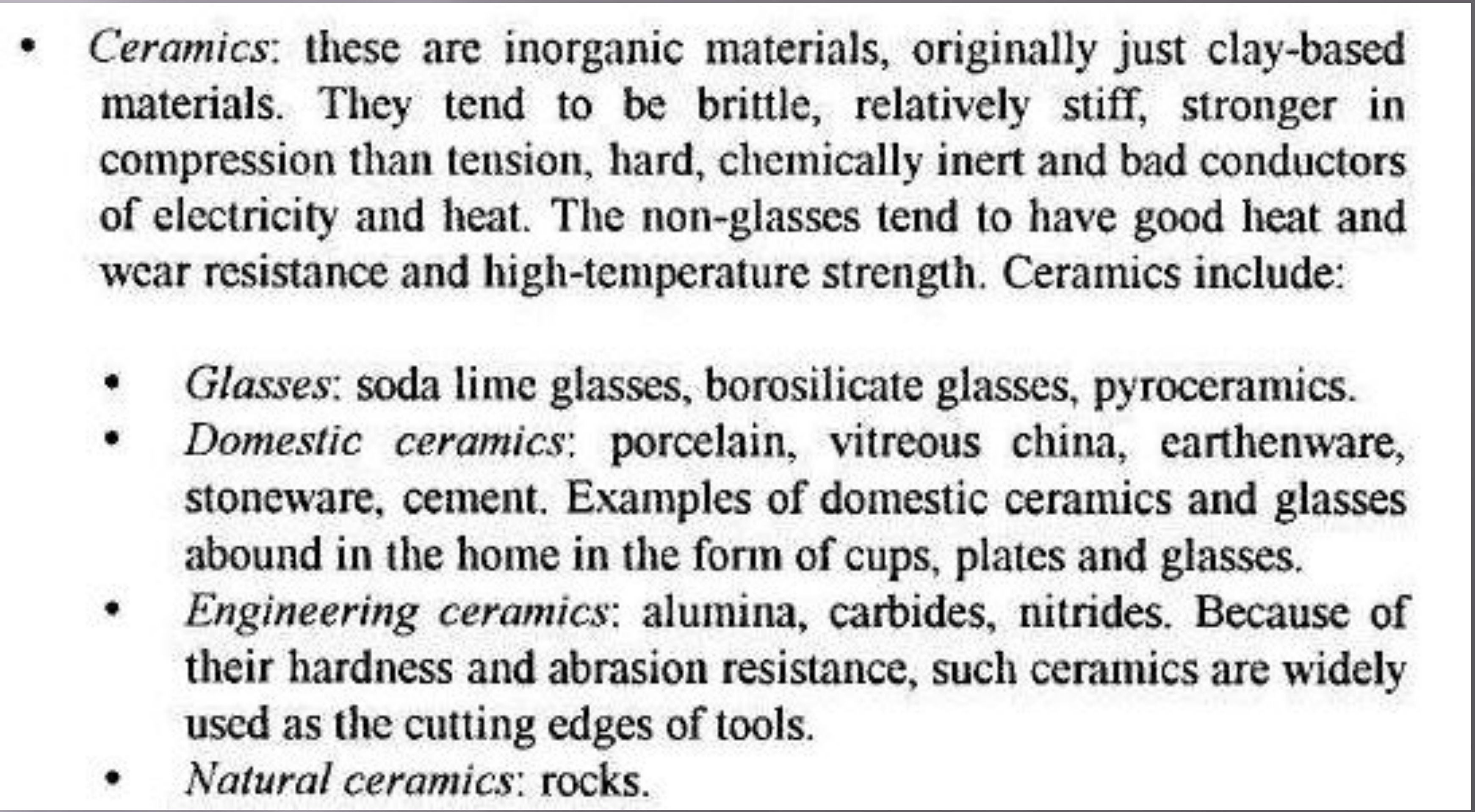
Non-ferrous alloys, i.e. not iron-based alloys, e.g. aluminium-based and copper-based alloys.



Polymers (plastics): these are based on long chain molecules, generally with carbon backbones. In general, polymers have low electrical conductivity and low thermal conductivity (hence their use for electrical and thermal insulation), and when compared with metals have lower densities, expand more when there is a change in temperature, generally more corrosion-resistant, a lower stiffness, stretch more and are not as hard. When loaded they tend to creep, i.e. the extension gradually changes with time. Their properties depend very much on the temperature so that a polymer which may be tough and flexible at room temperature may be brittle at 0°C and show considerable creep at 100°C. They can be classified as:

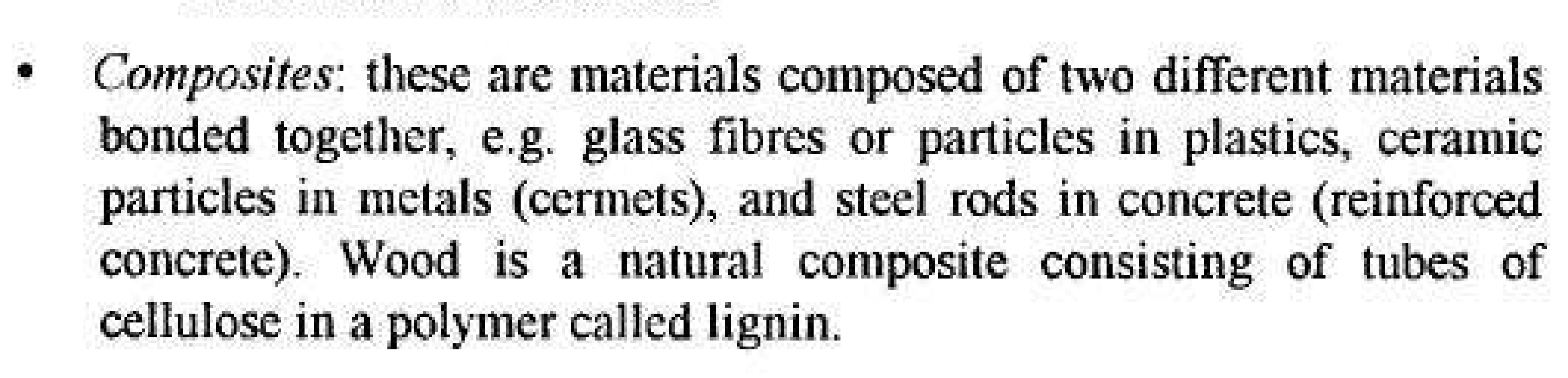


- *Thermoplastics*: these soften when heated and become hard again when the heat is removed. Thus they can be heated and bent to form required shapes, thermosets cannot. Thermoplastic materials are generally flexible and relatively soft. Polythene is an example of a thermoplastic, being widely used for such items as bags, 'squeeze' bottles, and wire and cable insulation.
- *Thermosets*: these do not soften when heated, but char and decompose. They are rigid and hard. Phenol formaldehyde, known as Bakelite, is a thermoset and is widely used for electrical plug casings, door knobs and handles.
- *Elastomers*: these are polymers which by their structure allow considerable extensions that are reversible, e.g. rubber bands.



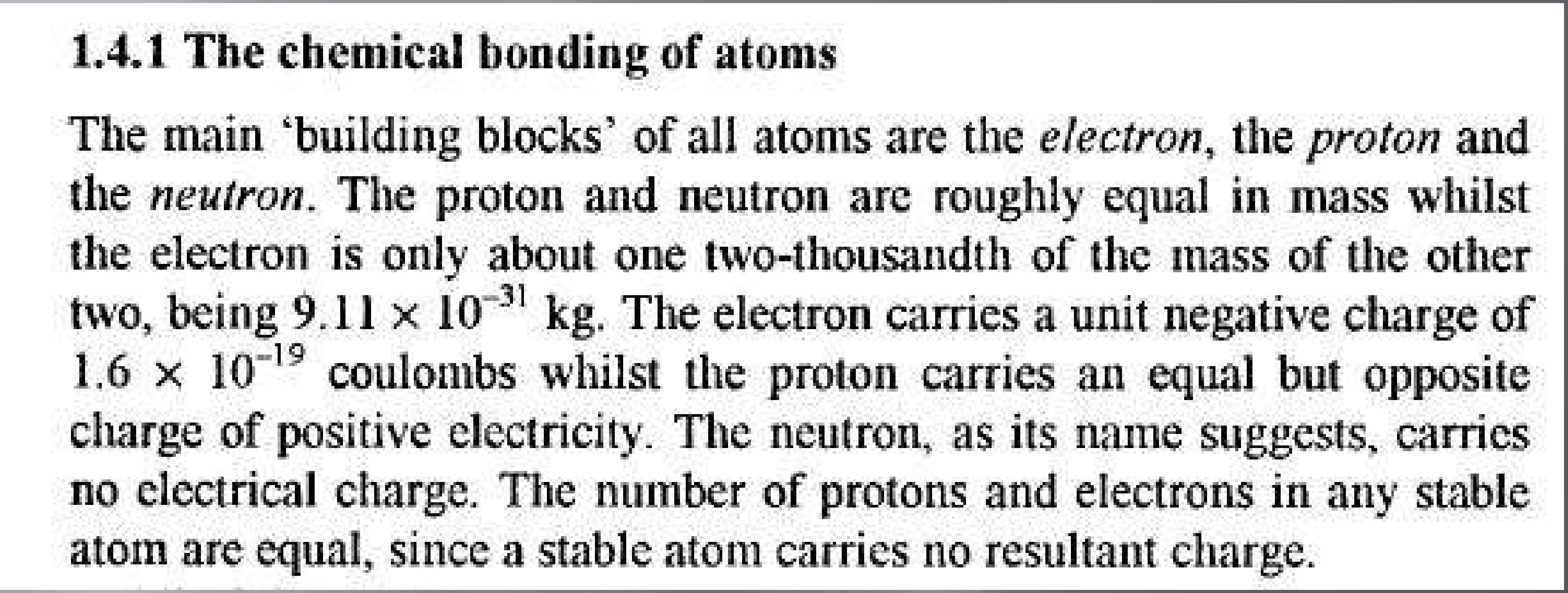
- *Ceramics*: these are inorganic materials, originally just clay-based materials. They tend to be brittle, relatively stiff, stronger in compression than tension, hard, chemically inert and bad conductors of electricity and heat. The non-glasses tend to have good heat and wear resistance and high-temperature strength. Ceramics include:

  - *Glasses*: soda lime glasses, borosilicate glasses, pyroceramics.
  - *Domestic ceramics*: porcelain, vitreous china, earthenware, stoneware, cement. Examples of domestic ceramics and glasses abound in the home in the form of cups, plates and glasses.
  - *Engineering ceramics*: alumina, carbides, nitrides. Because of their hardness and abrasion resistance, such ceramics are widely used as the cutting edges of tools.
  - *Natural ceramics*: rocks.



Natural ceramics: rocks.

- *Composites*: these are materials composed of two different materials bonded together, e.g. glass fibres or particles in plastics, ceramic particles in metals (cermets), and steel rods in concrete (reinforced concrete). Wood is a natural composite consisting of tubes of cellulose in a polymer called lignin.



1.4.1 The chemical bonding of atoms

The main 'building blocks' of all atoms are the *electron*, the *proton* and the *neutron*. The proton and neutron are roughly equal in mass whilst the electron is only about one two-thousandth of the mass of the other two, being 9.11×10^{-31} kg. The electron carries a unit negative charge of 1.6×10^{-19} coulombs whilst the proton carries an equal but opposite charge of positive electricity. The neutron, as its name suggests, carries no electrical charge. The number of protons and electrons in any stable atom are equal, since a stable atom carries no resultant charge.

1.4.2 The electrovalent (or ionic) bond

This bond between atoms occurs between metals and non-metals. Thus the extremely reactive metal sodium combines with the non-metallic gas chlorine to form crystals of sodium chloride (common table salt). Since the atomic structures involved are simpler, we will instead consider the similar combination which occurs between the metal lithium (now an essential element in the batteries used in electronic watches, automatic cameras and the like) and the non-metallic gas fluorine (the same group of elements as chlorine).

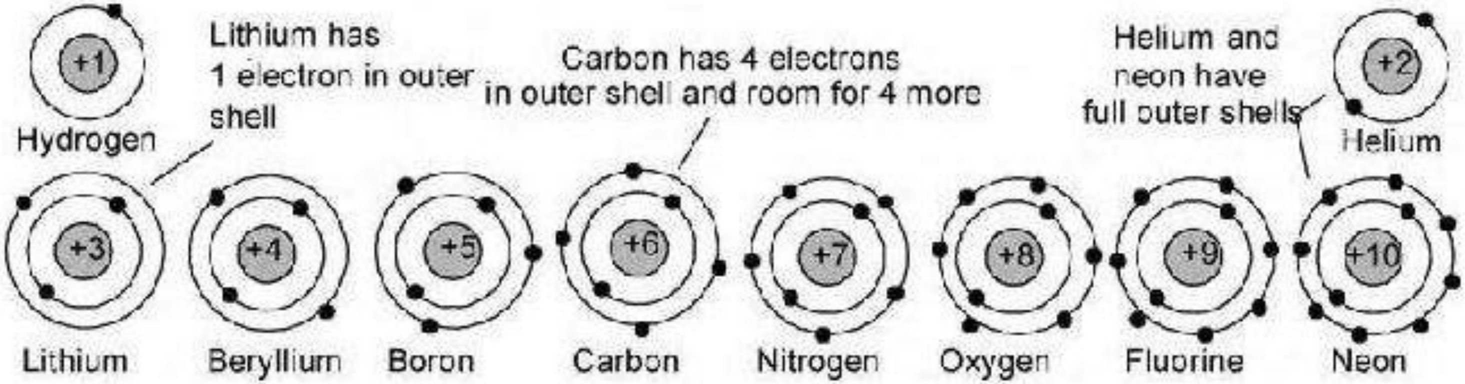
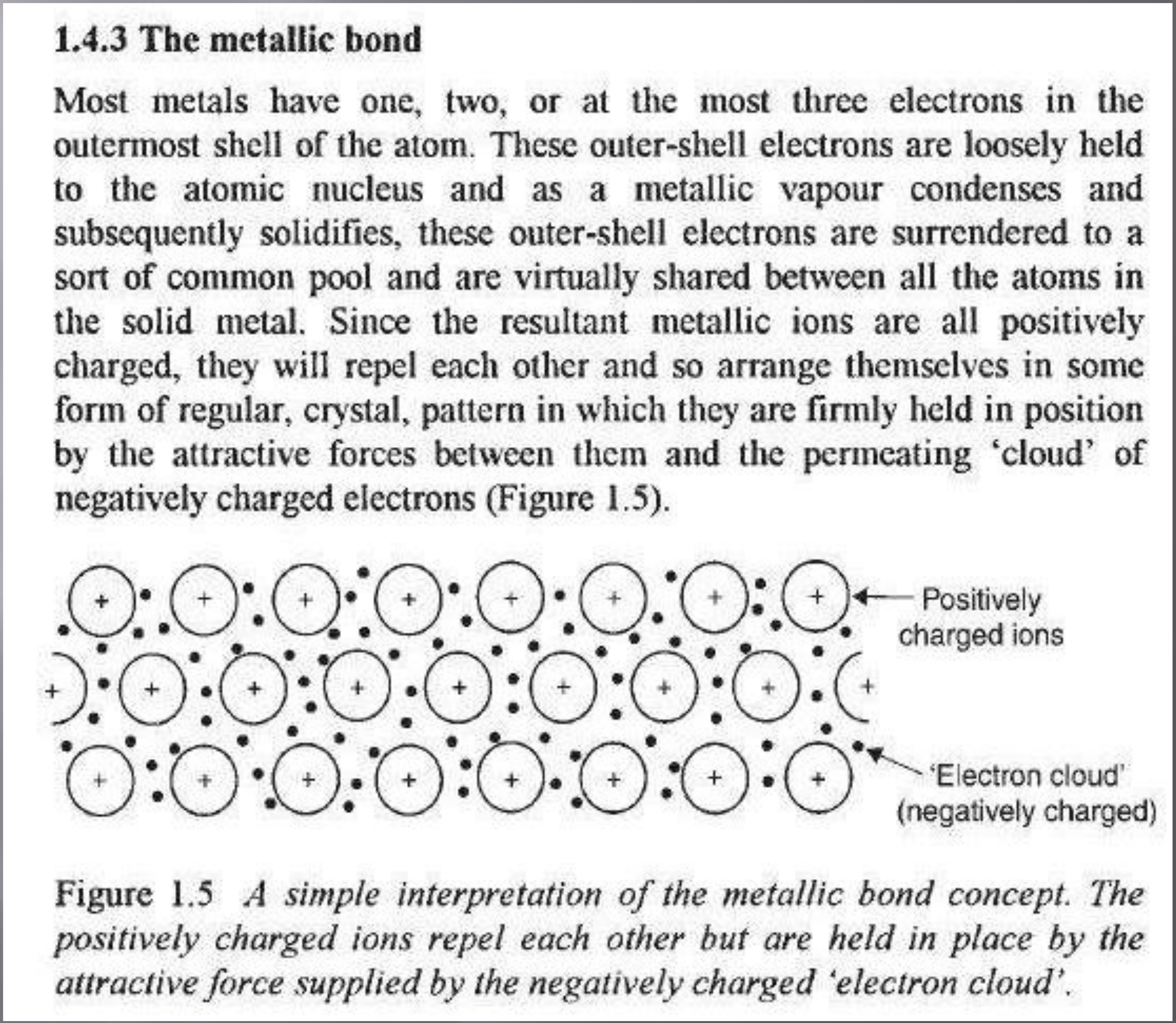


Figure 1.2 *The electron structure of the first ten elements in order of 'atomic number', i.e. the number of protons in the nucleus. Although these diagrams show electrons as being single discrete particles in fixed orbits, this interpretation should not be taken too literally. It is better to visualise an electron as a sort of mist of electricity surrounding the nucleus!*



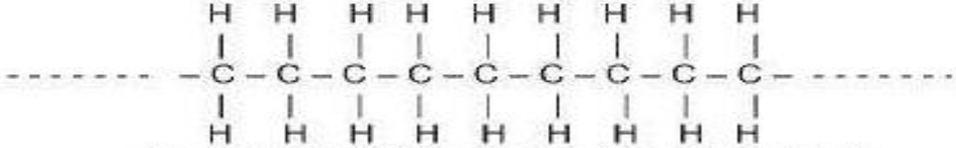
1.4.3 The metallic bond

Most metals have one, two, or at the most three electrons in the outermost shell of the atom. These outer-shell electrons are loosely held to the atomic nucleus and as a metallic vapour condenses and subsequently solidifies, these outer-shell electrons are surrendered to a sort of common pool and are virtually shared between all the atoms in the solid metal. Since the resultant metallic ions are all positively charged, they will repel each other and so arrange themselves in some form of regular, crystal, pattern in which they are firmly held in position by the attractive forces between them and the permeating 'cloud' of negatively charged electrons (Figure 1.5).

Figure 1.5 *A simple interpretation of the metallic bond concept. The positively charged ions repel each other but are held in place by the attractive force supplied by the negatively charged 'electron cloud'.*

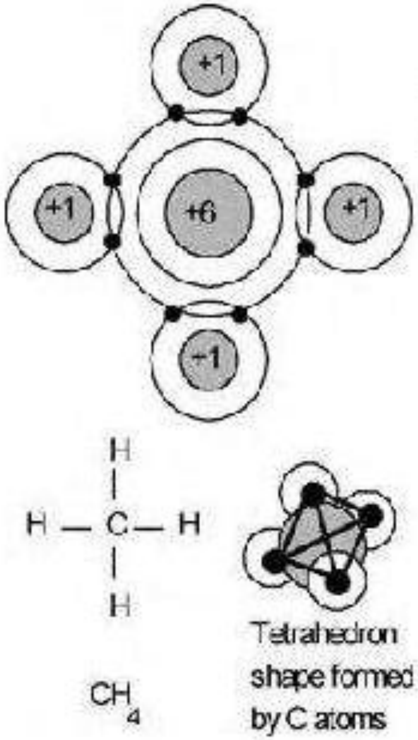
1.4.4 The covalent bond

The covalent bond is formed between atoms of those non-metallic elements in which, for various reasons, there is a strong attractive force between the nucleus and the outer-shell electrons. Hence, instead of a transfer of electrons from one atom to another to give an ionic bond, there is a *sharing* of electrons between two atoms to bind them together.



Approximately 1200 carbon atoms in the chain

Figure 1.7 *The long-chain like molecule of the plastics material polyethylene.*



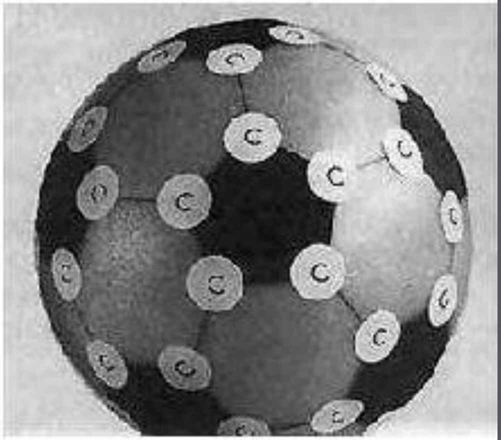


Figure 1.11 *A model of the fullerene molecule C_{60} which*

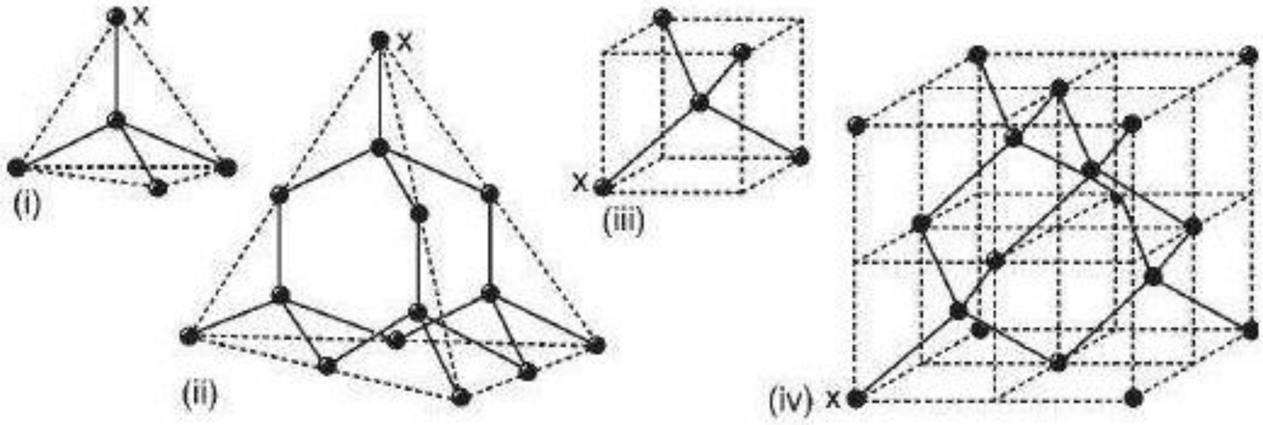
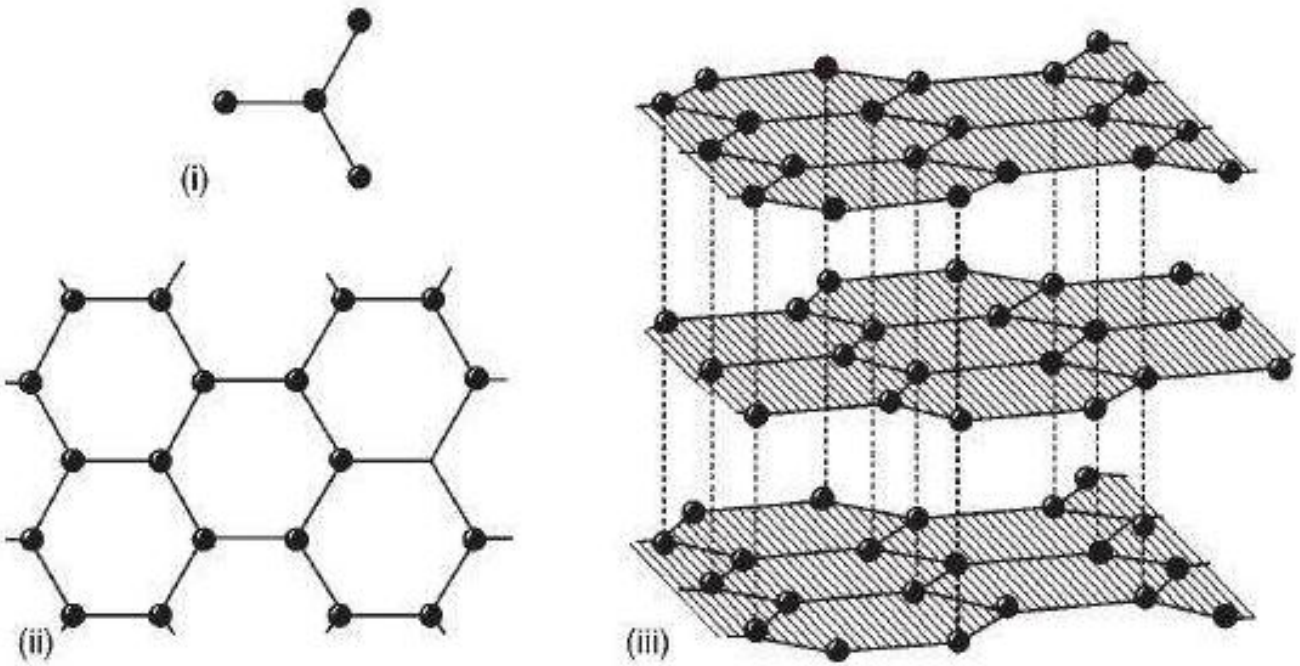
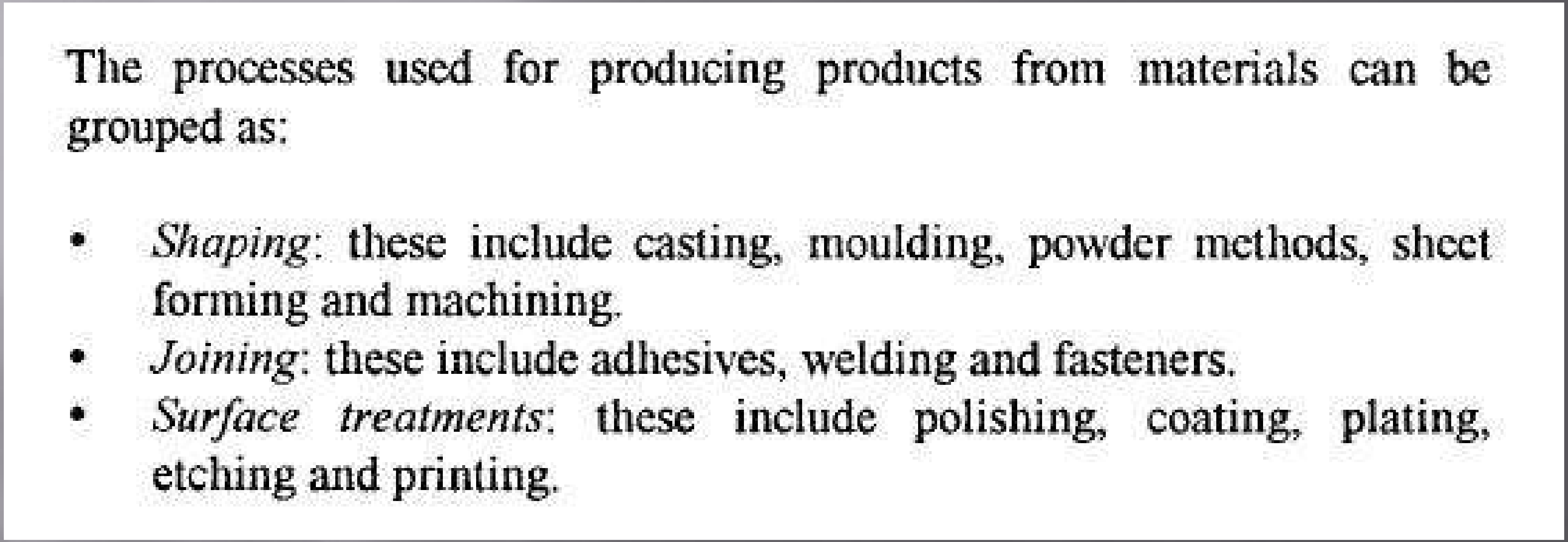


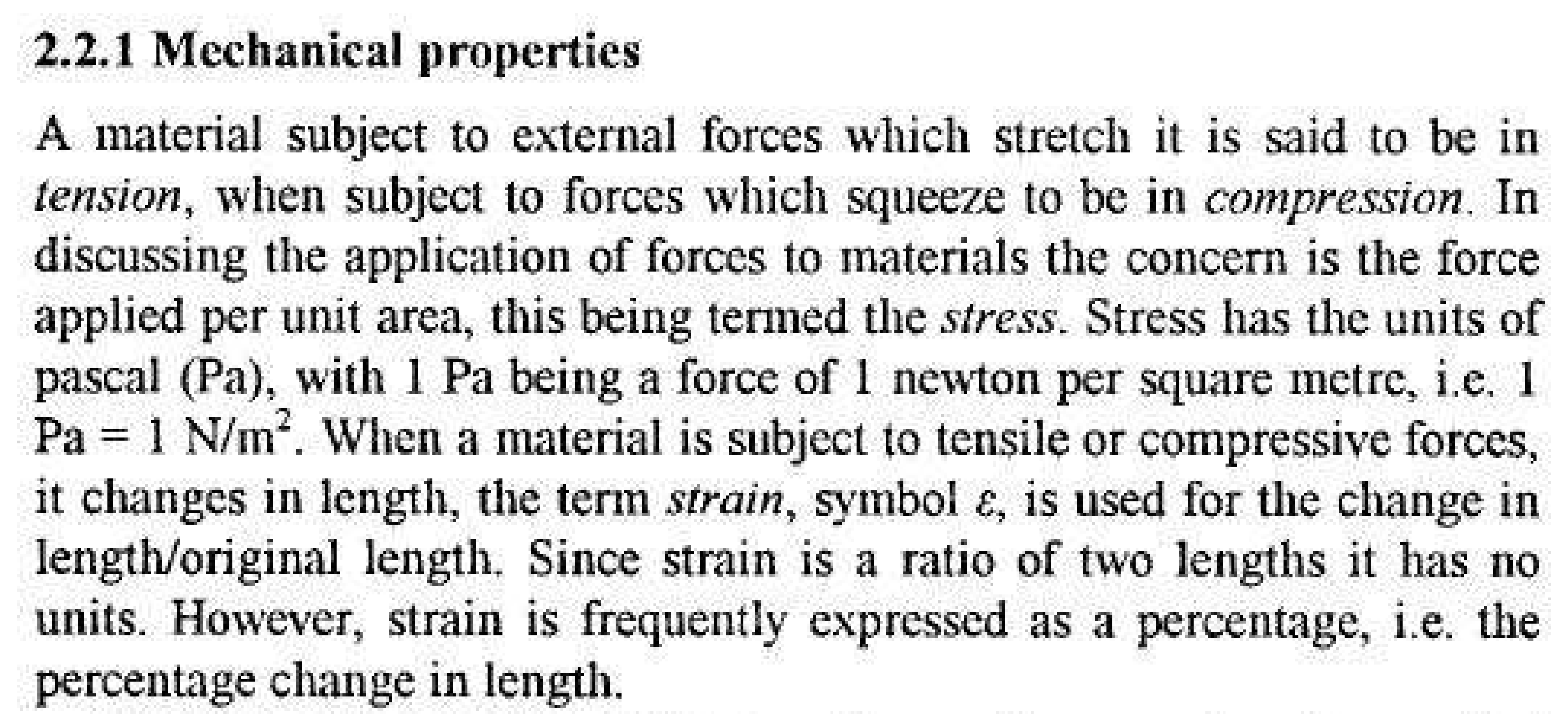
Figure 1.9 *The crystal structure of diamond*





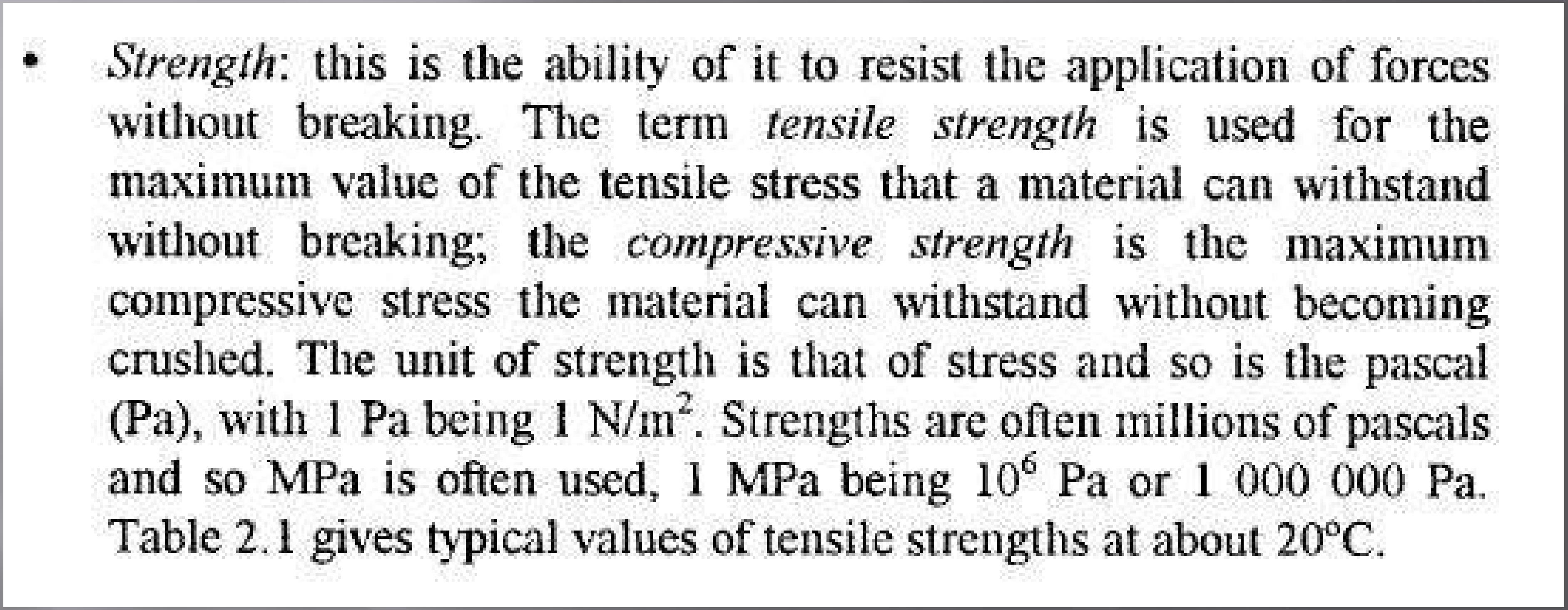
The processes used for producing products from materials can be grouped as:

- *Shaping*: these include casting, moulding, powder methods, sheet forming and machining.
- *Joining*: these include adhesives, welding and fasteners.
- *Surface treatments*: these include polishing, coating, plating, etching and printing.

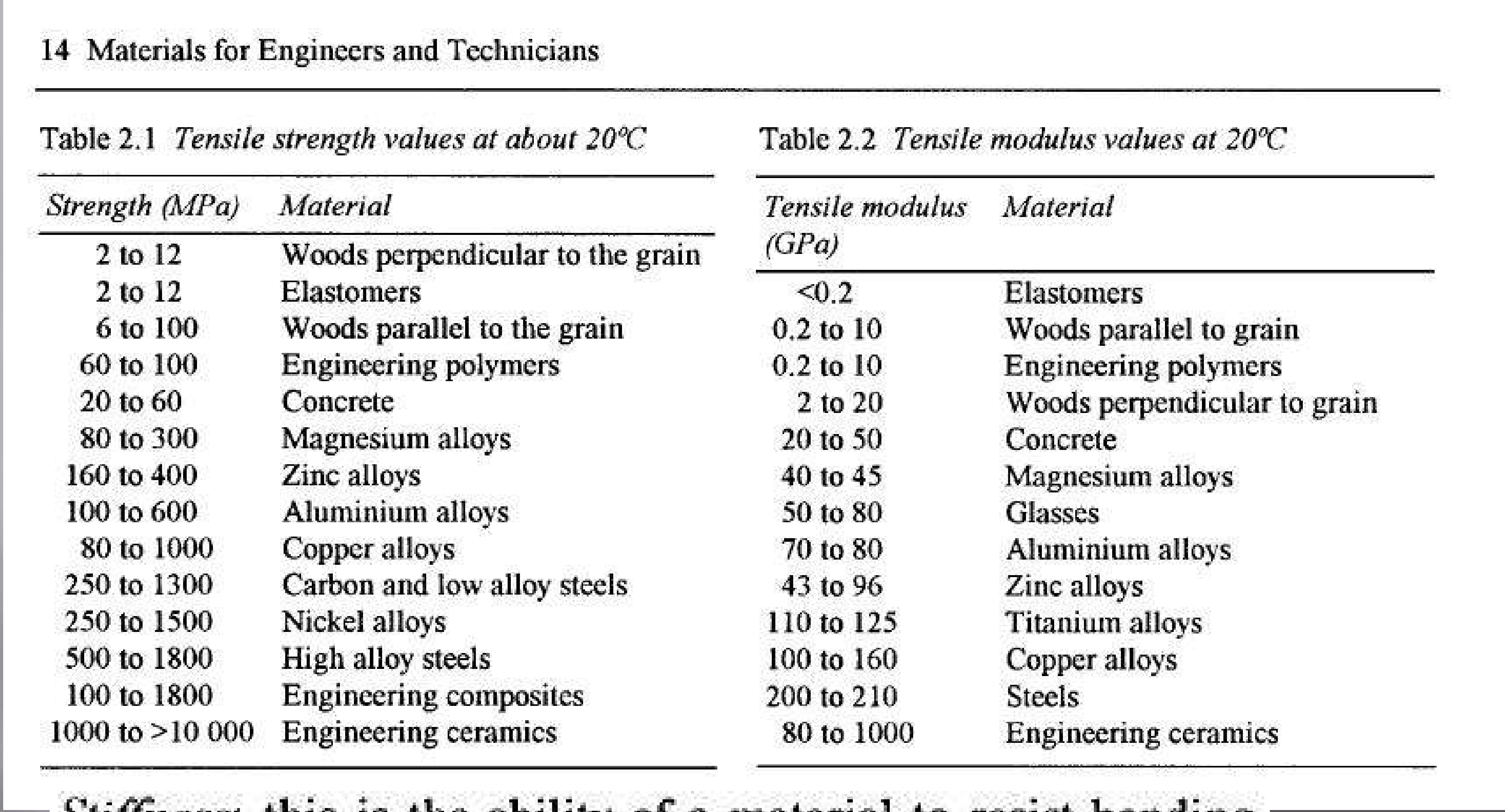


2.2.1 Mechanical properties

A material subject to external forces which stretch it is said to be in *tension*, when subject to forces which squeeze to be in *compression*. In discussing the application of forces to materials the concern is the force applied per unit area, this being termed the *stress*. Stress has the units of pascal (Pa), with 1 Pa being a force of 1 newton per square metre, i.e. 1 Pa = 1 N/m^2. When a material is subject to tensile or compressive forces, it changes in length, the term *strain*, symbol ε, is used for the change in length/original length. Since strain is a ratio of two lengths it has no units. However, strain is frequently expressed as a percentage, i.e. the percentage change in length.



- *Strength*: this is the ability of it to resist the application of forces without breaking. The term *tensile strength* is used for the maximum value of the tensile stress that a material can withstand without breaking; the *compressive strength* is the maximum compressive stress the material can withstand without becoming crushed. The unit of strength is that of stress and so is the pascal (Pa), with 1 Pa being 1 N/m^2. Strengths are often millions of pascals and so MPa is often used, 1 MPa being 10^6 Pa or 1 000 000 Pa. Table 2.1 gives typical values of tensile strengths at about 20°C.



14 Materials for Engineers and Technicians

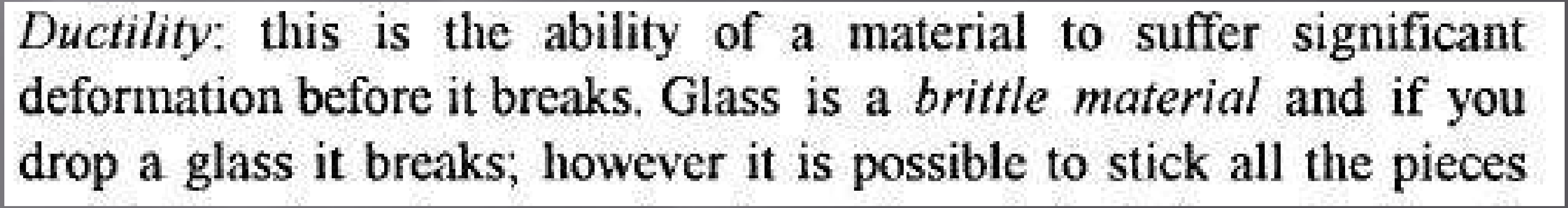
Table 2.1 *Tensile strength values at about 20°C*

Strength (MPa)	*Material*
2 to 12	Woods perpendicular to the grain
2 to 12	Elastomers
6 to 100	Woods parallel to the grain
60 to 100	Engineering polymers
20 to 60	Concrete
80 to 300	Magnesium alloys
160 to 400	Zinc alloys
100 to 600	Aluminium alloys
80 to 1000	Copper alloys
250 to 1300	Carbon and low alloy steels
250 to 1500	Nickel alloys
500 to 1800	High alloy steels
100 to 1800	Engineering composites
1000 to >10 000	Engineering ceramics

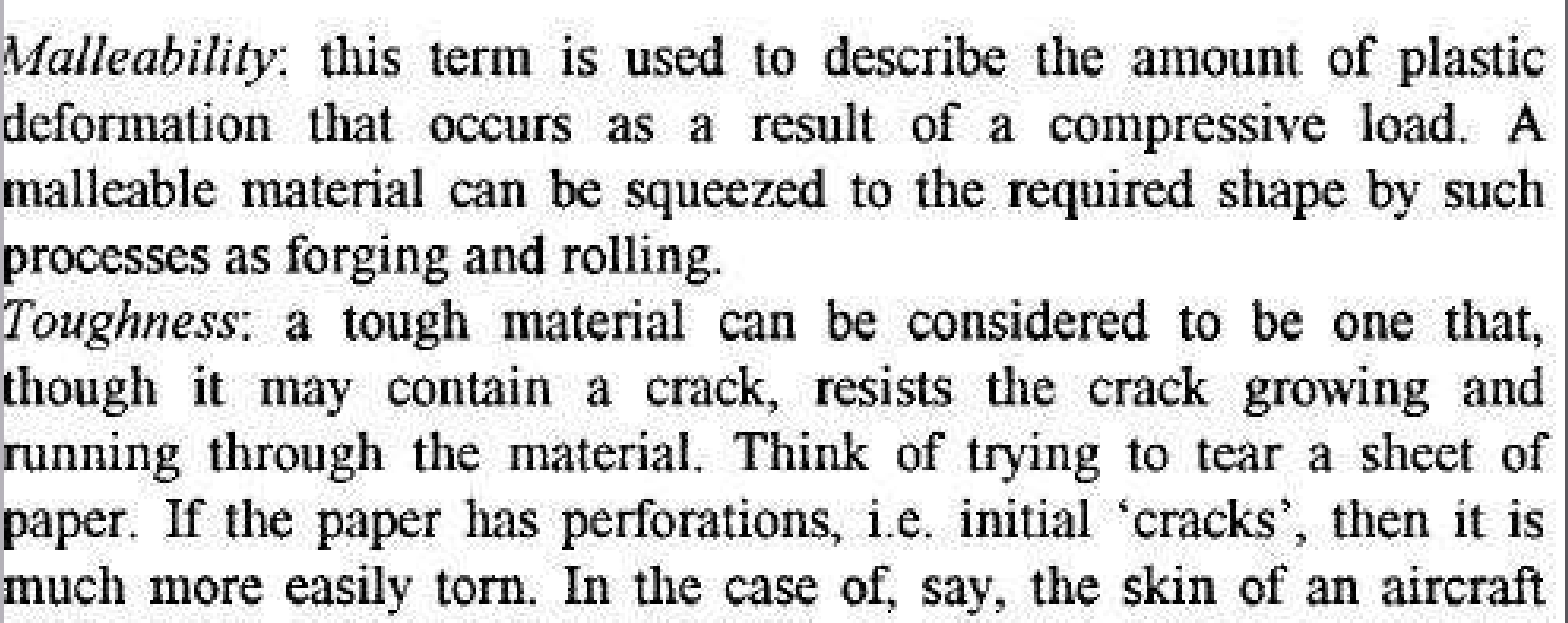
Table 2.2 *Tensile modulus values at 20°C*

Tensile modulus (GPa)	*Material*
<0.2	Elastomers
0.2 to 10	Woods parallel to grain
0.2 to 10	Engineering polymers
2 to 20	Woods perpendicular to grain
20 to 50	Concrete
40 to 45	Magnesium alloys
50 to 80	Glasses
70 to 80	Aluminium alloys
43 to 96	Zinc alloys
110 to 125	Titanium alloys
100 to 160	Copper alloys
200 to 210	Steels
80 to 1000	Engineering ceramics

Stiffness: this is the ability of a material to resist bending.

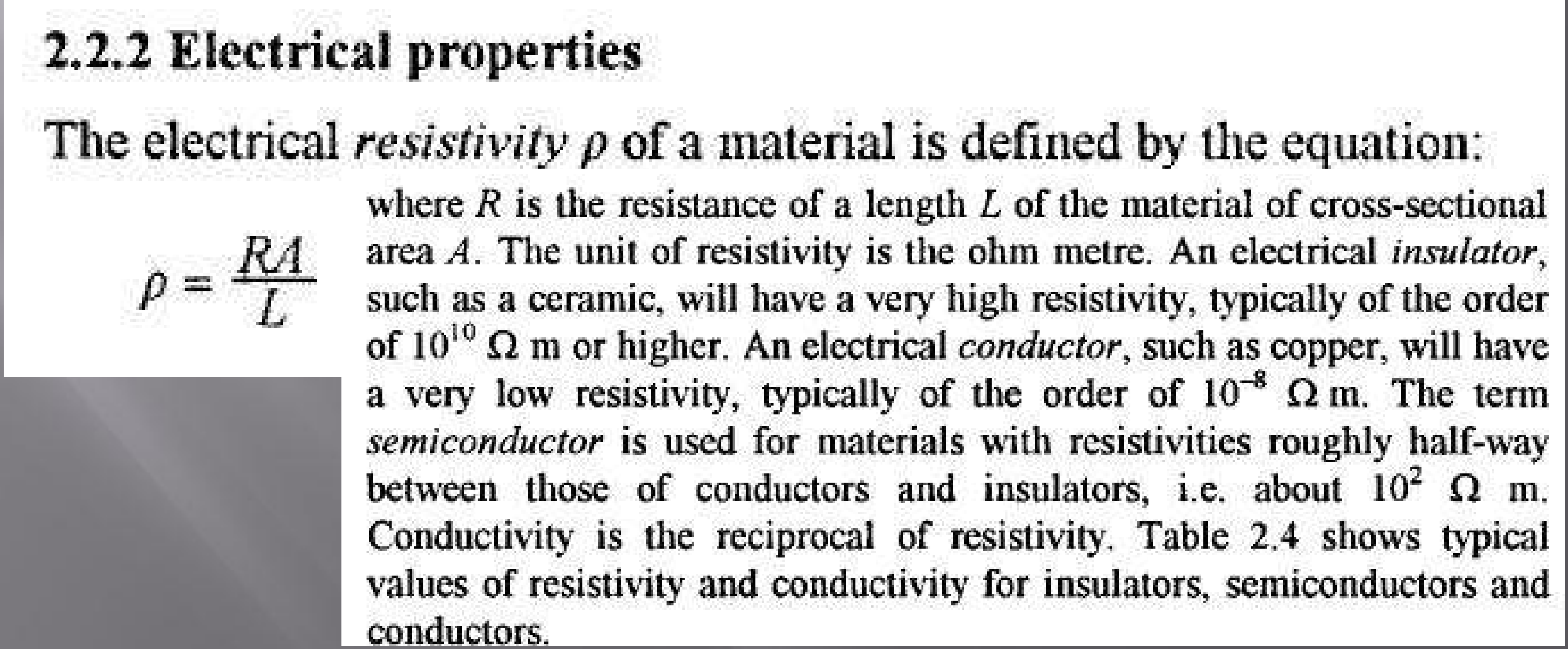


Ductility: this is the ability of a material to suffer significant deformation before it breaks. Glass is a *brittle material* and if you drop a glass it breaks; however it is possible to stick all the pieces



Malleability: this term is used to describe the amount of plastic deformation that occurs as a result of a compressive load. A malleable material can be squeezed to the required shape by such processes as forging and rolling.

Toughness: a tough material can be considered to be one that, though it may contain a crack, resists the crack growing and running through the material. Think of trying to tear a sheet of paper. If the paper has perforations, i.e. initial 'cracks', then it is much more easily torn. In the case of, say, the skin of an aircraft

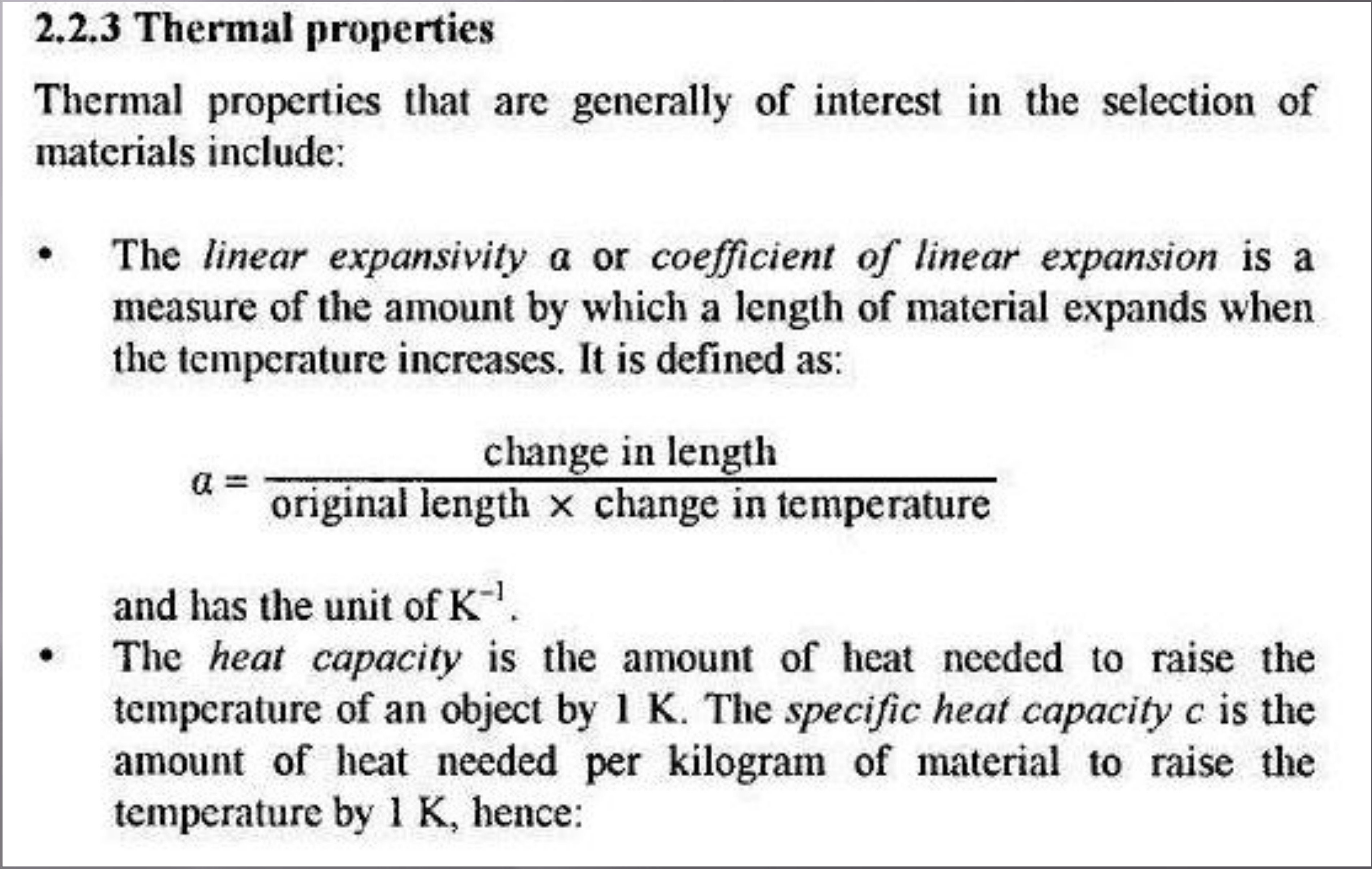


2.2.2 Electrical properties

The electrical *resistivity* ρ of a material is defined by the equation:

$$\rho = \frac{RA}{L}$$

where R is the resistance of a length L of the material of cross-sectional area A. The unit of resistivity is the ohm metre. An electrical *insulator*, such as a ceramic, will have a very high resistivity, typically of the order of $10^{10}\ \Omega$ m or higher. An electrical *conductor*, such as copper, will have a very low resistivity, typically of the order of $10^{-8}\ \Omega$ m. The term *semiconductor* is used for materials with resistivities roughly half-way between those of conductors and insulators, i.e. about $10^{2}\ \Omega$ m. Conductivity is the reciprocal of resistivity. Table 2.4 shows typical values of resistivity and conductivity for insulators, semiconductors and conductors.



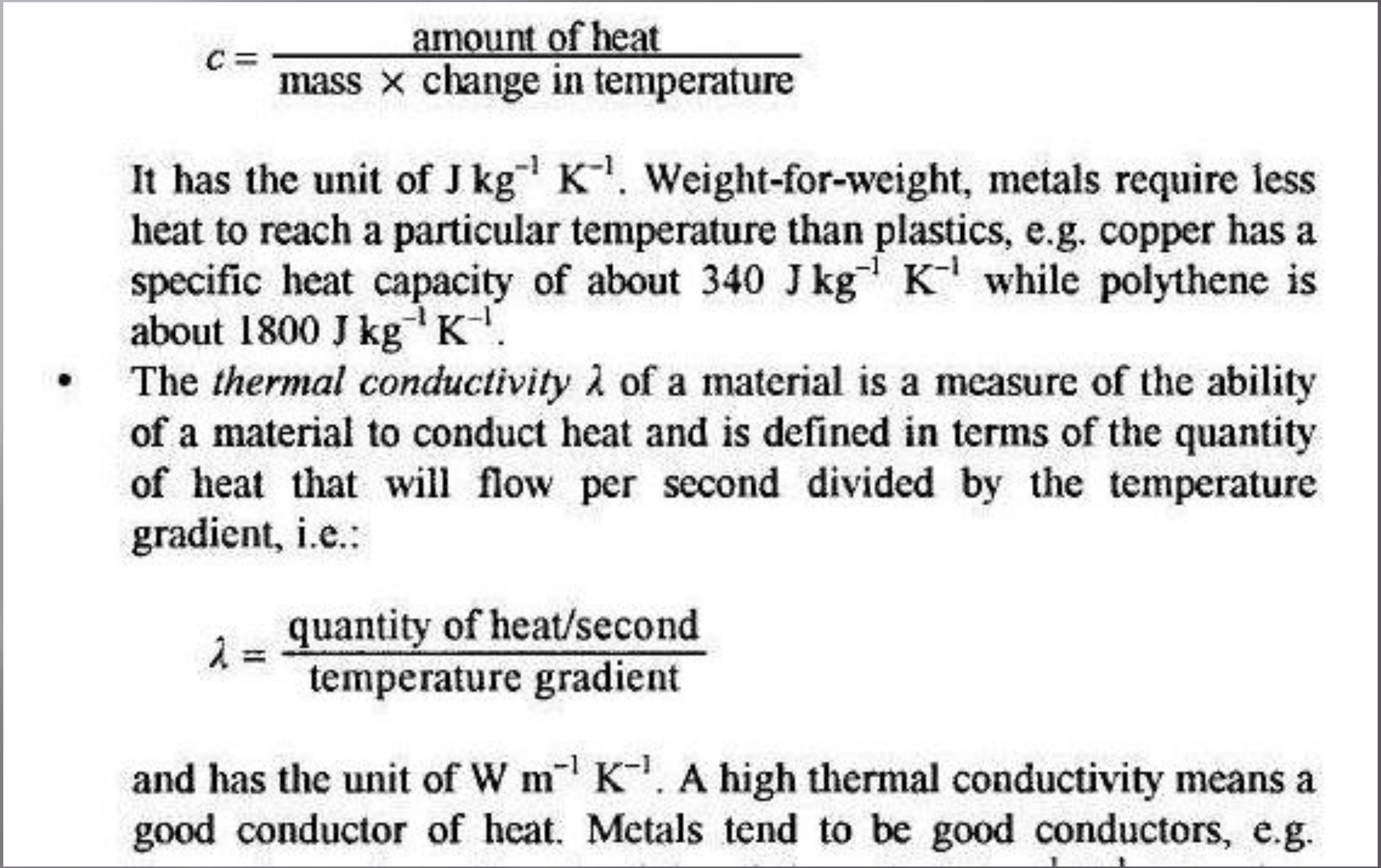
2.2.3 Thermal properties

Thermal properties that are generally of interest in the selection of materials include:

- The *linear expansivity* α or *coefficient of linear expansion* is a measure of the amount by which a length of material expands when the temperature increases. It is defined as:

$$\alpha = \frac{\text{change in length}}{\text{original length} \times \text{change in temperature}}$$

  and has the unit of K^{-1}.
- The *heat capacity* is the amount of heat needed to raise the temperature of an object by 1 K. The *specific heat capacity* c is the amount of heat needed per kilogram of material to raise the temperature by 1 K, hence:



$$c = \frac{\text{amount of heat}}{\text{mass} \times \text{change in temperature}}$$

It has the unit of J kg^{-1} K^{-1}. Weight-for-weight, metals require less heat to reach a particular temperature than plastics, e.g. copper has a specific heat capacity of about 340 J kg^{-1} K^{-1} while polythene is about 1800 J kg^{-1} K^{-1}.

- The *thermal conductivity* λ of a material is a measure of the ability of a material to conduct heat and is defined in terms of the quantity of heat that will flow per second divided by the temperature gradient, i.e.:

$$\lambda = \frac{\text{quantity of heat/second}}{\text{temperature gradient}}$$

and has the unit of W m^{-1} K^{-1}. A high thermal conductivity means a good conductor of heat. Metals tend to be good conductors, e.g.

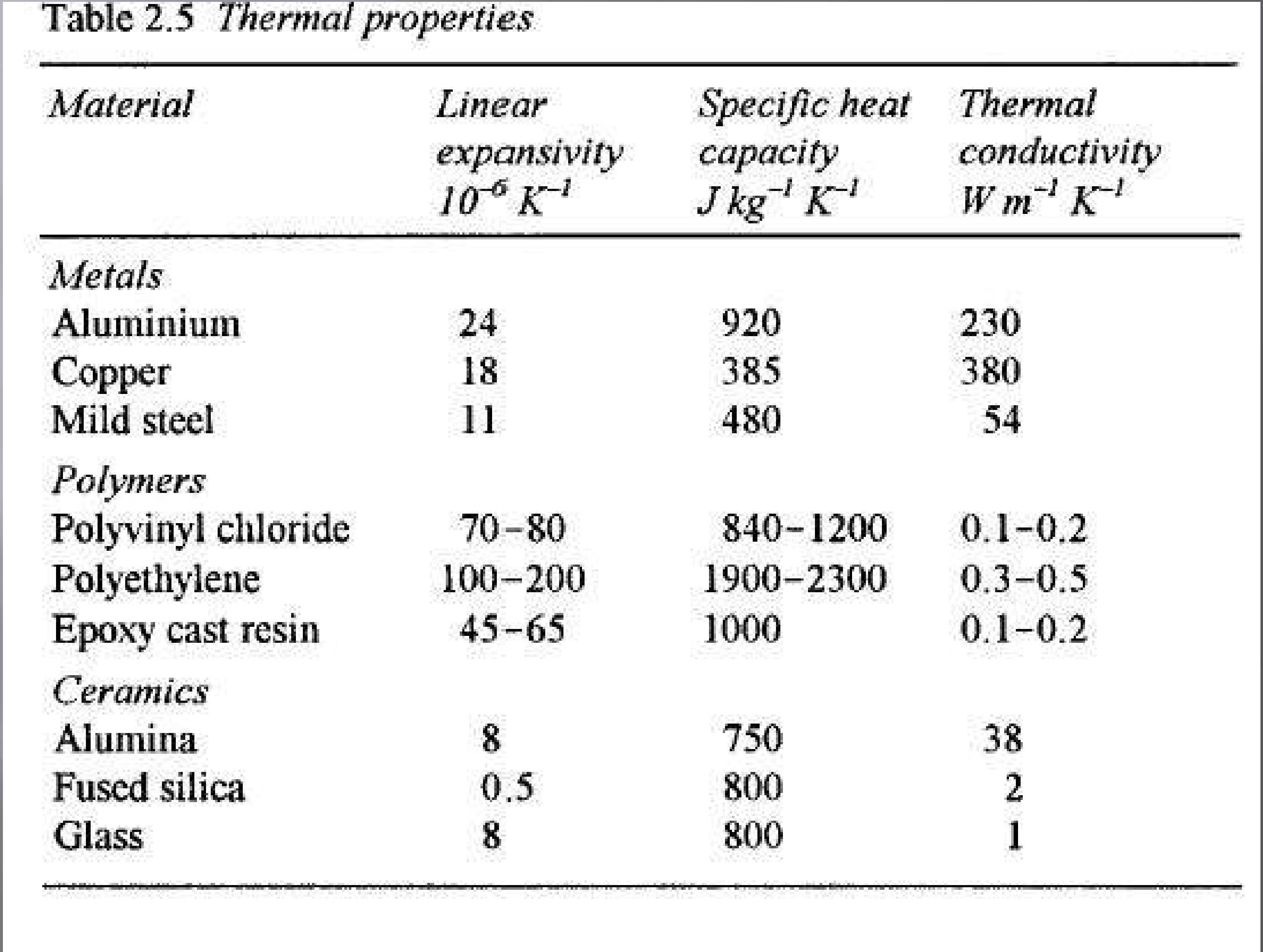
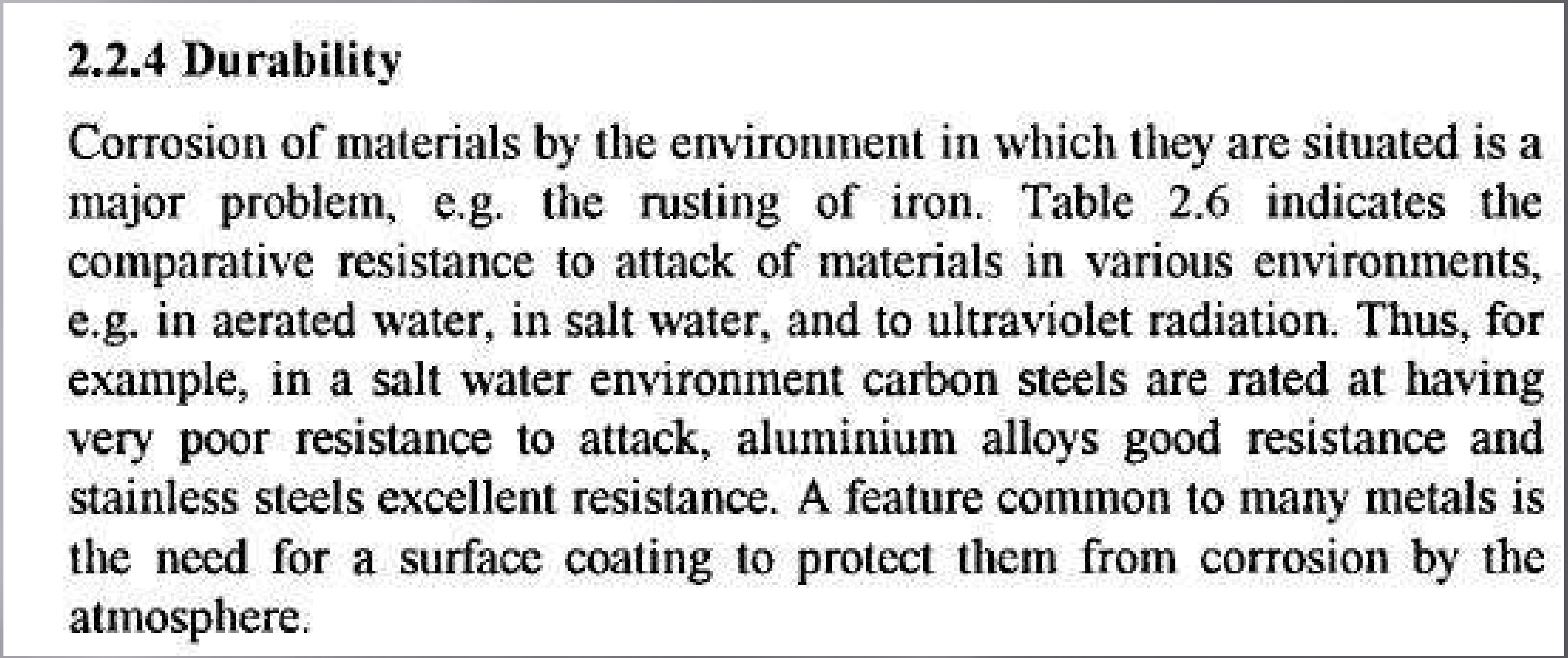


Table 2.5 *Thermal properties*

Material	*Linear expansivity* $10^{-6}\ K^{-1}$	*Specific heat capacity* $J\ kg^{-1}\ K^{-1}$	*Thermal conductivity* $W\ m^{-1}\ K^{-1}$
Metals			
Aluminium	24	920	230
Copper	18	385	380
Mild steel	11	480	54
Polymers			
Polyvinyl chloride	70–80	840–1200	0.1–0.2
Polyethylene	100–200	1900–2300	0.3–0.5
Epoxy cast resin	45–65	1000	0.1–0.2
Ceramics			
Alumina	8	750	38
Fused silica	0.5	800	2
Glass	8	800	1



2.2.4 Durability

Corrosion of materials by the environment in which they are situated is a major problem, e.g. the rusting of iron. Table 2.6 indicates the comparative resistance to attack of materials in various environments, e.g. in aerated water, in salt water, and to ultraviolet radiation. Thus, for example, in a salt water environment carbon steels are rated at having very poor resistance to attack, aluminium alloys good resistance and stainless steels excellent resistance. A feature common to many metals is the need for a surface coating to protect them from corrosion by the atmosphere.

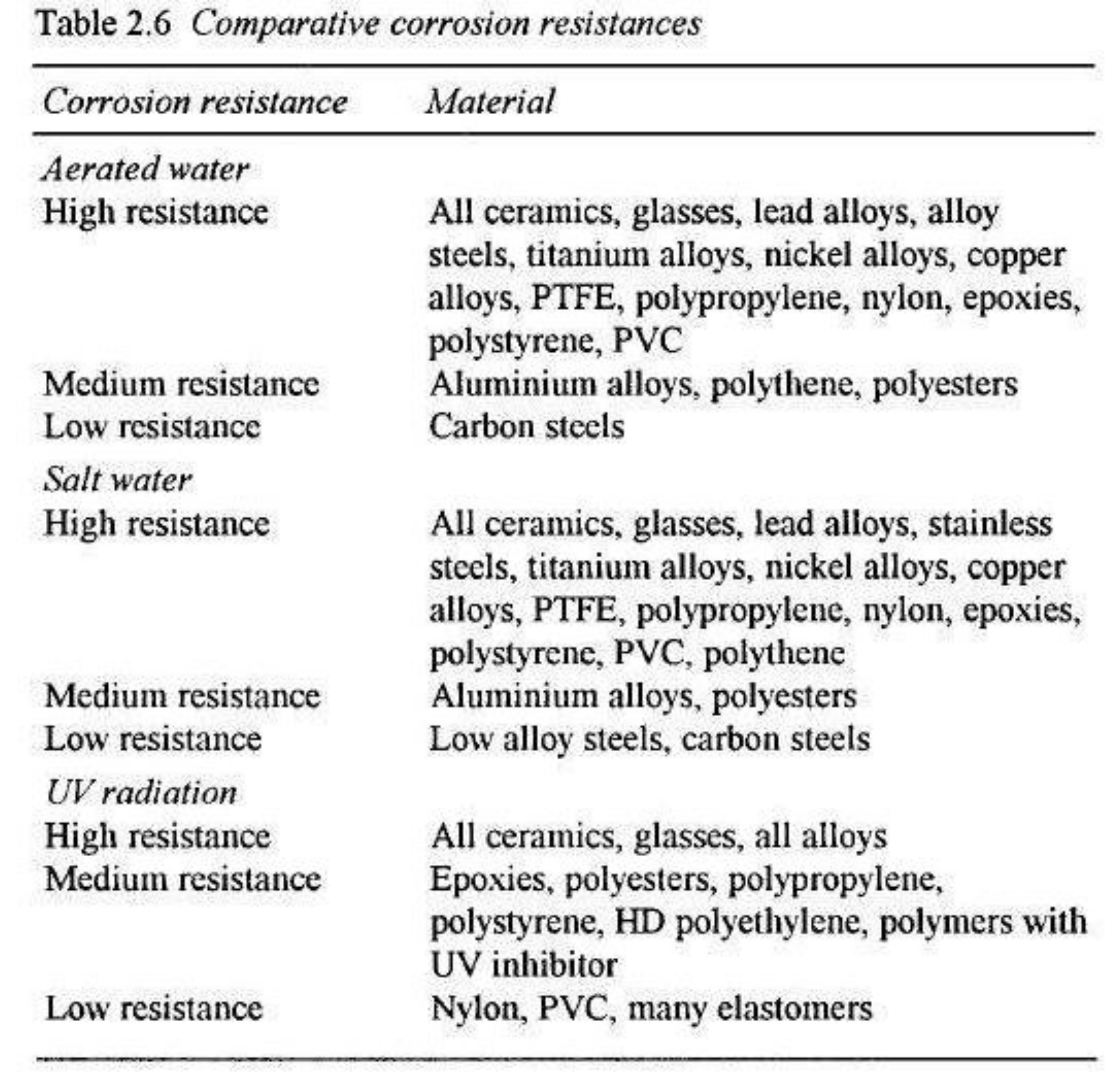
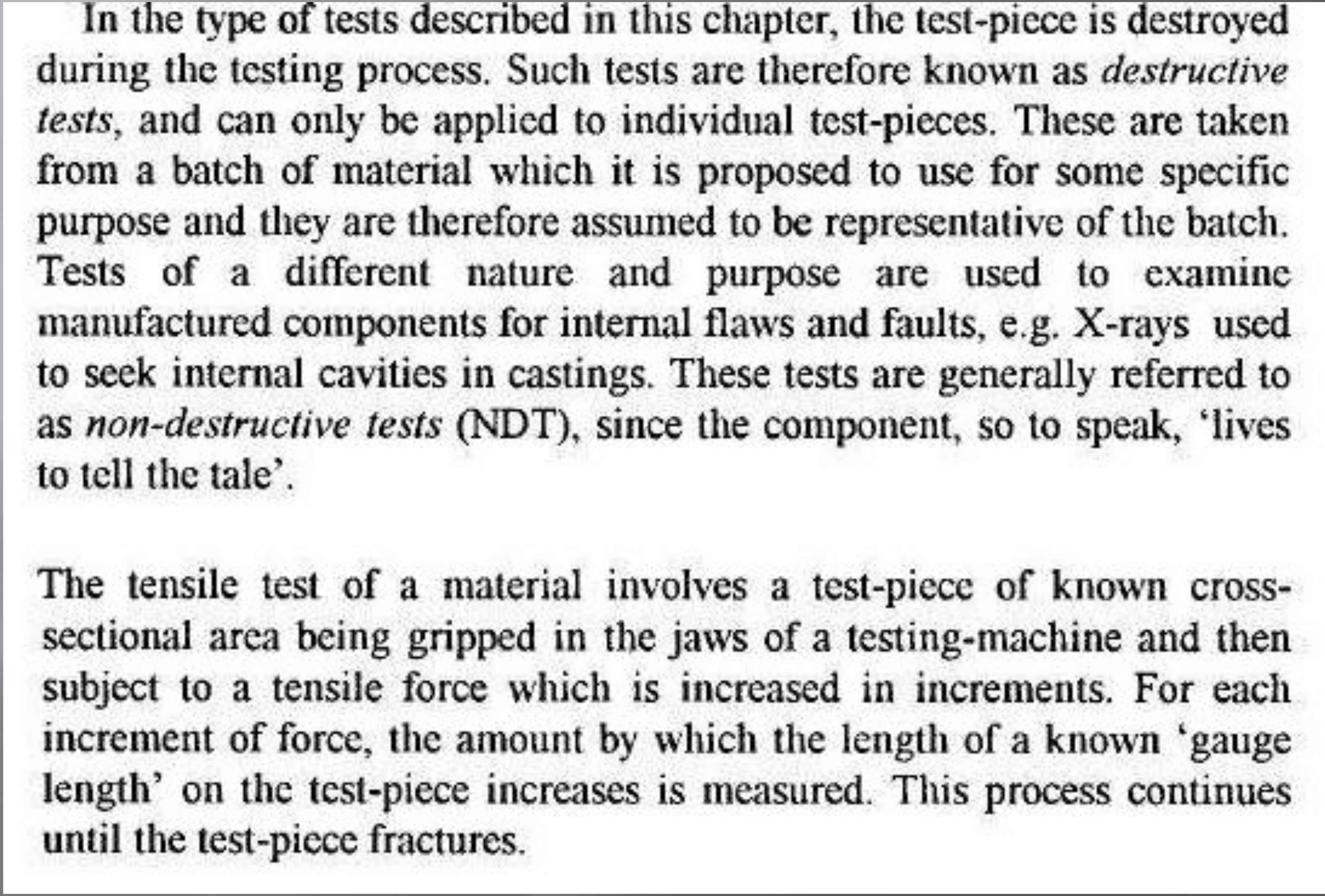


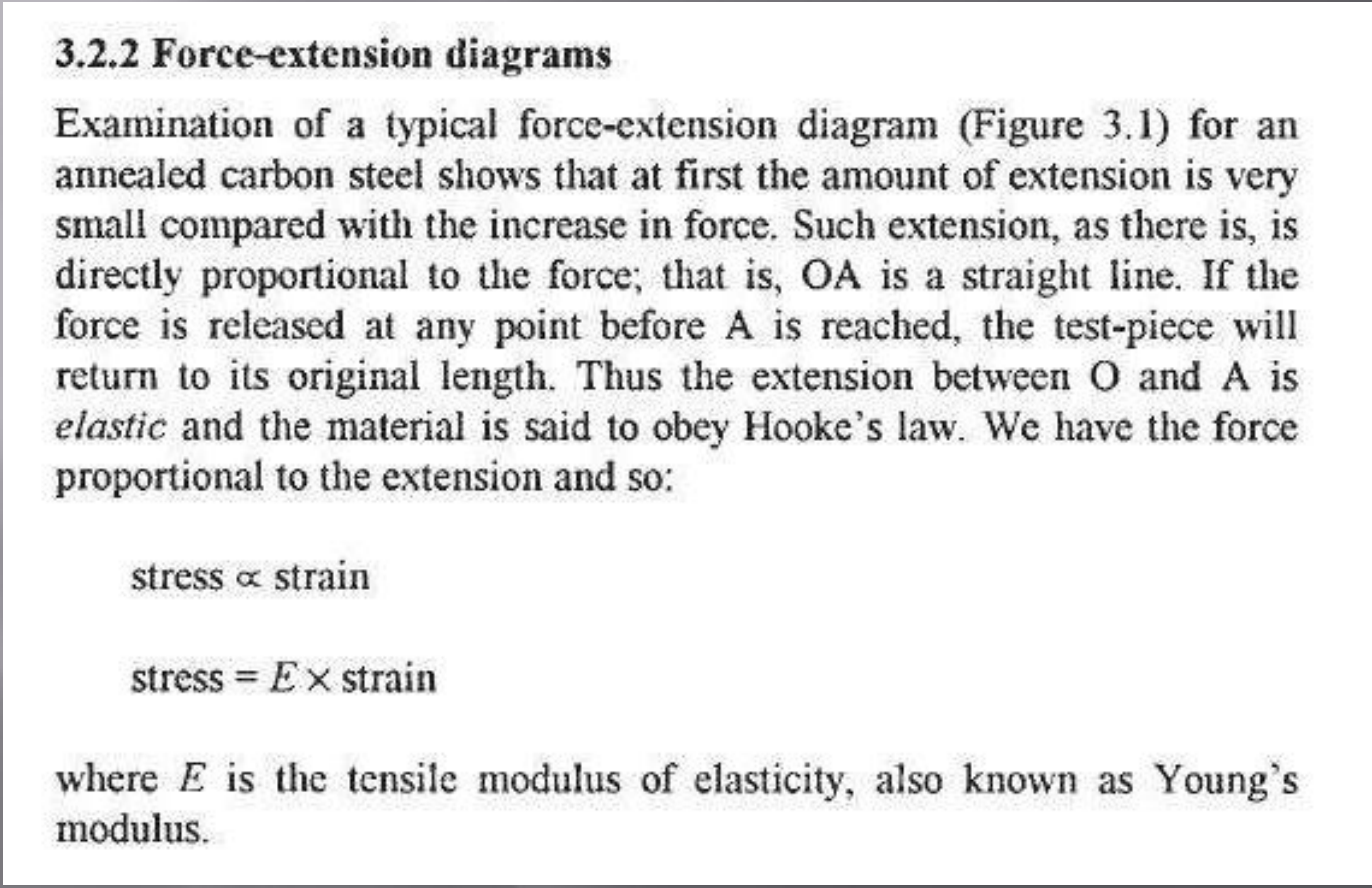
Table 2.6 *Comparative corrosion resistances*

Corrosion resistance	*Material*
Aerated water	
High resistance	All ceramics, glasses, lead alloys, alloy steels, titanium alloys, nickel alloys, copper alloys, PTFE, polypropylene, nylon, epoxies, polystyrene, PVC
Medium resistance	Aluminium alloys, polythene, polyesters
Low resistance	Carbon steels
Salt water	
High resistance	All ceramics, glasses, lead alloys, stainless steels, titanium alloys, nickel alloys, copper alloys, PTFE, polypropylene, nylon, epoxies, polystyrene, PVC, polythene
Medium resistance	Aluminium alloys, polyesters
Low resistance	Low alloy steels, carbon steels
UV radiation	
High resistance	All ceramics, glasses, all alloys
Medium resistance	Epoxies, polyesters, polypropylene, polystyrene, HD polyethylene, polymers with UV inhibitor
Low resistance	Nylon, PVC, many elastomers



In the type of tests described in this chapter, the test-piece is destroyed during the testing process. Such tests are therefore known as *destructive tests*, and can only be applied to individual test-pieces. These are taken from a batch of material which it is proposed to use for some specific purpose and they are therefore assumed to be representative of the batch. Tests of a different nature and purpose are used to examine manufactured components for internal flaws and faults, e.g. X-rays used to seek internal cavities in castings. These tests are generally referred to as *non-destructive tests* (NDT), since the component, so to speak, 'lives to tell the tale'.

The tensile test of a material involves a test-piece of known cross-sectional area being gripped in the jaws of a testing-machine and then subject to a tensile force which is increased in increments. For each increment of force, the amount by which the length of a known 'gauge length' on the test-piece increases is measured. This process continues until the test-piece fractures.



3.2.2 Force-extension diagrams

Examination of a typical force-extension diagram (Figure 3.1) for an annealed carbon steel shows that at first the amount of extension is very small compared with the increase in force. Such extension, as there is, is directly proportional to the force; that is, OA is a straight line. If the force is released at any point before A is reached, the test-piece will return to its original length. Thus the extension between O and A is *elastic* and the material is said to obey Hooke's law. We have the force proportional to the extension and so:

$$\text{stress} \propto \text{strain}$$

$$\text{stress} = E \times \text{strain}$$

where E is the tensile modulus of elasticity, also known as Young's modulus.

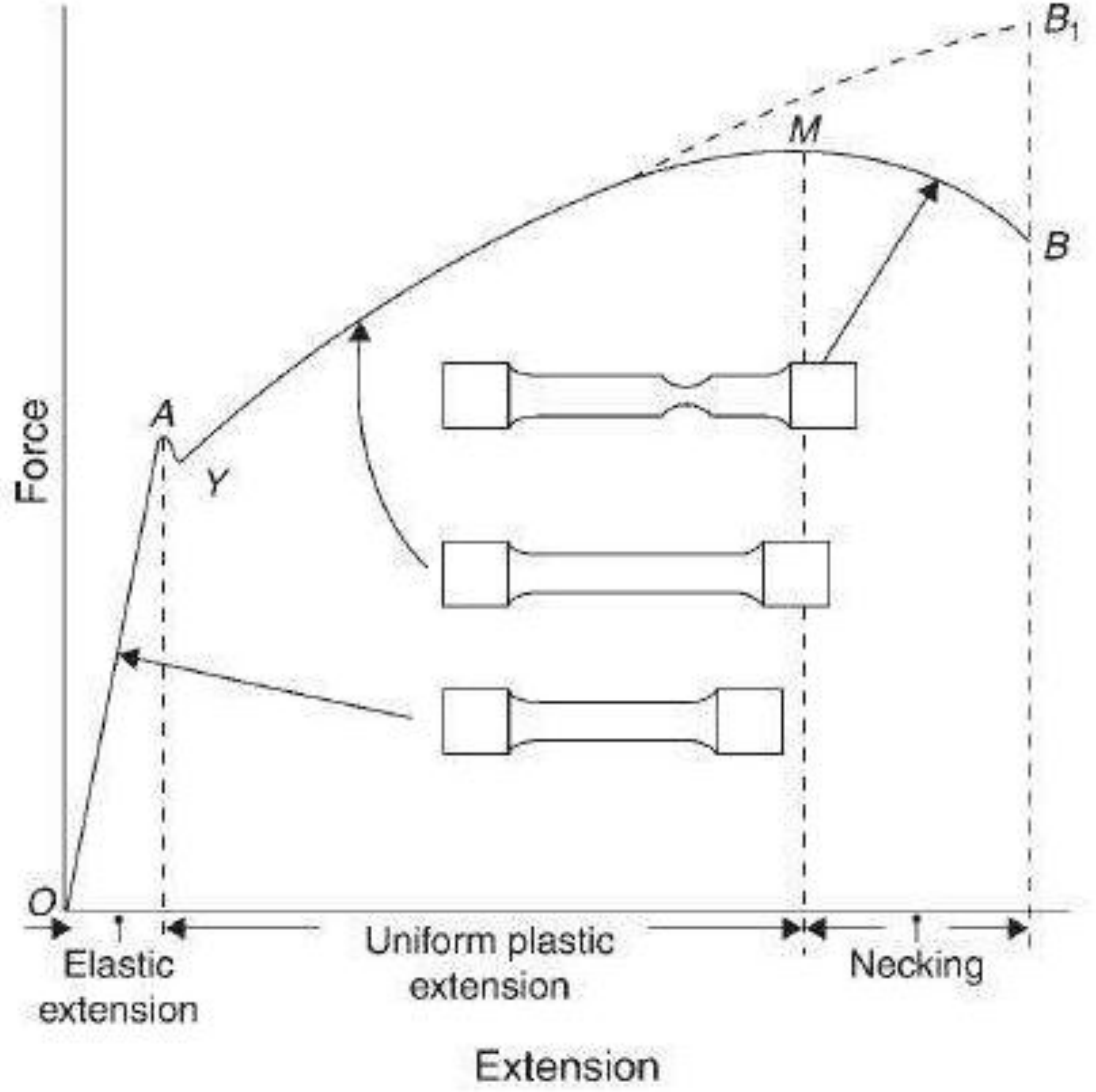
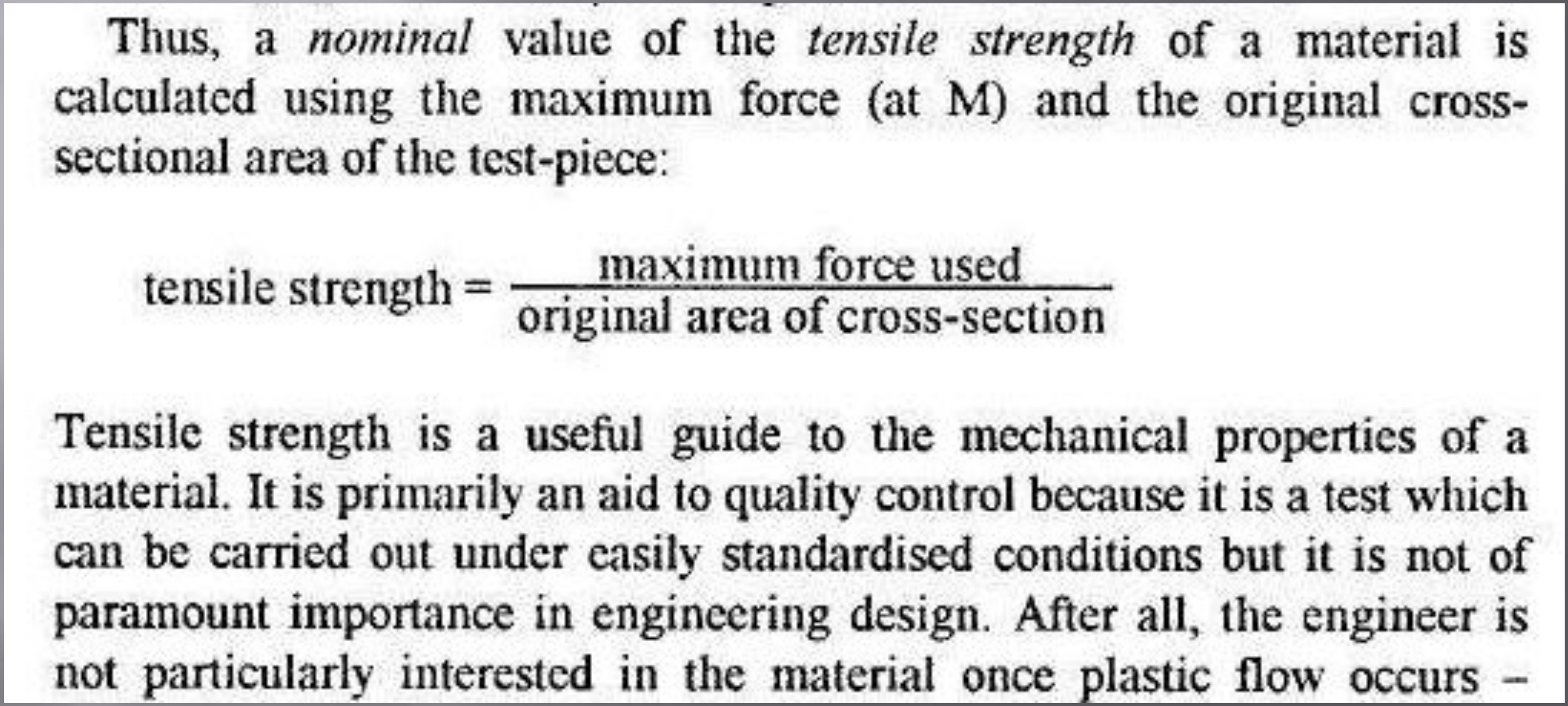


Figure 3.1 *Force-extension diagram for an annealed low-carbon steel.*



Thus, a *nominal* value of the *tensile strength* of a material is calculated using the maximum force (at M) and the original cross-sectional area of the test-piece:

$$\text{tensile strength} = \frac{\text{maximum force used}}{\text{original area of cross-section}}$$

Tensile strength is a useful guide to the mechanical properties of a material. It is primarily an aid to quality control because it is a test which can be carried out under easily standardised conditions but it is not of paramount importance in engineering design. After all, the engineer is not particularly interested in the material once plastic flow occurs –

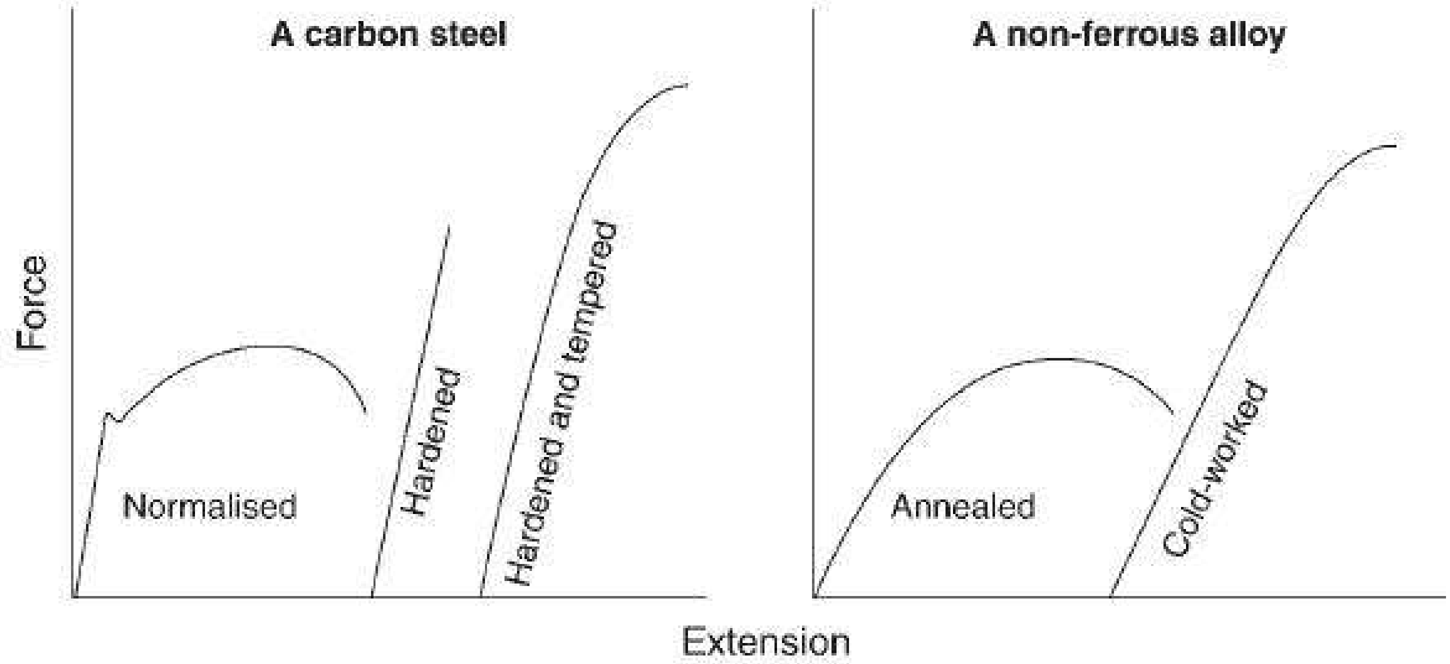
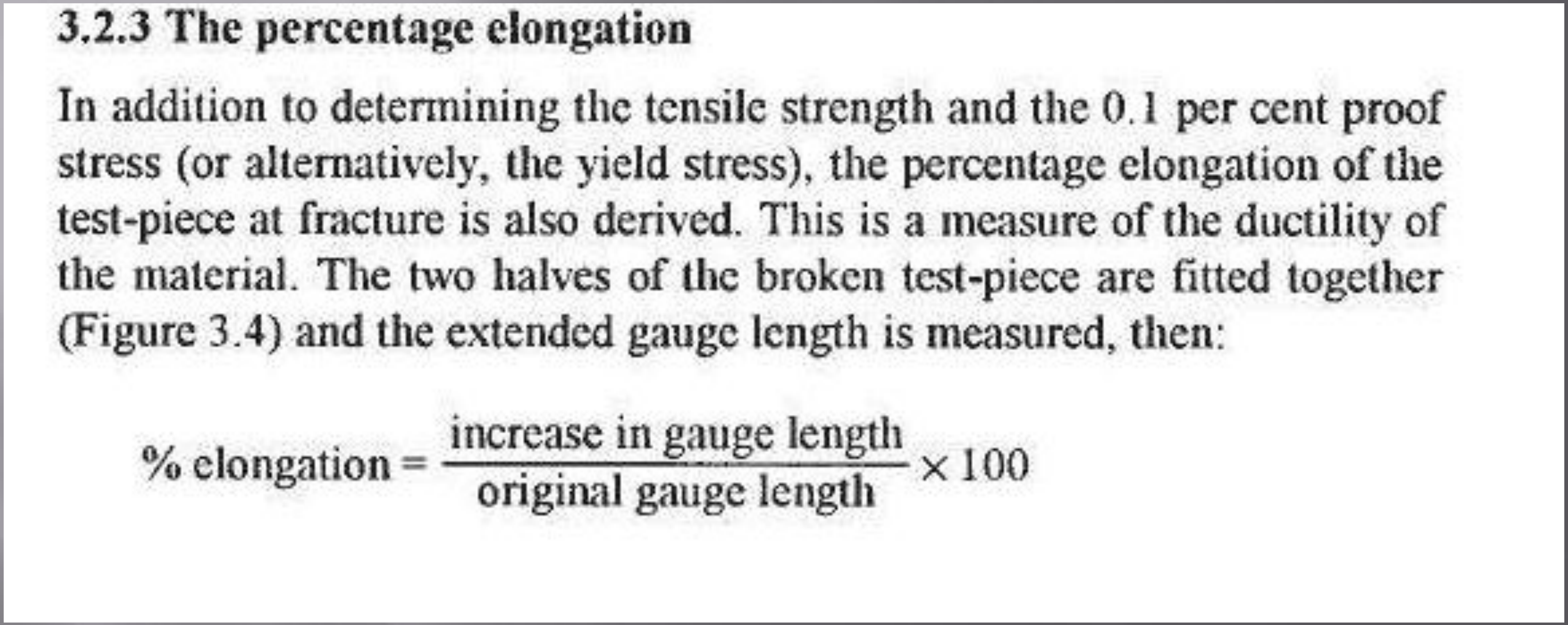


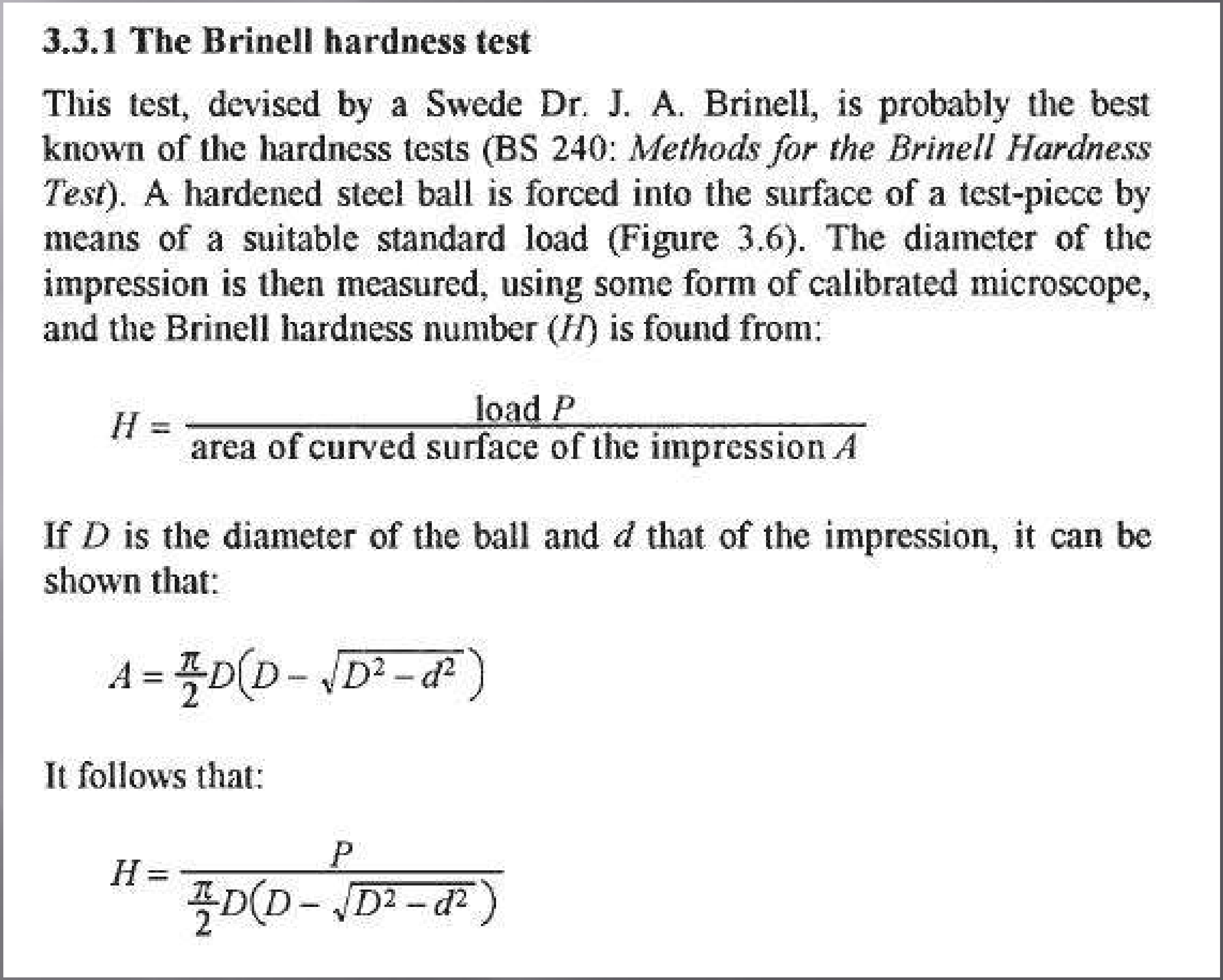
Figure 3.2 *Typical force-extension diagrams for both carbon steels and non-ferrous materials.*



3.2.3 The percentage elongation

In addition to determining the tensile strength and the 0.1 per cent proof stress (or alternatively, the yield stress), the percentage elongation of the test-piece at fracture is also derived. This is a measure of the ductility of the material. The two halves of the broken test-piece are fitted together (Figure 3.4) and the extended gauge length is measured, then:

$$\% \text{ elongation} = \frac{\text{increase in gauge length}}{\text{original gauge length}} \times 100$$



3.3.1 The Brinell hardness test

This test, devised by a Swede Dr. J. A. Brinell, is probably the best known of the hardness tests (BS 240: *Methods for the Brinell Hardness Test*). A hardened steel ball is forced into the surface of a test-piece by means of a suitable standard load (Figure 3.6). The diameter of the impression is then measured, using some form of calibrated microscope, and the Brinell hardness number (H) is found from:

$$H = \frac{\text{load } P}{\text{area of curved surface of the impression } A}$$

If D is the diameter of the ball and d that of the impression, it can be shown that:

$$A = \frac{\pi}{2} D\left(D - \sqrt{D^2 - d^2}\right)$$

It follows that:

$$H = \frac{P}{\frac{\pi}{2} D\left(D - \sqrt{D^2 - d^2}\right)}$$

To make tedious calculations unnecessary, H is generally found by reference to tables which relate H to d – a different set of tables being used for each possible combination of P and D.

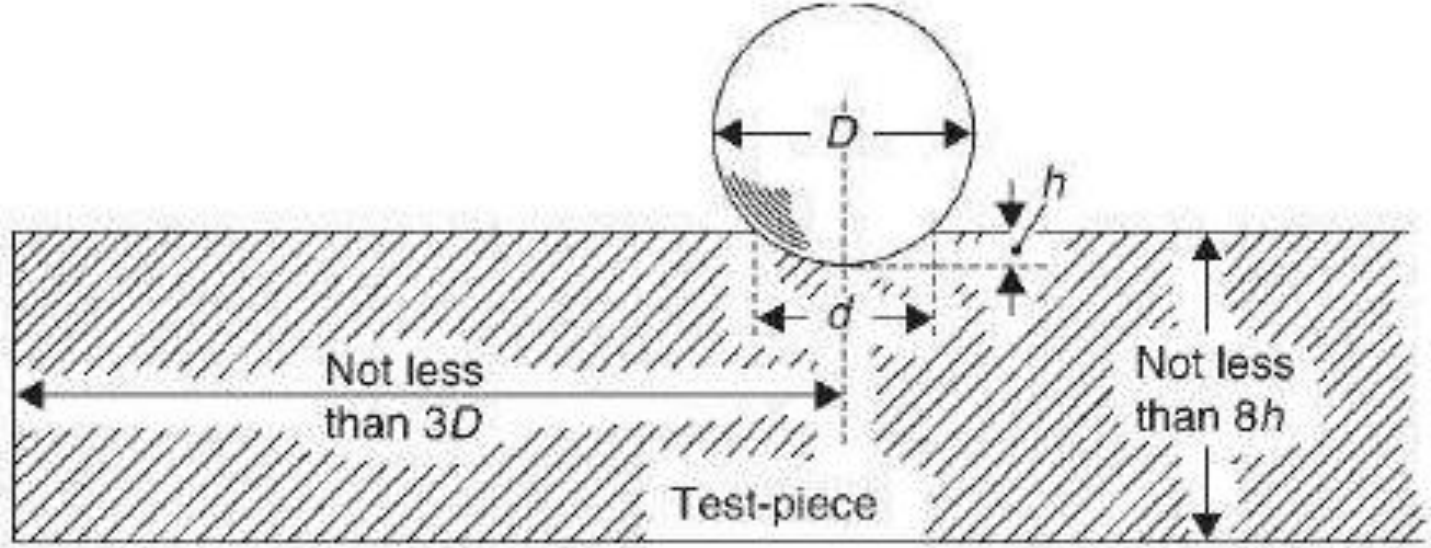
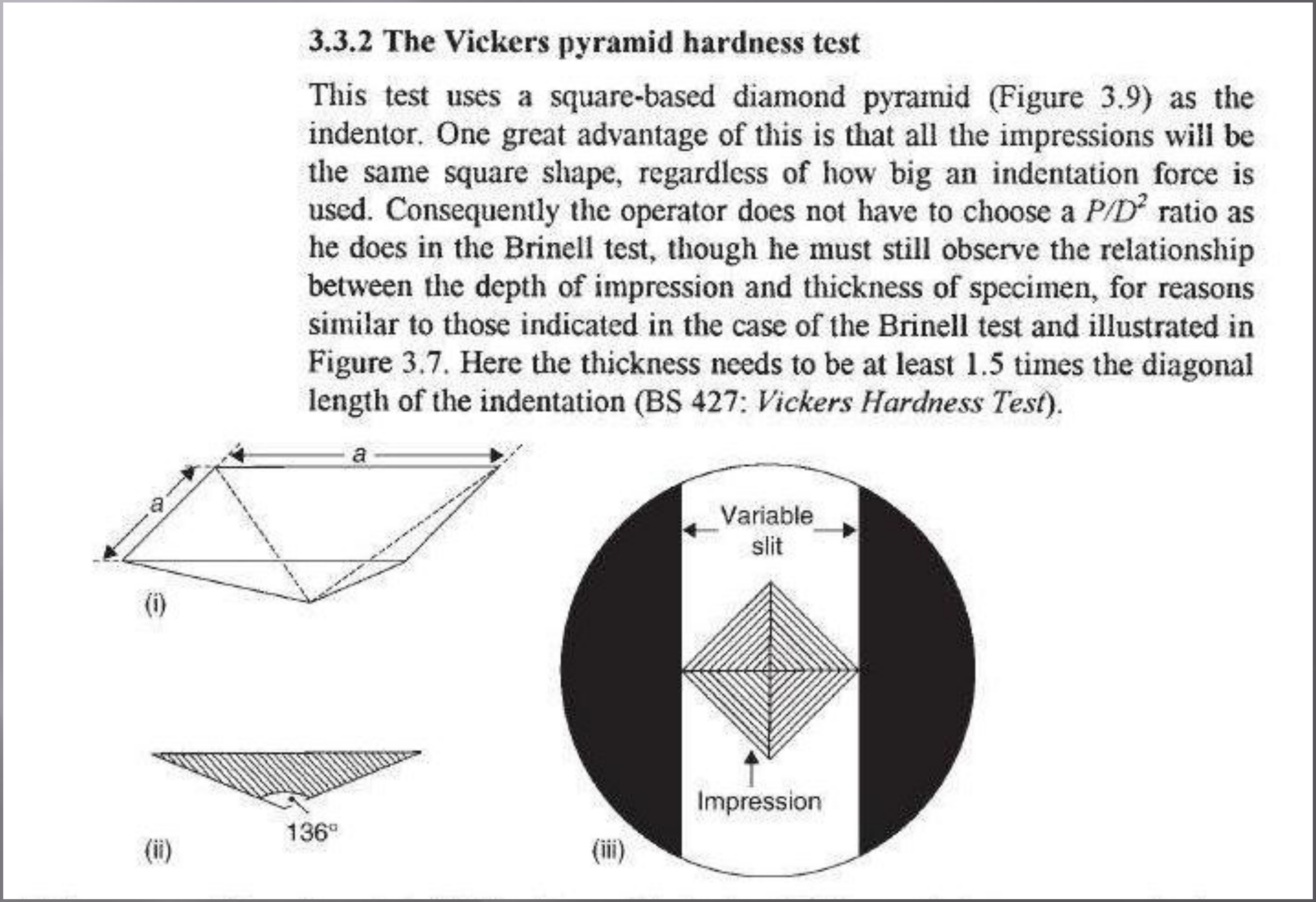


Figure 3.6 *The relationship between ball diameter D, depth of impression h and dimensions of the test-piece in the Brinell test.*



3.3.2 The Vickers pyramid hardness test

This test uses a square-based diamond pyramid (Figure 3.9) as the indentor. One great advantage of this is that all the impressions will be the same square shape, regardless of how big an indentation force is used. Consequently the operator does not have to choose a P/D^2 ratio as he does in the Brinell test, though he must still observe the relationship between the depth of impression and thickness of specimen, for reasons similar to those indicated in the case of the Brinell test and illustrated in Figure 3.7. Here the thickness needs to be at least 1.5 times the diagonal length of the indentation (BS 427: *Vickers Hardness Test*).

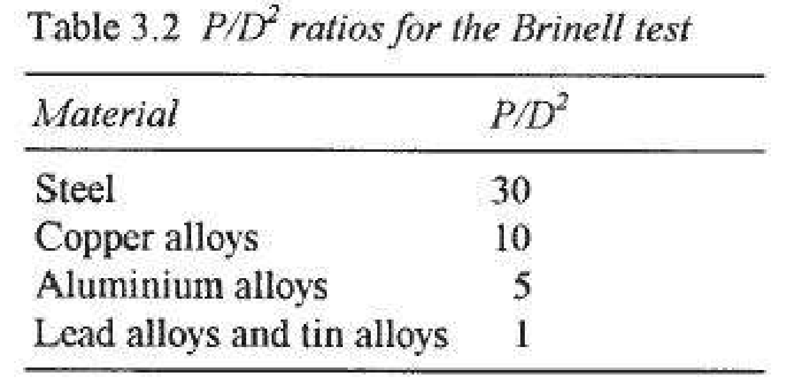
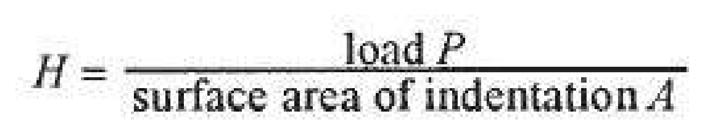


Table 3.2 *P/D^2 ratios for the Brinell test*

Material	*P/D^2*
Steel	30
Copper alloys	10
Aluminium alloys	5
Lead alloys and tin alloys	1



$$H = \frac{\text{load } P}{\text{surface area of indentation } A}$$

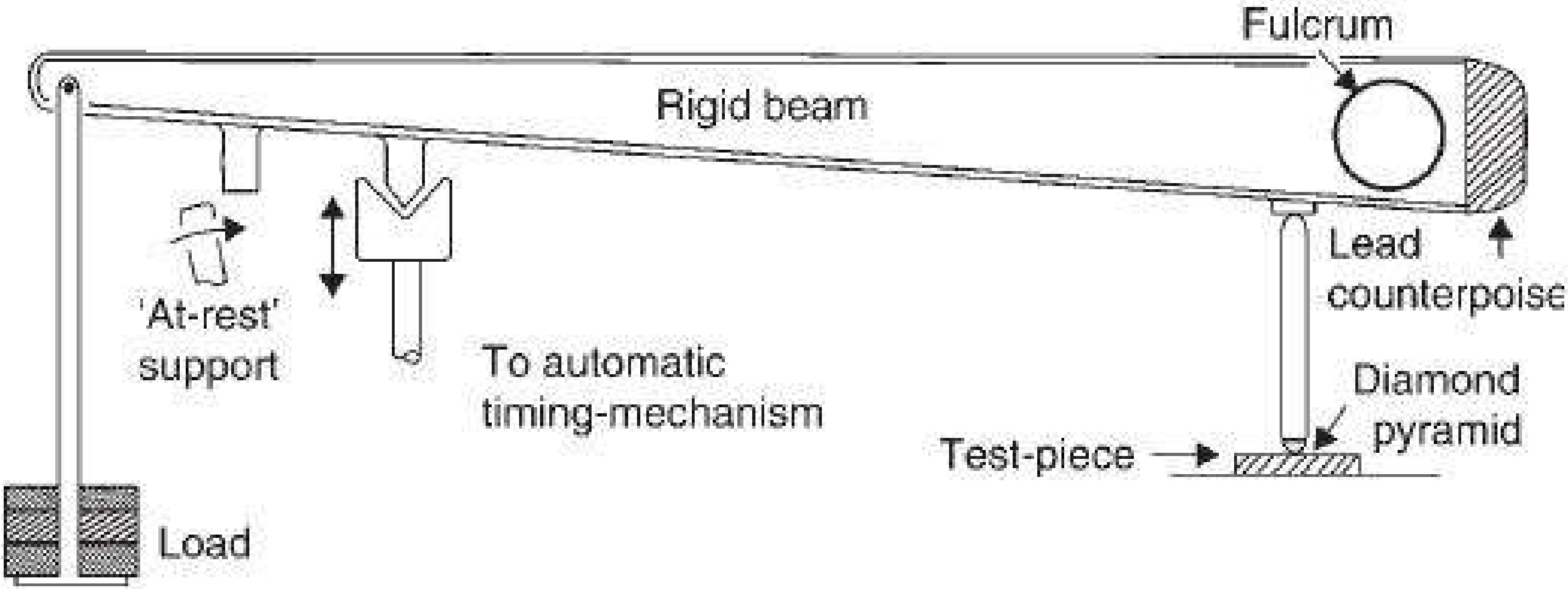
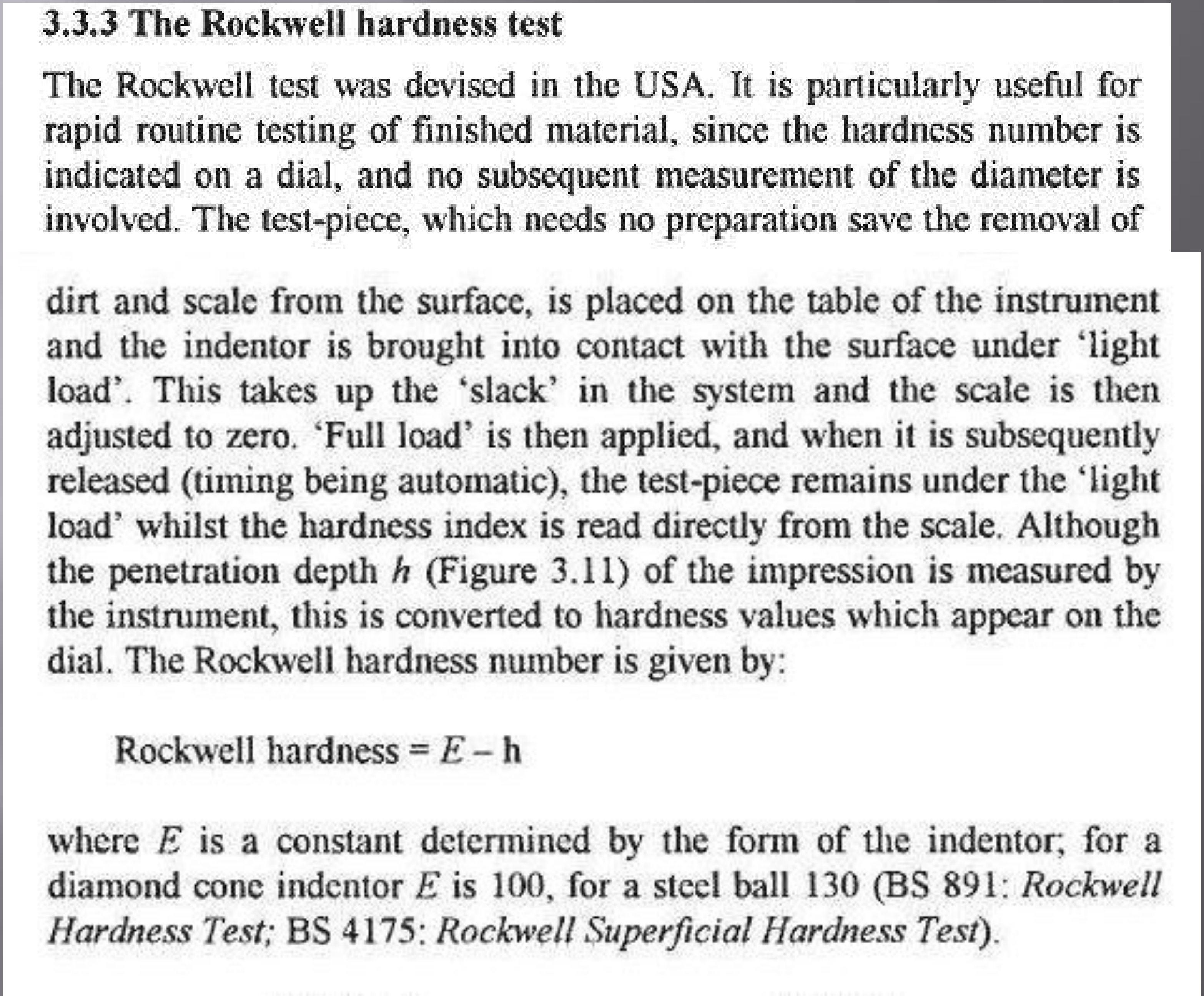


Figure 3.10 *The loading system for the Vickers pyramid hardness machine. It is essentially a second-order lever system. The fifteen-second period of load application is timed by an oil dashpot system.*

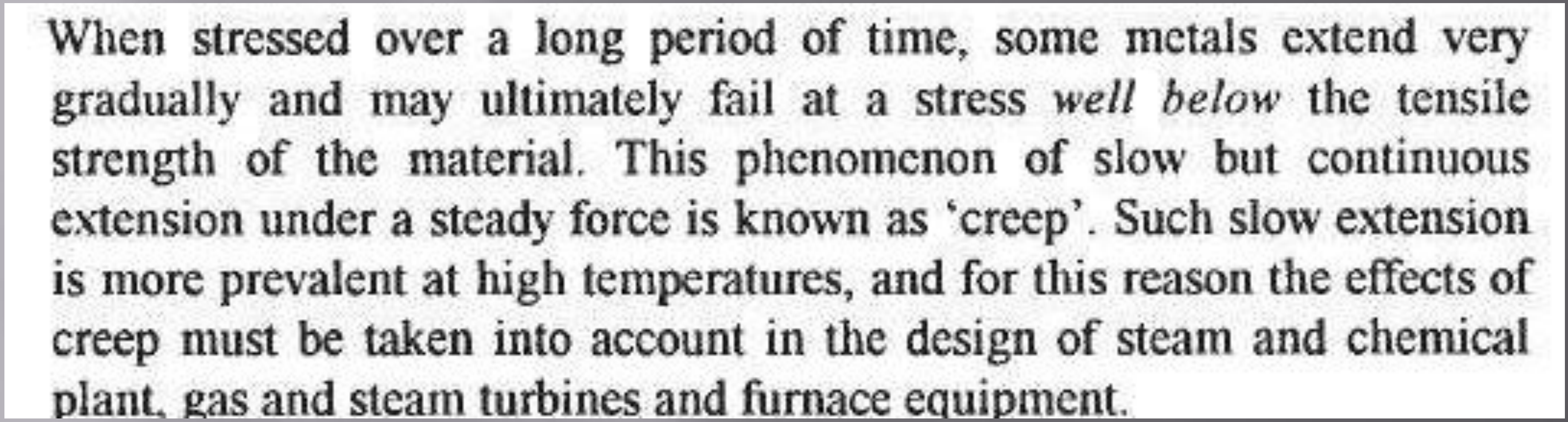


3.3.3 The Rockwell hardness test

The Rockwell test was devised in the USA. It is particularly useful for rapid routine testing of finished material, since the hardness number is indicated on a dial, and no subsequent measurement of the diameter is involved. The test-piece, which needs no preparation save the removal of dirt and scale from the surface, is placed on the table of the instrument and the indentor is brought into contact with the surface under 'light load'. This takes up the 'slack' in the system and the scale is then adjusted to zero. 'Full load' is then applied, and when it is subsequently released (timing being automatic), the test-piece remains under the 'light load' whilst the hardness index is read directly from the scale. Although the penetration depth h (Figure 3.11) of the impression is measured by the instrument, this is converted to hardness values which appear on the dial. The Rockwell hardness number is given by:

$$\text{Rockwell hardness} = E - \text{h}$$

where E is a constant determined by the form of the indentor; for a diamond cone indentor E is 100, for a steel ball 130 (BS 891: *Rockwell Hardness Test;* BS 4175: *Rockwell Superficial Hardness Test*).



When stressed over a long period of time, some metals extend very gradually and may ultimately fail at a stress *well below* the tensile strength of the material. This phenomenon of slow but continuous extension under a steady force is known as 'creep'. Such slow extension is more prevalent at high temperatures, and for this reason the effects of creep must be taken into account in the design of steam and chemical plant, gas and steam turbines and furnace equipment.

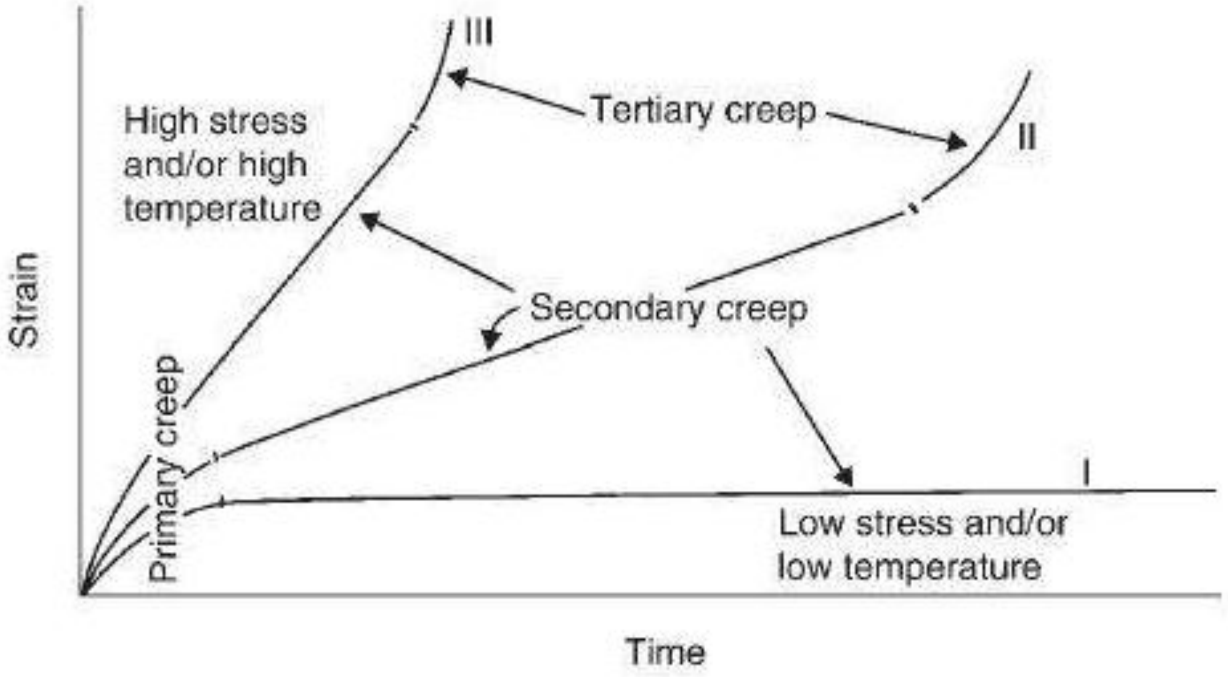
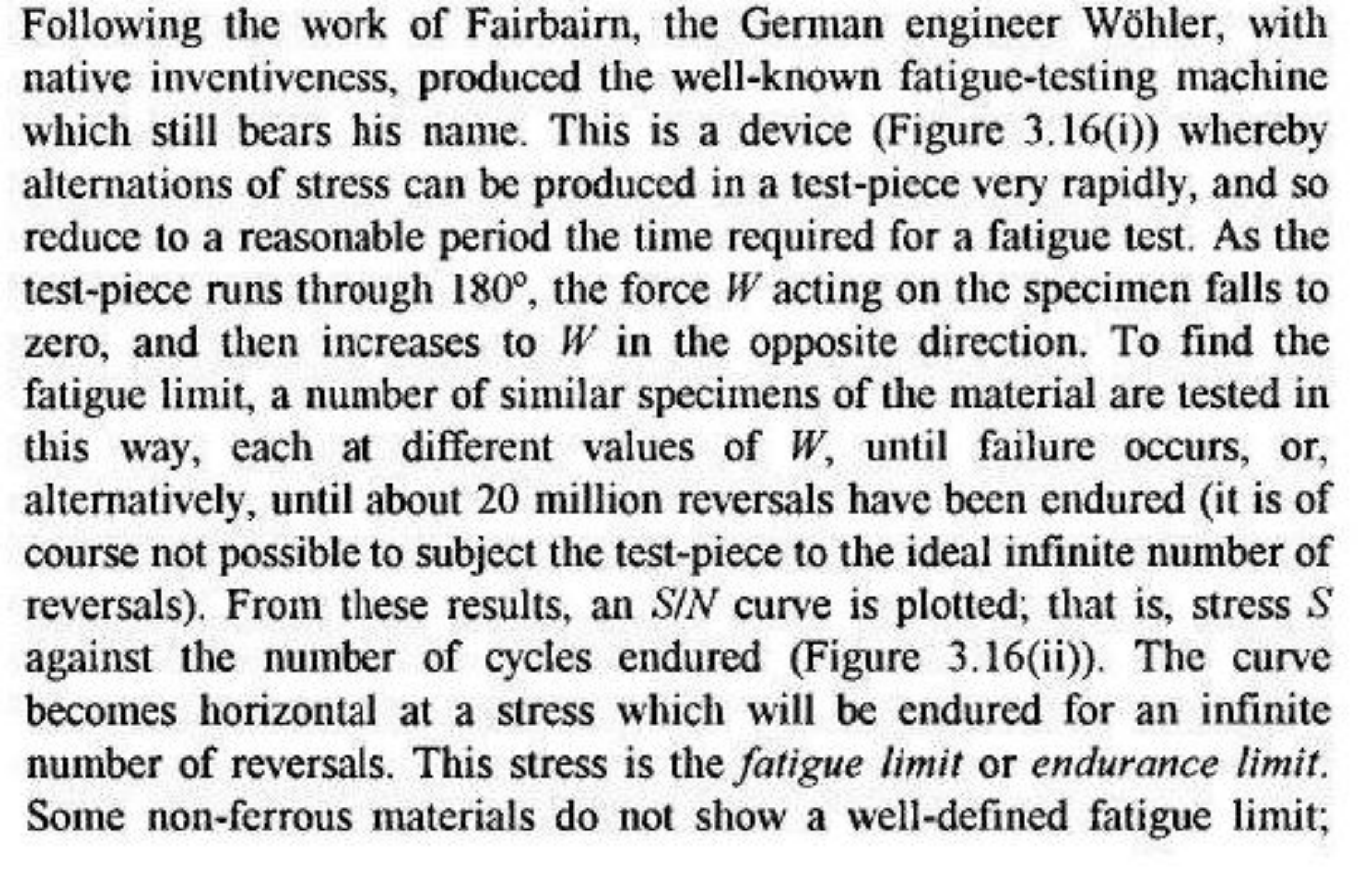


Figure 3.15 *The variation of creep rate with stress and temperature.*

Fatigue



Following the work of Fairbairn, the German engineer Wöhler, with native inventiveness, produced the well-known fatigue-testing machine which still bears his name. This is a device (Figure 3.16(i)) whereby alternations of stress can be produced in a test-piece very rapidly, and so reduce to a reasonable period the time required for a fatigue test. As the test-piece runs through 180°, the force W acting on the specimen falls to zero, and then increases to W in the opposite direction. To find the fatigue limit, a number of similar specimens of the material are tested in this way, each at different values of W, until failure occurs, or, alternatively, until about 20 million reversals have been endured (it is of course not possible to subject the test-piece to the ideal infinite number of reversals). From these results, an S/N curve is plotted; that is, stress S against the number of cycles endured (Figure 3.16(ii)). The curve becomes horizontal at a stress which will be endured for an infinite number of reversals. This stress is the *fatigue limit* or *endurance limit*. Some non-ferrous materials do not show a well-defined fatigue limit;

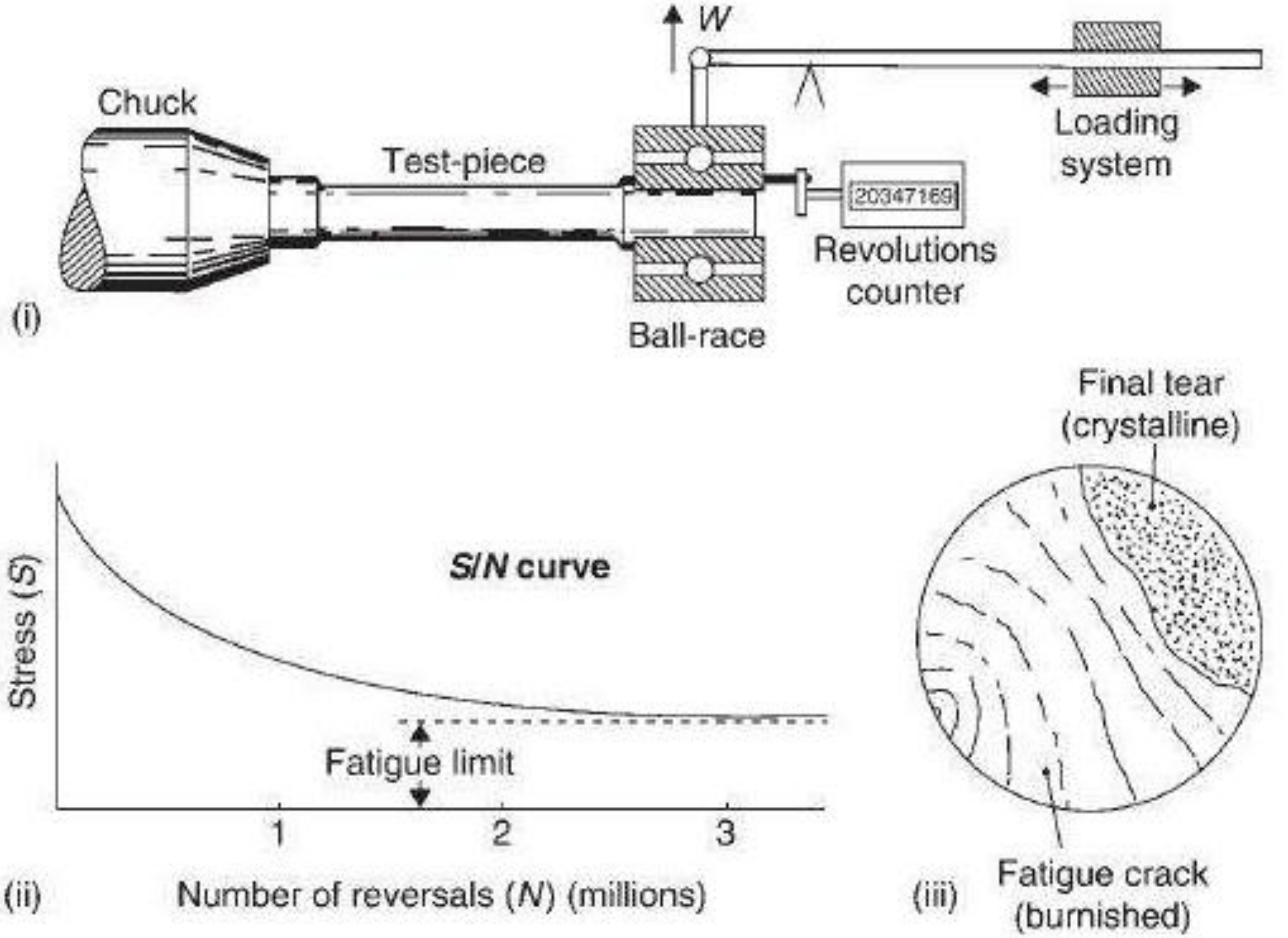
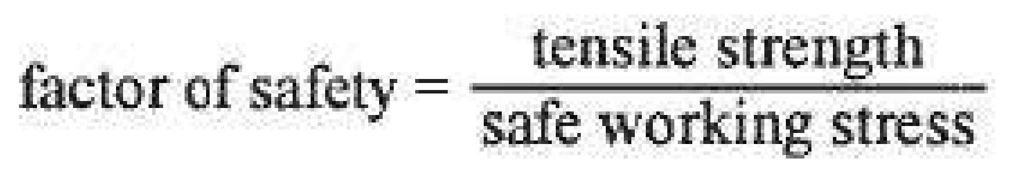
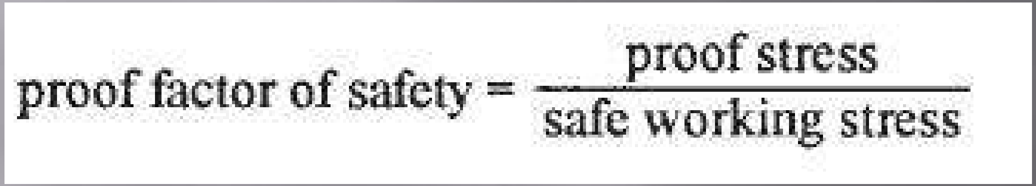


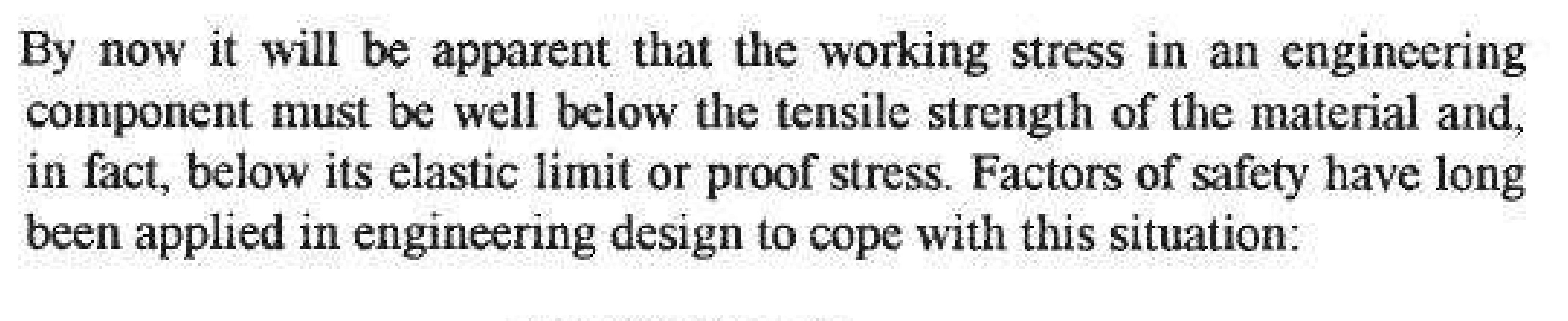
Figure 3.16 *(i) The principle of a simple fatigue-testing machine. (ii) A typical S/N curve obtained from a series of tests. (iii) The appearance of the fractured surface of a shaft which has failed due to fatigue.*



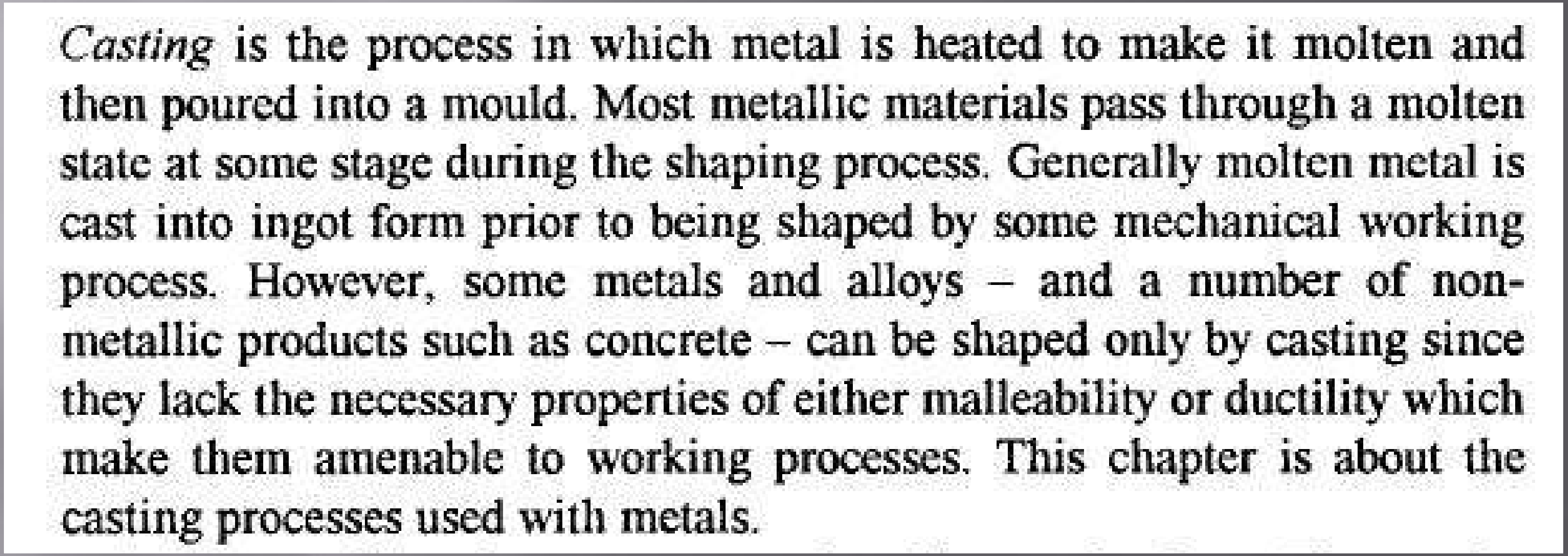
$$\text{factor of safety} = \frac{\text{tensile strength}}{\text{safe working stress}}$$



$$\text{proof factor of safety} = \frac{\text{proof stress}}{\text{safe working stress}}$$

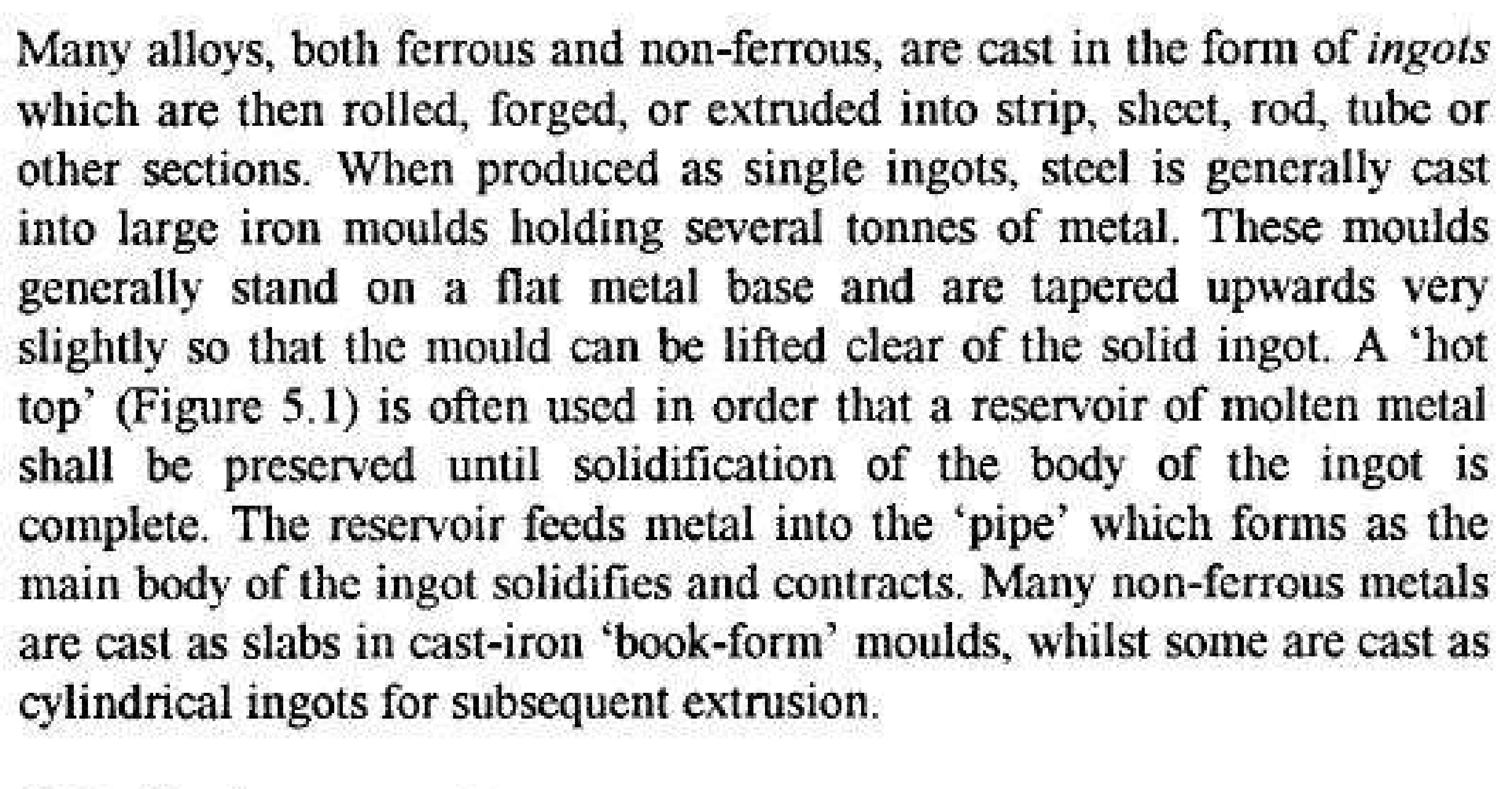


By now it will be apparent that the working stress in an engineering component must be well below the tensile strength of the material and, in fact, below its elastic limit or proof stress. Factors of safety have long been applied in engineering design to cope with this situation:



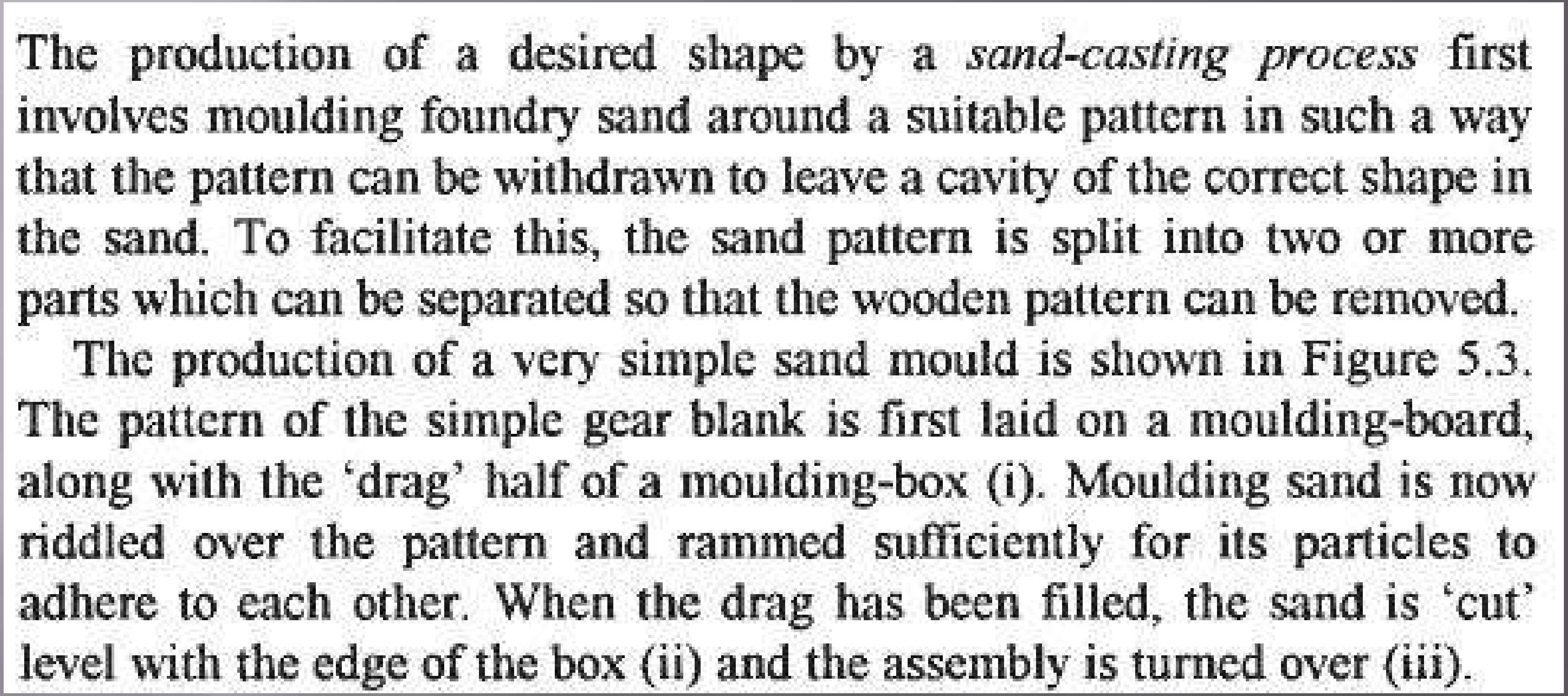
Casting is the process in which metal is heated to make it molten and then poured into a mould. Most metallic materials pass through a molten state at some stage during the shaping process. Generally molten metal is cast into ingot form prior to being shaped by some mechanical working process. However, some metals and alloys – and a number of non-metallic products such as concrete – can be shaped only by casting since they lack the necessary properties of either malleability or ductility which make them amenable to working processes. This chapter is about the casting processes used with metals.

Ingot casting



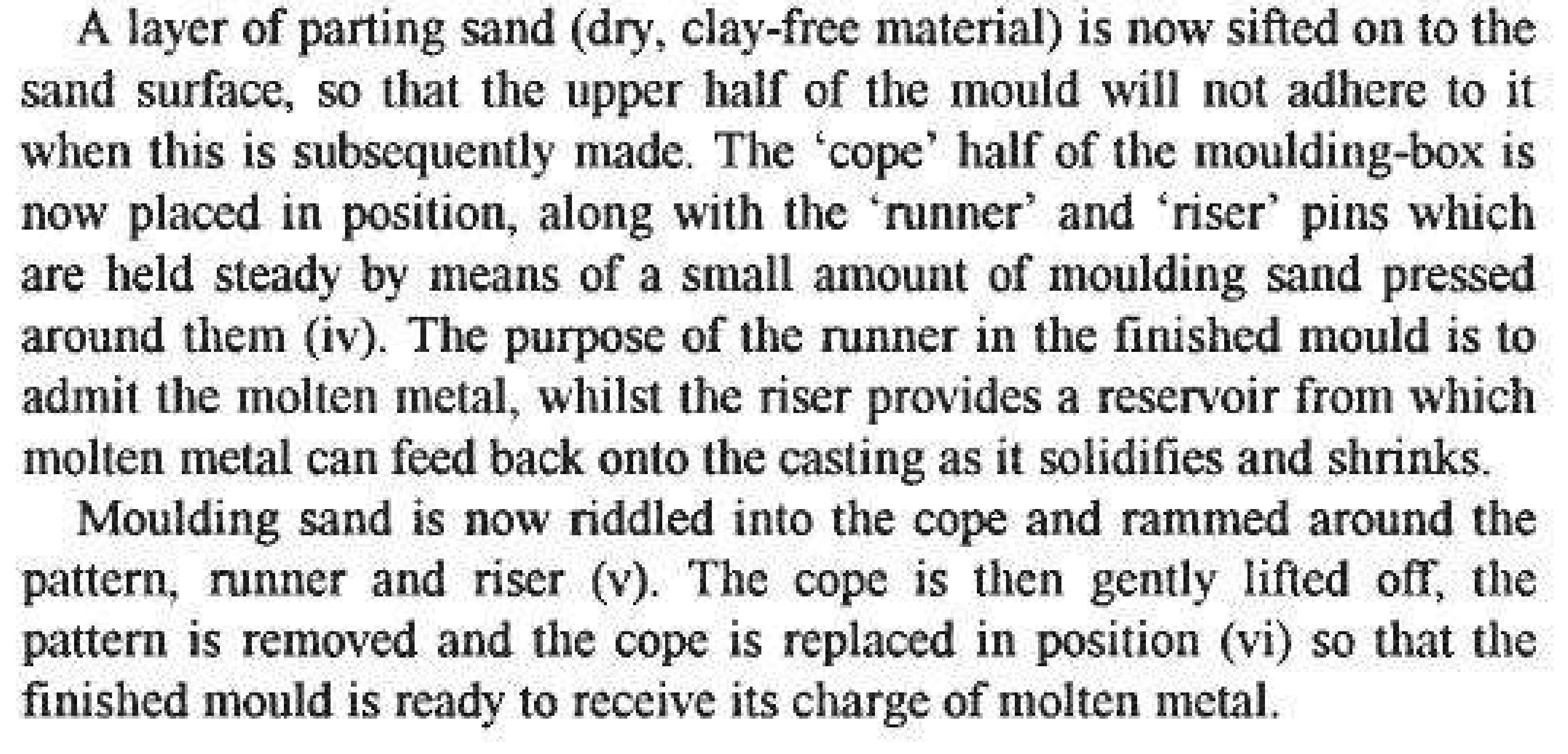
Many alloys, both ferrous and non-ferrous, are cast in the form of *ingots* which are then rolled, forged, or extruded into strip, sheet, rod, tube or other sections. When produced as single ingots, steel is generally cast into large iron moulds holding several tonnes of metal. These moulds generally stand on a flat metal base and are tapered upwards very slightly so that the mould can be lifted clear of the solid ingot. A 'hot top' (Figure 5.1) is often used in order that a reservoir of molten metal shall be preserved until solidification of the body of the ingot is complete. The reservoir feeds metal into the 'pipe' which forms as the main body of the ingot solidifies and contracts. Many non-ferrous metals are cast as slabs in cast-iron 'book-form' moulds, whilst some are cast as cylindrical ingots for subsequent extrusion.

Sand-casting



The production of a desired shape by a *sand-casting process* first involves moulding foundry sand around a suitable pattern in such a way that the pattern can be withdrawn to leave a cavity of the correct shape in the sand. To facilitate this, the sand pattern is split into two or more parts which can be separated so that the wooden pattern can be removed.

The production of a very simple sand mould is shown in Figure 5.3. The pattern of the simple gear blank is first laid on a moulding-board, along with the 'drag' half of a moulding-box (i). Moulding sand is now riddled over the pattern and rammed sufficiently for its particles to adhere to each other. When the drag has been filled, the sand is 'cut' level with the edge of the box (ii) and the assembly is turned over (iii).



A layer of parting sand (dry, clay-free material) is now sifted on to the sand surface, so that the upper half of the mould will not adhere to it when this is subsequently made. The 'cope' half of the moulding-box is now placed in position, along with the 'runner' and 'riser' pins which are held steady by means of a small amount of moulding sand pressed around them (iv). The purpose of the runner in the finished mould is to admit the molten metal, whilst the riser provides a reservoir from which molten metal can feed back onto the casting as it solidifies and shrinks.

Moulding sand is now riddled into the cope and rammed around the pattern, runner and riser (v). The cope is then gently lifted off, the pattern is removed and the cope is replaced in position (vi) so that the finished mould is ready to receive its charge of molten metal.

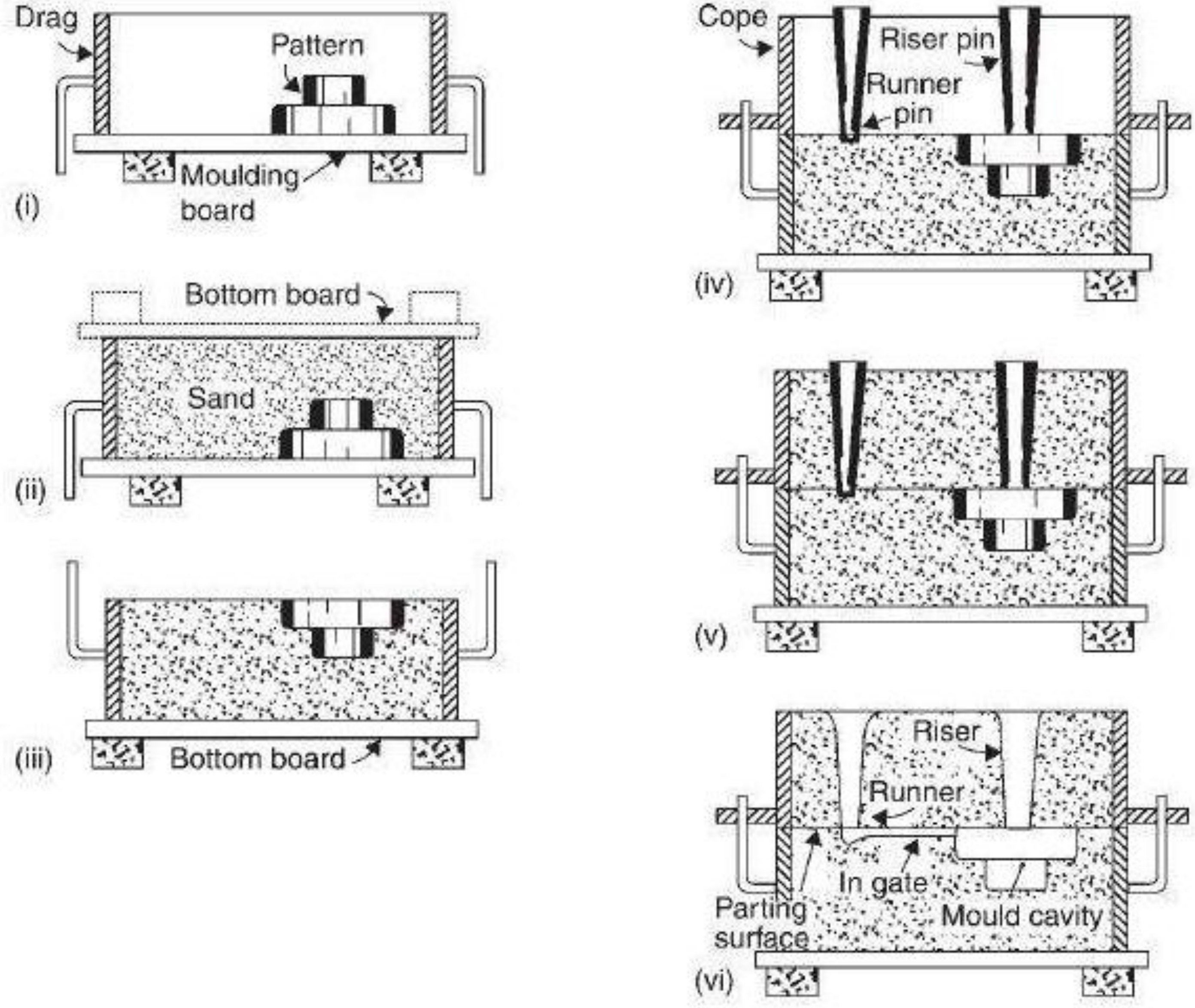
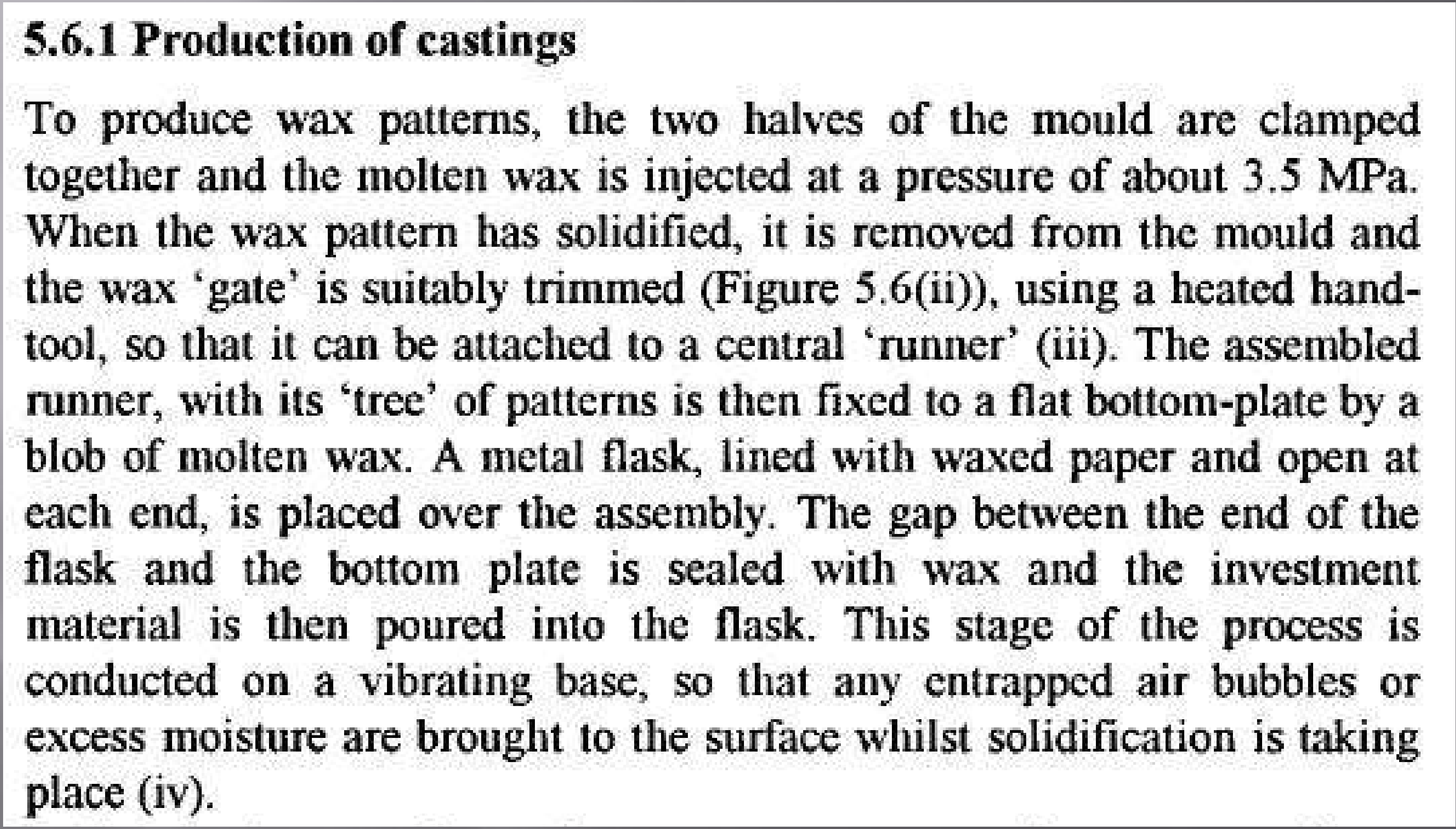
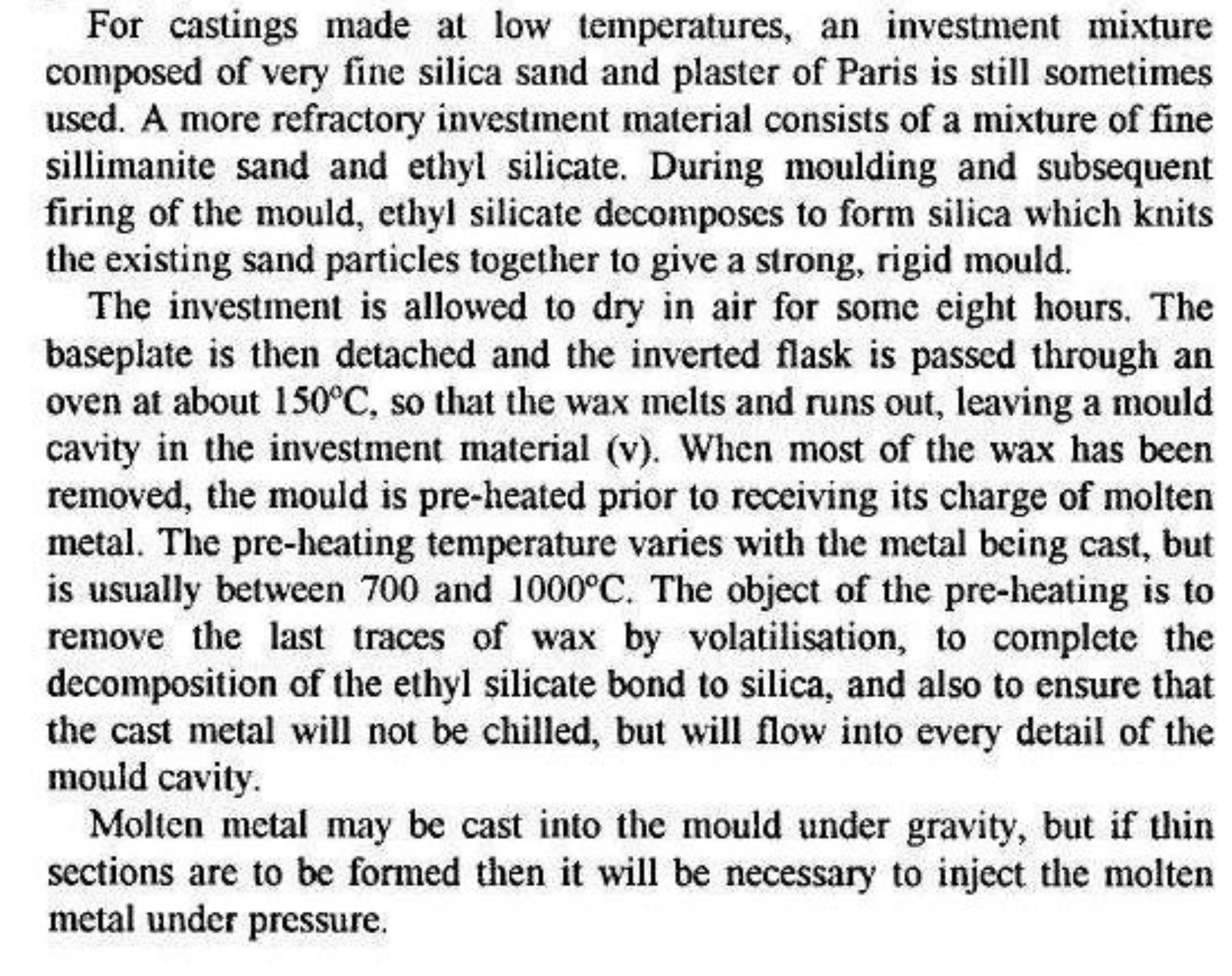


Figure 5.3 *Moulding with a simple pattern.*



5.6.1 Production of castings

To produce wax patterns, the two halves of the mould are clamped together and the molten wax is injected at a pressure of about 3.5 MPa. When the wax pattern has solidified, it is removed from the mould and the wax 'gate' is suitably trimmed (Figure 5.6(ii)), using a heated hand-tool, so that it can be attached to a central 'runner' (iii). The assembled runner, with its 'tree' of patterns is then fixed to a flat bottom-plate by a blob of molten wax. A metal flask, lined with waxed paper and open at each end, is placed over the assembly. The gap between the end of the flask and the bottom plate is sealed with wax and the investment material is then poured into the flask. This stage of the process is conducted on a vibrating base, so that any entrapped air bubbles or excess moisture are brought to the surface whilst solidification is taking place (iv).



For castings made at low temperatures, an investment mixture composed of very fine silica sand and plaster of Paris is still sometimes used. A more refractory investment material consists of a mixture of fine sillimanite sand and ethyl silicate. During moulding and subsequent firing of the mould, ethyl silicate decomposes to form silica which knits the existing sand particles together to give a strong, rigid mould.

The investment is allowed to dry in air for some eight hours. The baseplate is then detached and the inverted flask is passed through an oven at about 150°C, so that the wax melts and runs out, leaving a mould cavity in the investment material (v). When most of the wax has been removed, the mould is pre-heated prior to receiving its charge of molten metal. The pre-heating temperature varies with the metal being cast, but is usually between 700 and 1000°C. The object of the pre-heating is to remove the last traces of wax by volatilisation, to complete the decomposition of the ethyl silicate bond to silica, and also to ensure that the cast metal will not be chilled, but will flow into every detail of the mould cavity.

Molten metal may be cast into the mould under gravity, but if thin sections are to be formed then it will be necessary to inject the molten metal under pressure.

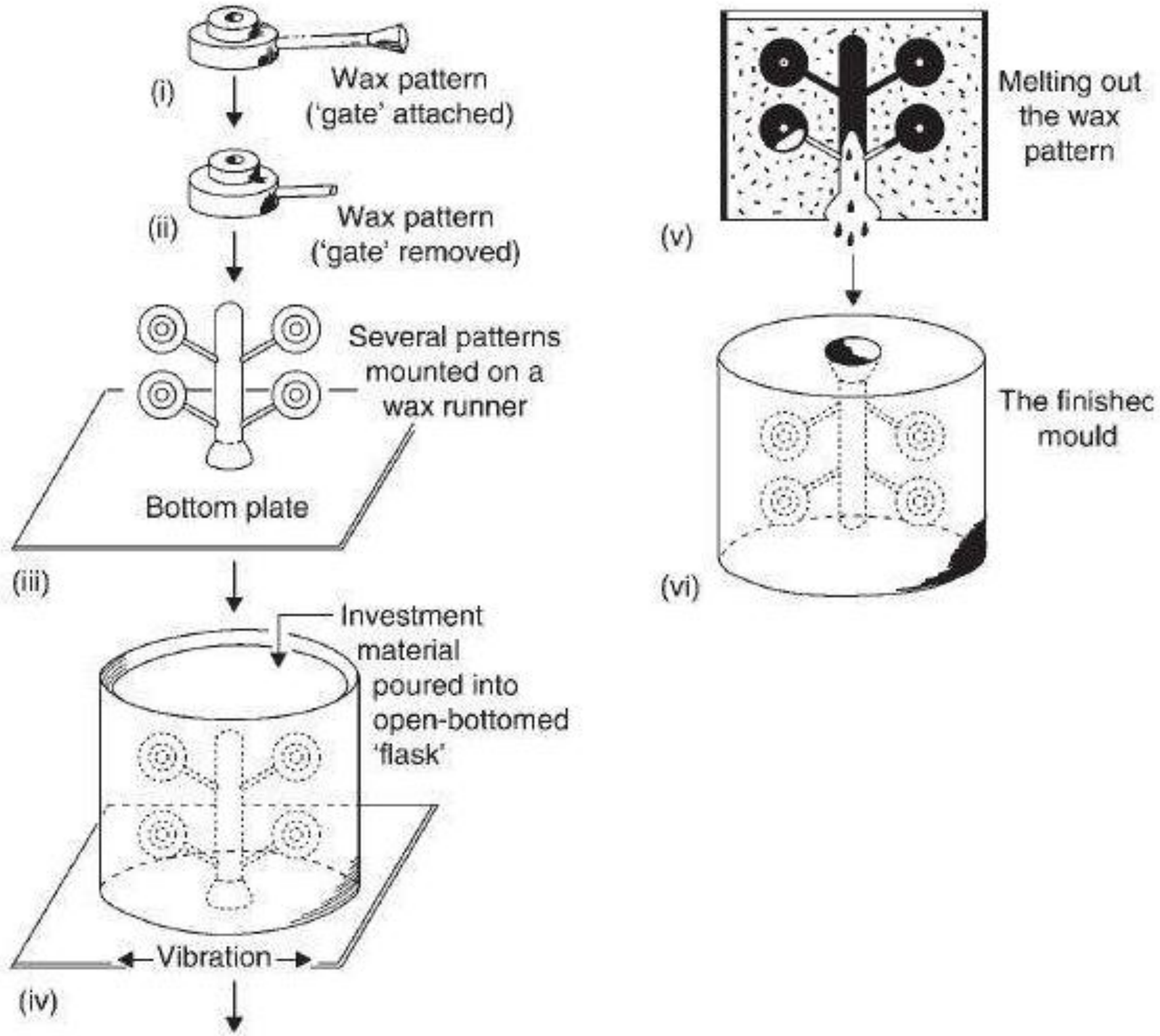
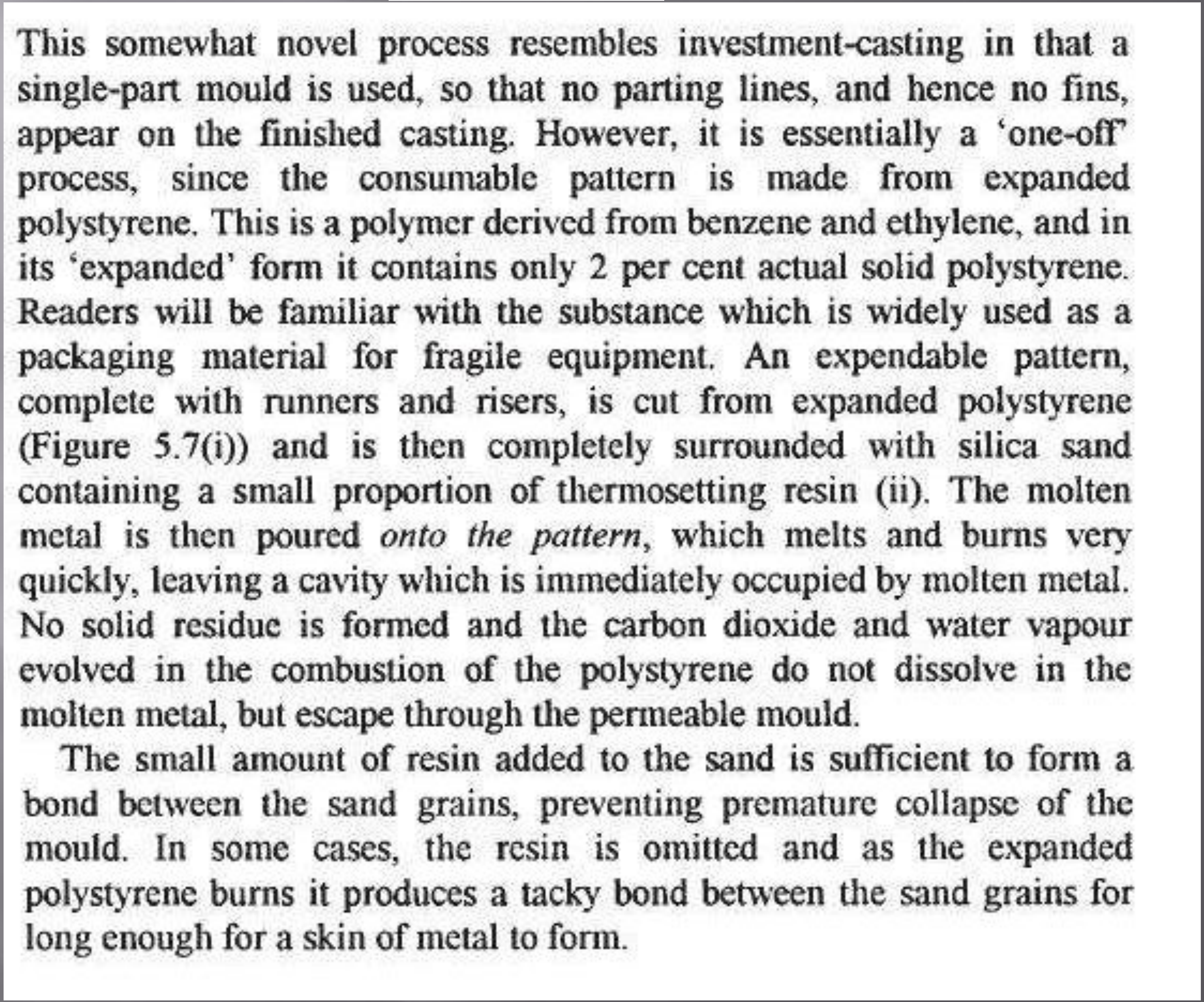


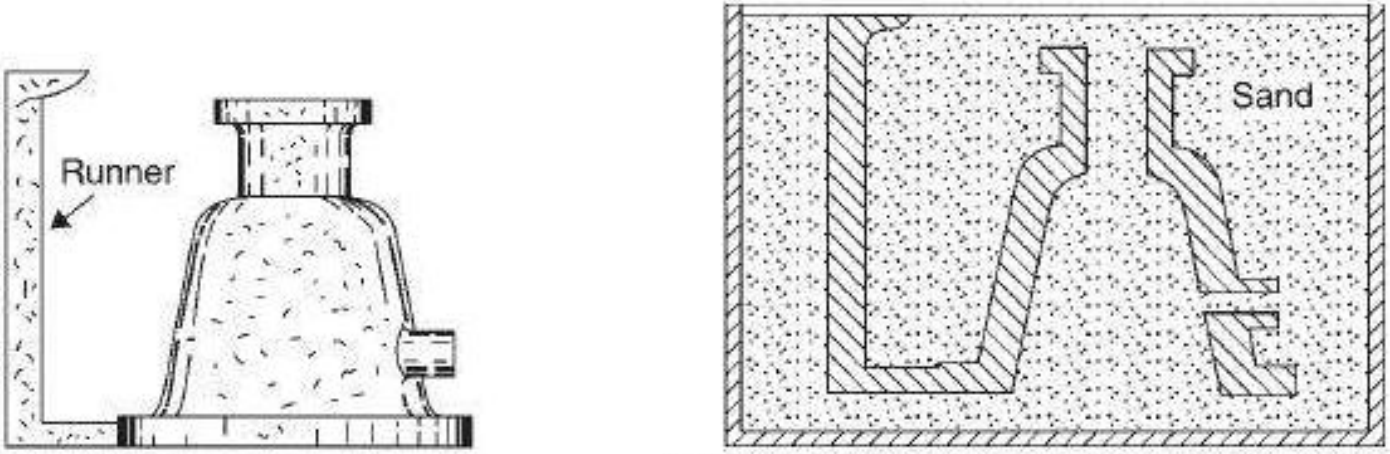
Figure 5.6 *The investment-casting (or 'lost-wax') process.*

Full-mould process



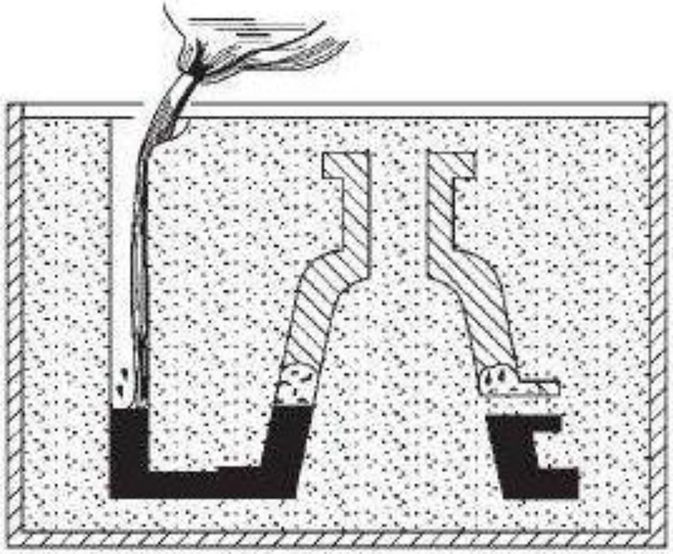
This somewhat novel process resembles investment-casting in that a single-part mould is used, so that no parting lines, and hence no fins, appear on the finished casting. However, it is essentially a 'one-off' process, since the consumable pattern is made from expanded polystyrene. This is a polymer derived from benzene and ethylene, and in its 'expanded' form it contains only 2 per cent actual solid polystyrene. Readers will be familiar with the substance which is widely used as a packaging material for fragile equipment. An expendable pattern, complete with runners and risers, is cut from expanded polystyrene (Figure 5.7(i)) and is then completely surrounded with silica sand containing a small proportion of thermosetting resin (ii). The molten metal is then poured *onto the pattern*, which melts and burns very quickly, leaving a cavity which is immediately occupied by molten metal. No solid residue is formed and the carbon dioxide and water vapour evolved in the combustion of the polystyrene do not dissolve in the molten metal, but escape through the permeable mould.

The small amount of resin added to the sand is sufficient to form a bond between the sand grains, preventing premature collapse of the mould. In some cases, the resin is omitted and as the expanded polystyrene burns it produces a tacky bond between the sand grains for long enough for a skin of metal to form.



(i) Polystyrene pattern

(ii) Pattern moulded in single-part flask

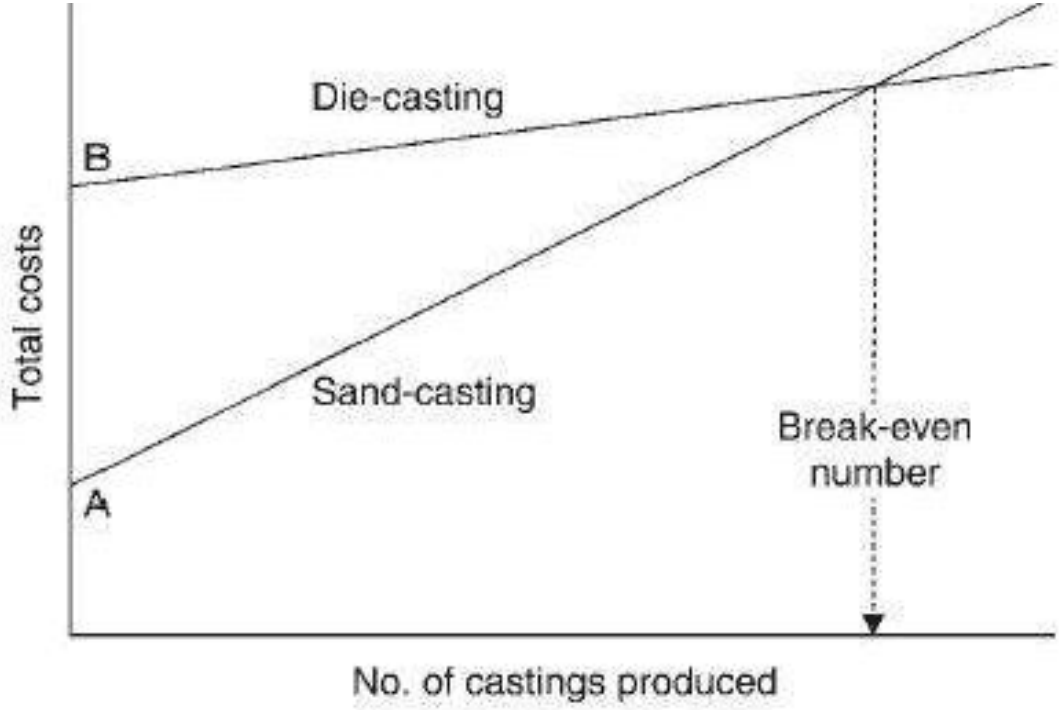


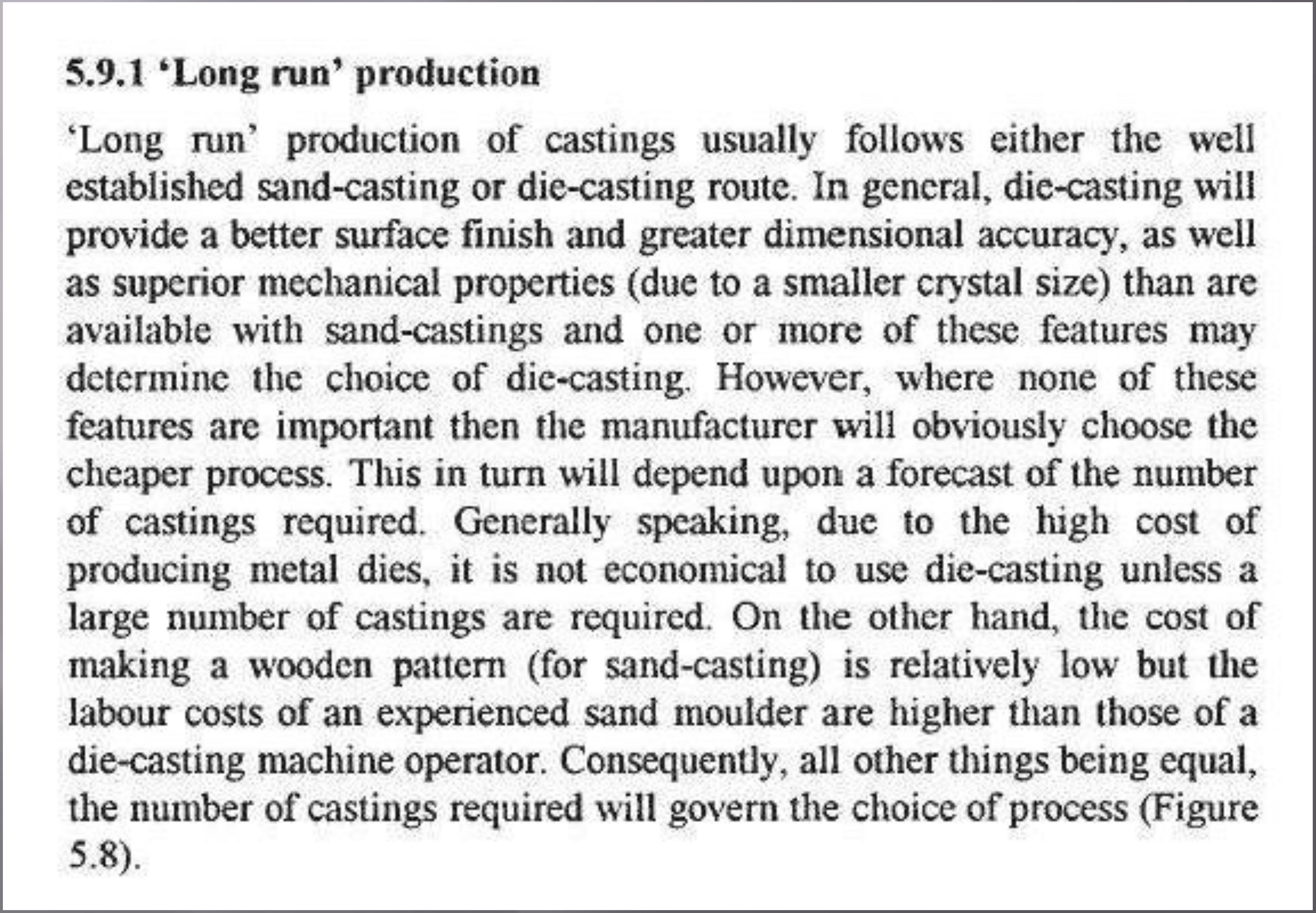
(iii) Casting in progress

The 'full-mould' process, which uses an expendable polystyrene pattern.

If dimensional accuracy is the main criterion in choosing a casting method then those processes described above could be considered in the following order:

1. Investment-casting
2. Die-casting
3. Sand-casting
4. Full-mould process

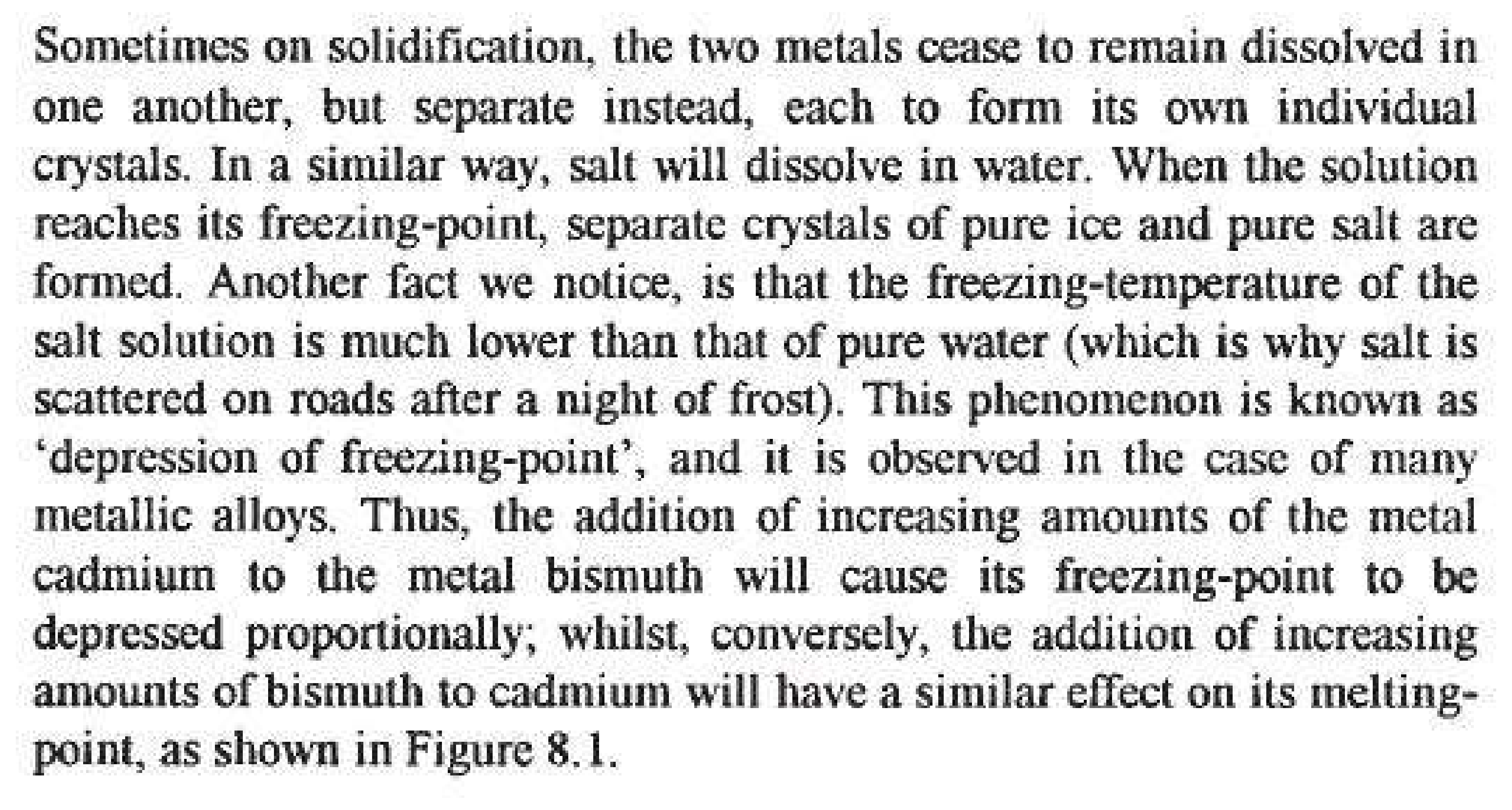




5.9.1 'Long run' production

'Long run' production of castings usually follows either the well established sand-casting or die-casting route. In general, die-casting will provide a better surface finish and greater dimensional accuracy, as well as superior mechanical properties (due to a smaller crystal size) than are available with sand-castings and one or more of these features may determine the choice of die-casting. However, where none of these features are important then the manufacturer will obviously choose the cheaper process. This in turn will depend upon a forecast of the number of castings required. Generally speaking, due to the high cost of producing metal dies, it is not economical to use die-casting unless a large number of castings are required. On the other hand, the cost of making a wooden pattern (for sand-casting) is relatively low but the labour costs of an experienced sand moulder are higher than those of a die-casting machine operator. Consequently, all other things being equal, the number of castings required will govern the choice of process (Figure 5.8).

Eutectics



Sometimes on solidification, the two metals cease to remain dissolved in one another, but separate instead, each to form its own individual crystals. In a similar way, salt will dissolve in water. When the solution reaches its freezing-point, separate crystals of pure ice and pure salt are formed. Another fact we notice, is that the freezing-temperature of the salt solution is much lower than that of pure water (which is why salt is scattered on roads after a night of frost). This phenomenon is known as 'depression of freezing-point', and it is observed in the case of many metallic alloys. Thus, the addition of increasing amounts of the metal cadmium to the metal bismuth will cause its freezing-point to be depressed proportionally; whilst, conversely, the addition of increasing amounts of bismuth to cadmium will have a similar effect on its melting-point, as shown in Figure 8.1.

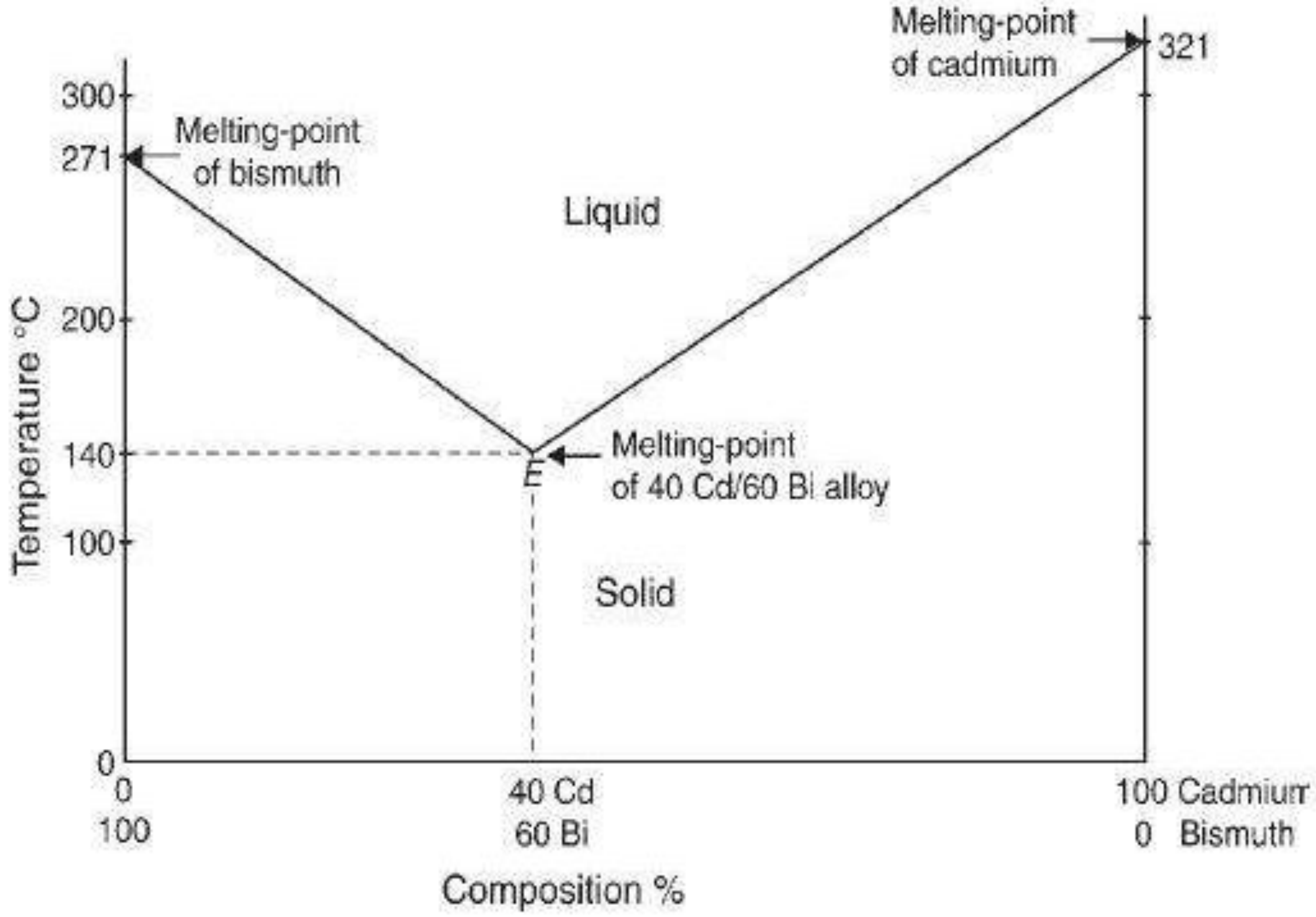
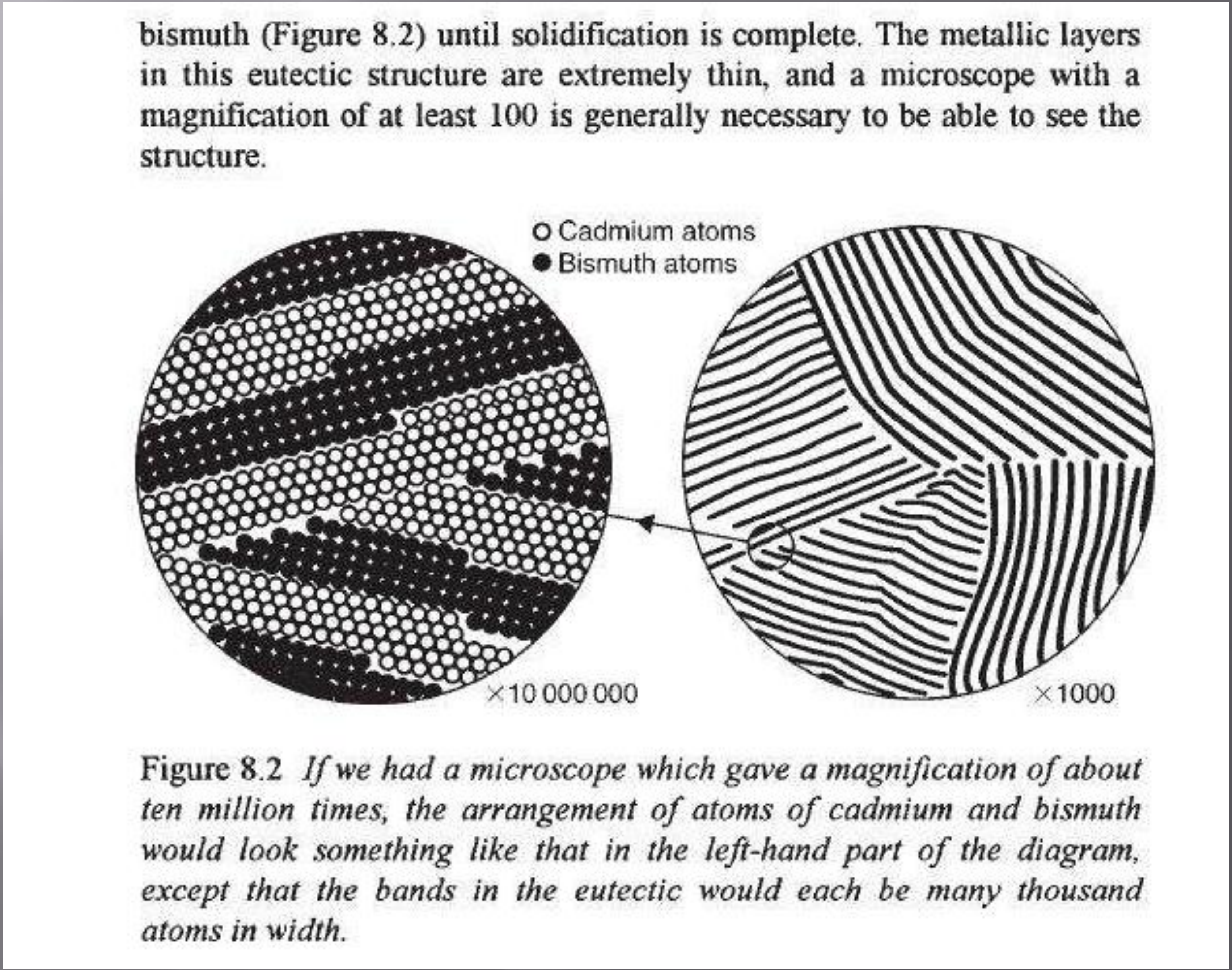
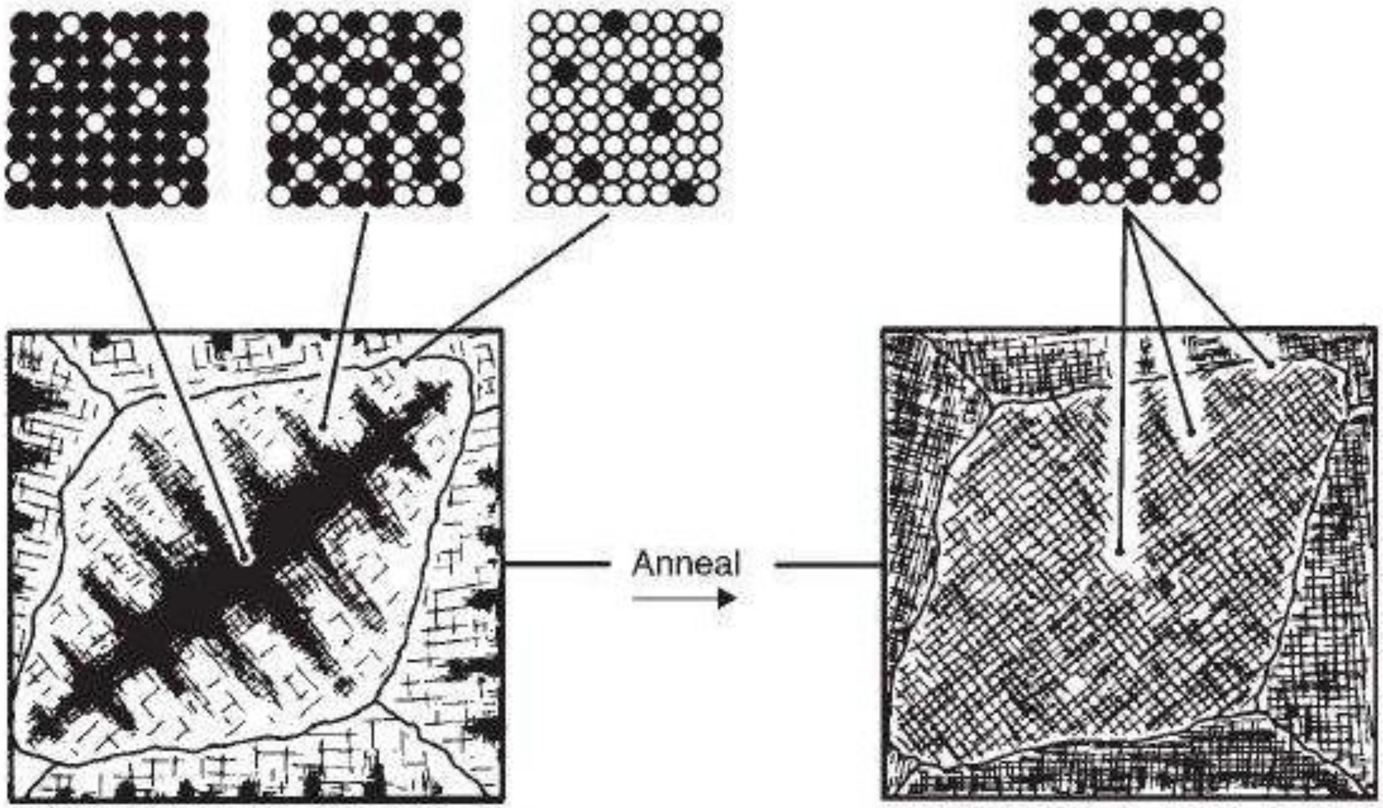


Figure 8.1 *The freezing-points (melting-points) of both bismuth and cadmium are depressed by adding each to the other. A minimum freezing-point – or 'eutectic point' – is produced.*



bismuth (Figure 8.2) until solidification is complete. The metallic layers in this eutectic structure are extremely thin, and a microscope with a magnification of at least 100 is generally necessary to be able to see the structure.

Figure 8.2 *If we had a microscope which gave a magnification of about ten million times, the arrangement of atoms of cadmium and bismuth would look something like that in the left-hand part of the diagram, except that the bands in the eutectic would each be many thousand atoms in width.*

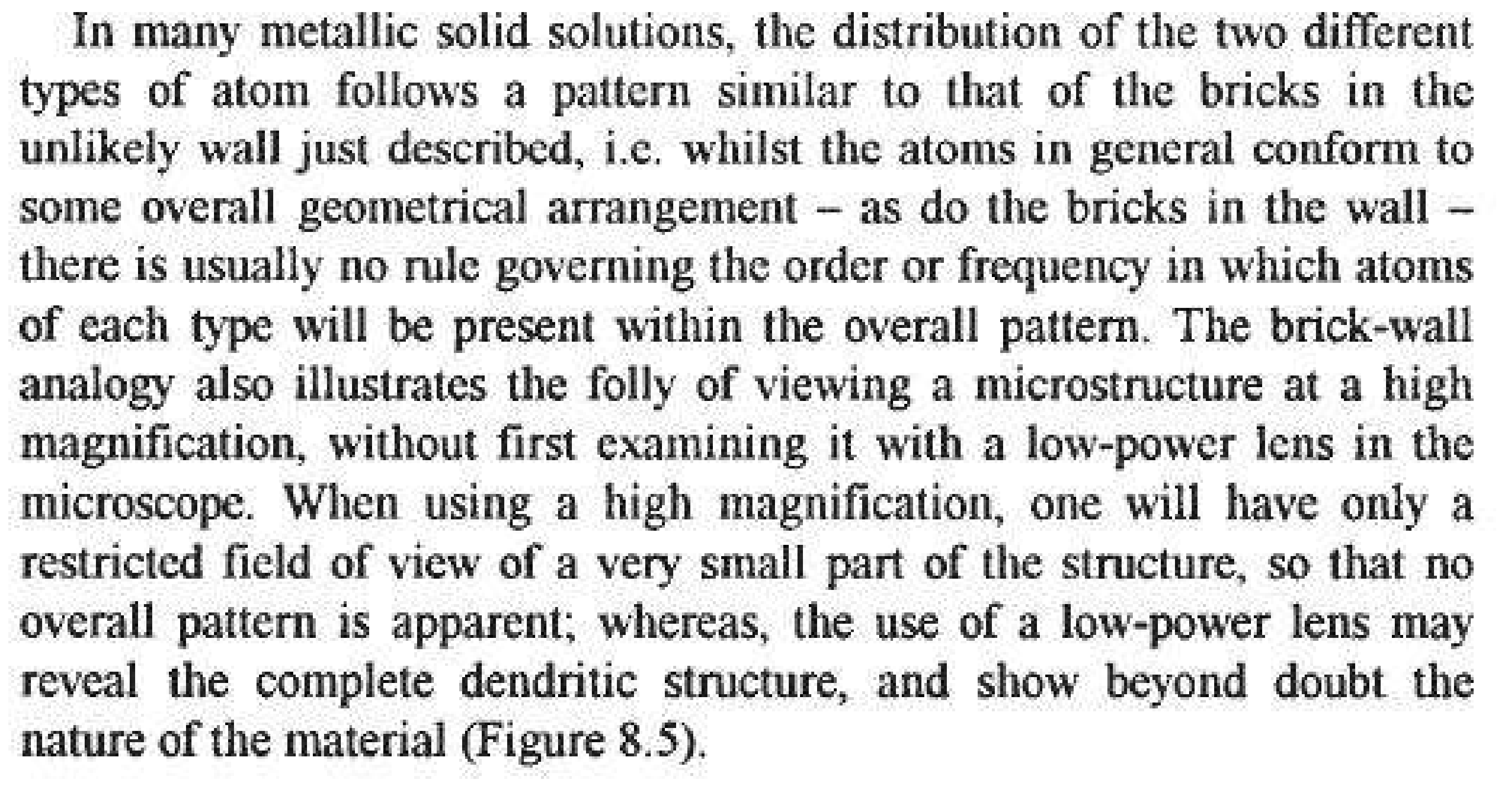


In the cast condition, the cores of the crystals contain more atoms of the metal with the higher melting-point. The outer fringes are therefore richer in atoms of the metal with the lower melting-point.

Annealing has resulted in diffusion so that atoms of both metals are now uniformly distributed throughout the crystal structure.

● Atoms of the metal with the higher melting-point
○ Atoms of the metal with the lower melting-point

Figure 8.3 *The variations in composition in a cored solid solution. The coring can be dispersed by annealing.*



In many metallic solid solutions, the distribution of the two different types of atom follows a pattern similar to that of the bricks in the unlikely wall just described, i.e. whilst the atoms in general conform to some overall geometrical arrangement – as do the bricks in the wall – there is usually no rule governing the order or frequency in which atoms of each type will be present within the overall pattern. The brick-wall analogy also illustrates the folly of viewing a microstructure at a high magnification, without first examining it with a low-power lens in the microscope. When using a high magnification, one will have only a restricted field of view of a very small part of the structure, so that no overall pattern is apparent; whereas, the use of a low-power lens may reveal the complete dendritic structure, and show beyond doubt the nature of the material (Figure 8.5).

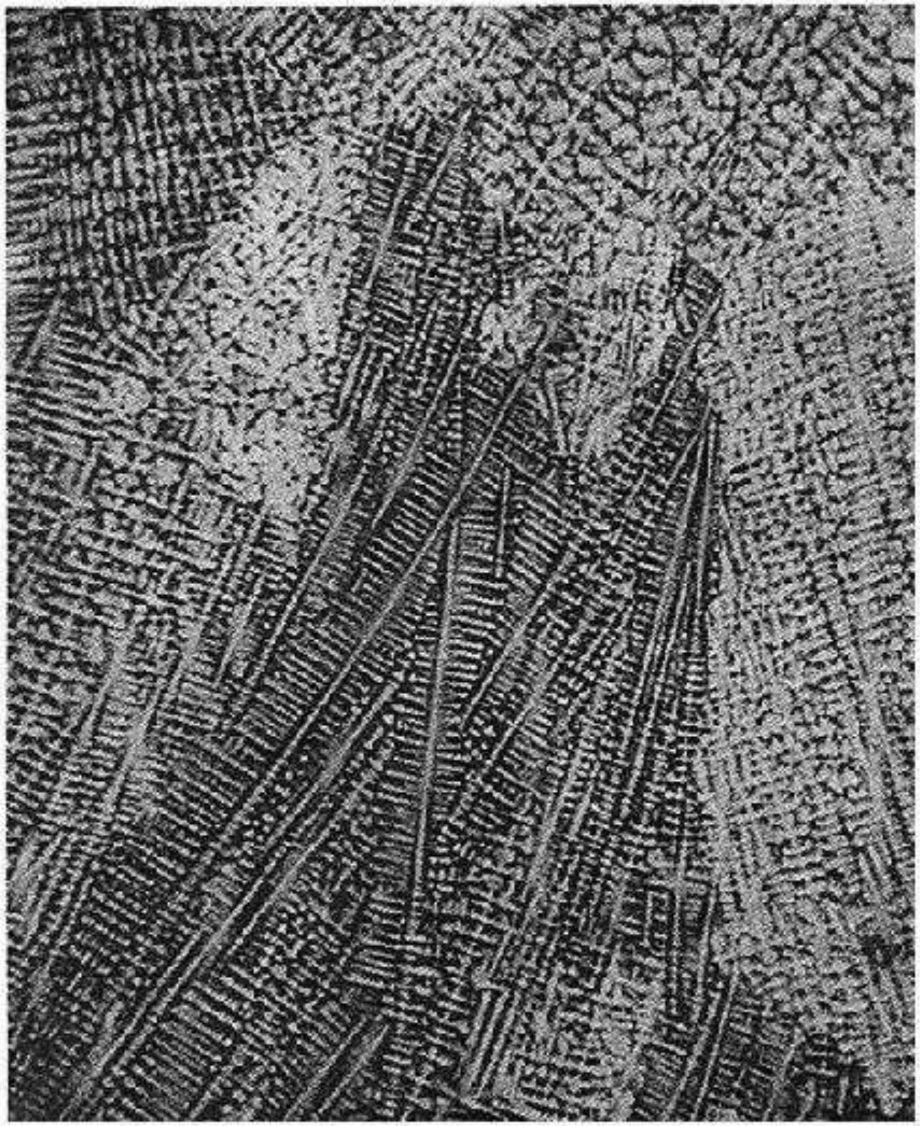
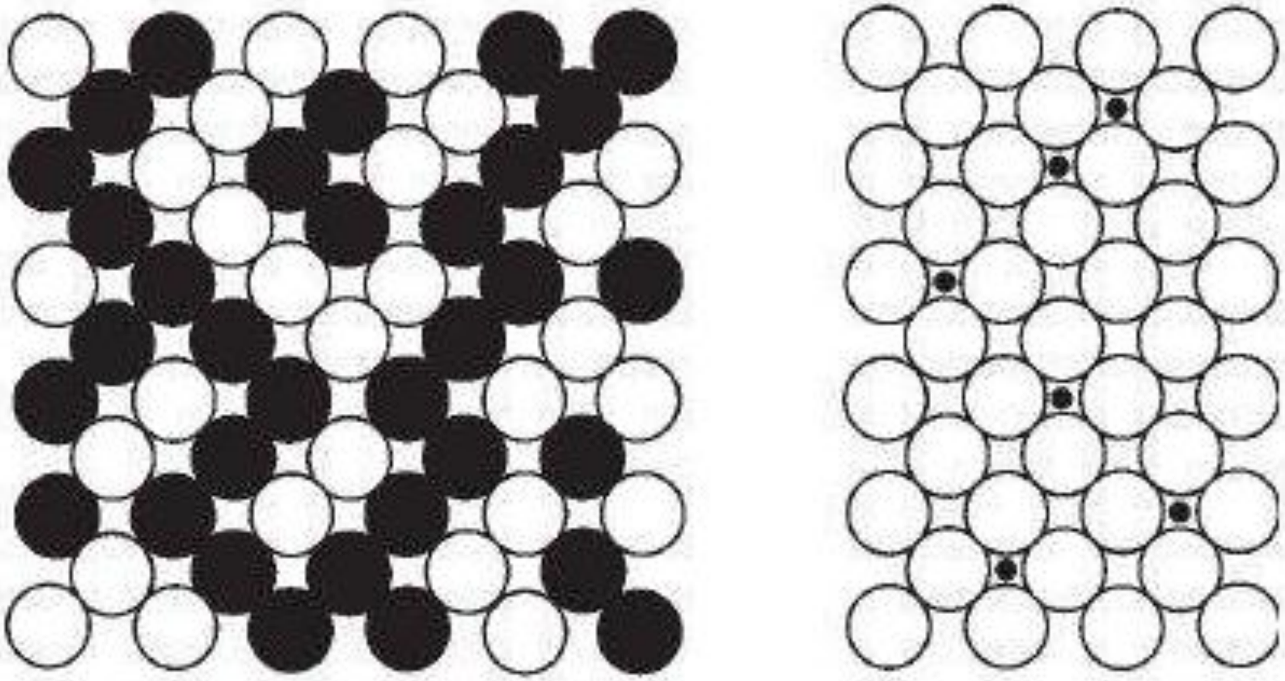


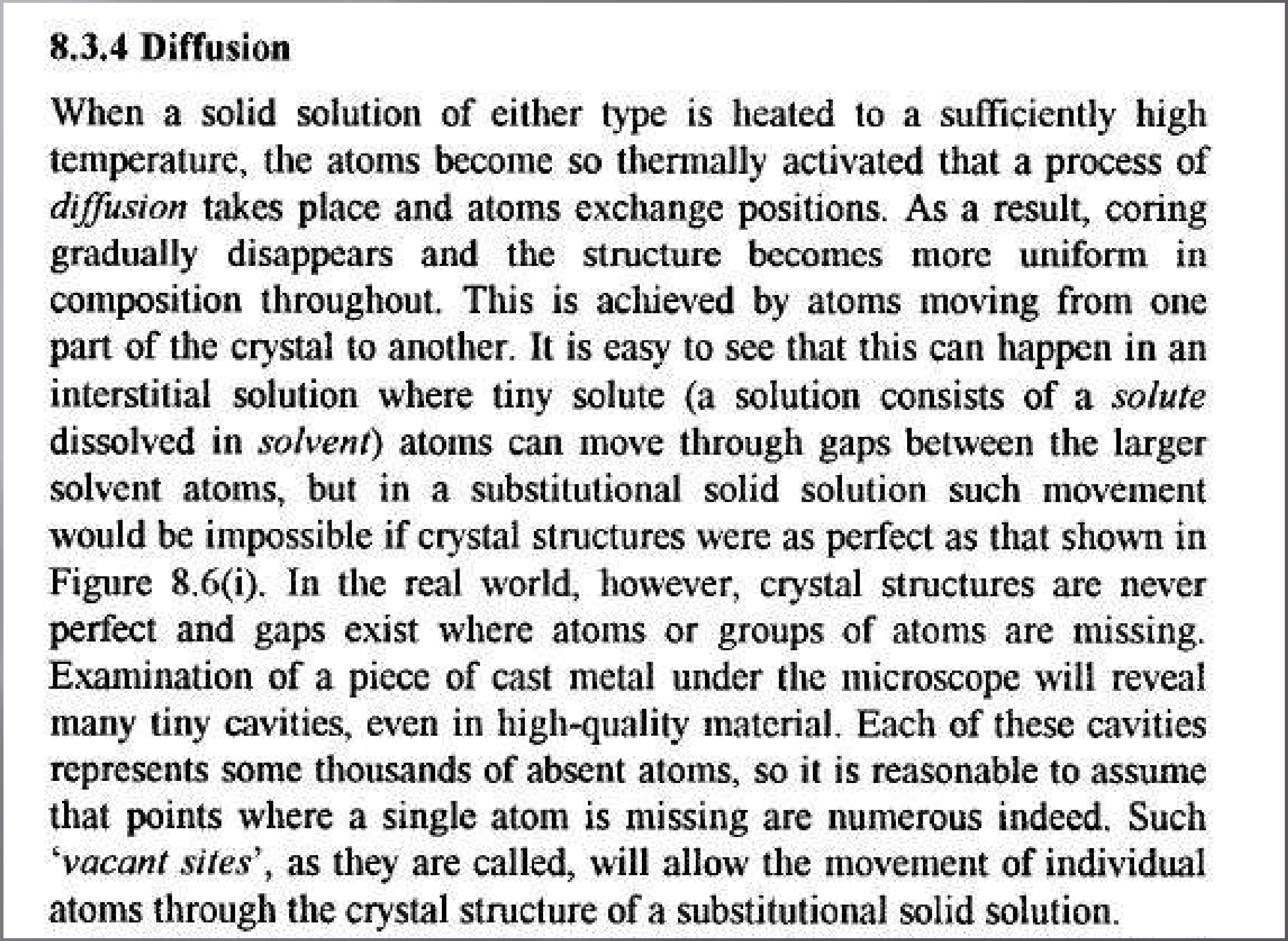
Figure 8.5 *The dendritic structure of a cast alloy. This is a photomicrograph of cast 70–30 brass at a magnification of ×39. The dendrites would not be visible were it not for the coring of the solid solution.*



(i) Substitutional

(ii) Interstitial

Figure 8.6 *The two main types of solid solution: (i) a substitutional solid solution, (ii) an interstitial solid solution.*



8.3.4 Diffusion

When a solid solution of either type is heated to a sufficiently high temperature, the atoms become so thermally activated that a process of *diffusion* takes place and atoms exchange positions. As a result, coring gradually disappears and the structure becomes more uniform in composition throughout. This is achieved by atoms moving from one part of the crystal to another. It is easy to see that this can happen in an interstitial solution where tiny solute (a solution consists of a *solute* dissolved in *solvent*) atoms can move through gaps between the larger solvent atoms, but in a substitutional solid solution such movement would be impossible if crystal structures were as perfect as that shown in Figure 8.6(i). In the real world, however, crystal structures are never perfect and gaps exist where atoms or groups of atoms are missing. Examination of a piece of cast metal under the microscope will reveal many tiny cavities, even in high-quality material. Each of these cavities represents some thousands of absent atoms, so it is reasonable to assume that points where a single atom is missing are numerous indeed. Such '*vacant sites*', as they are called, will allow the movement of individual atoms through the crystal structure of a substitutional solid solution.

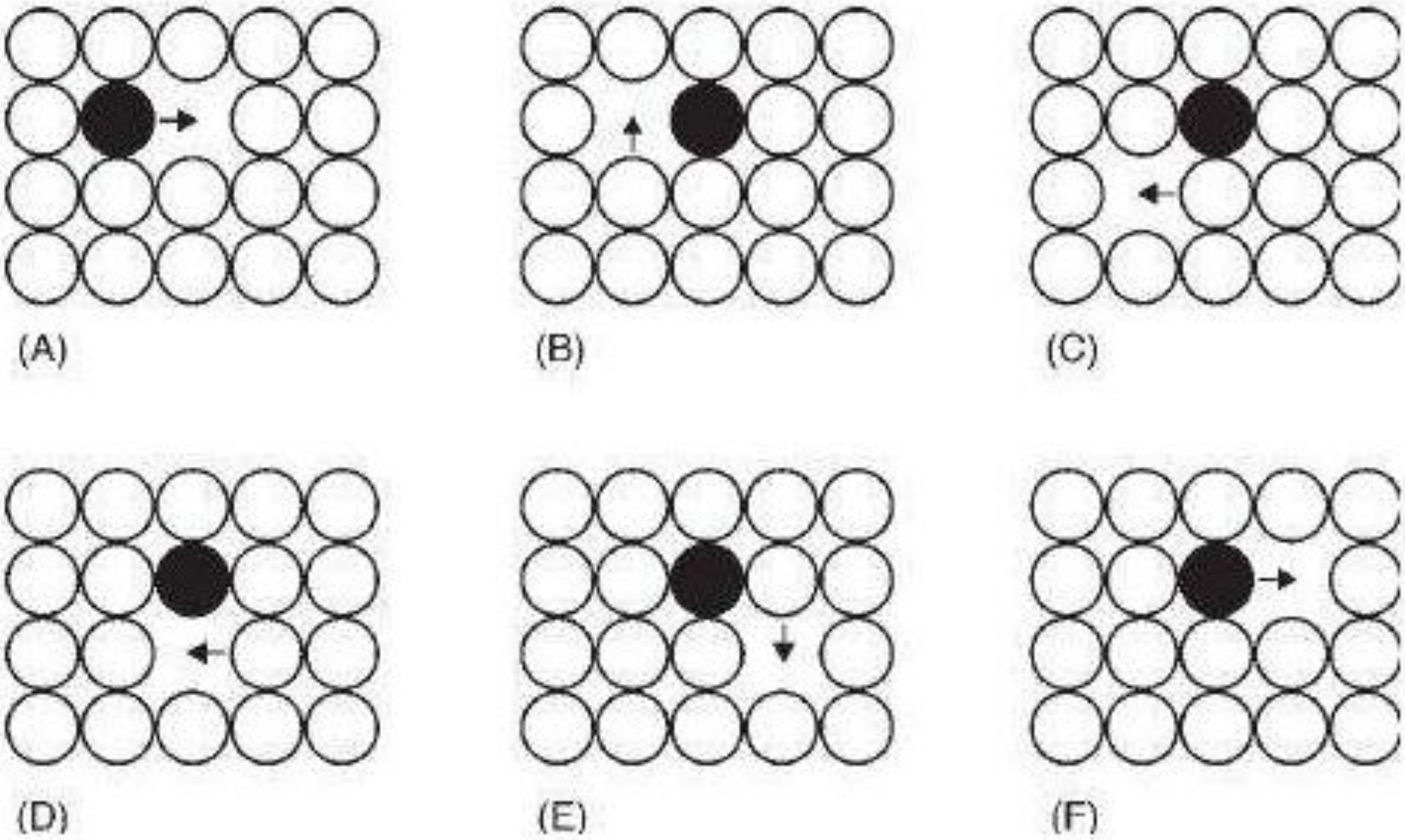
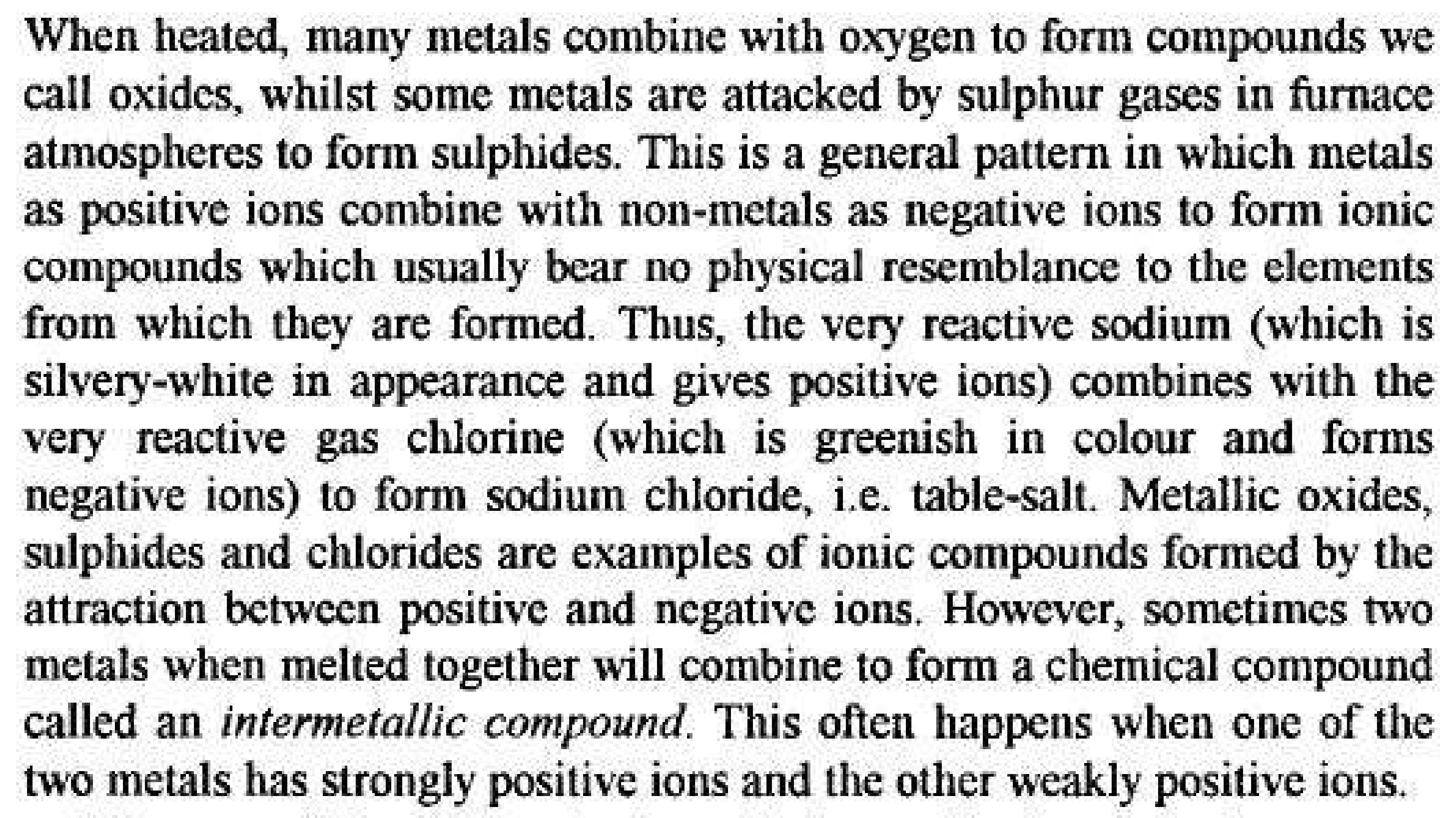


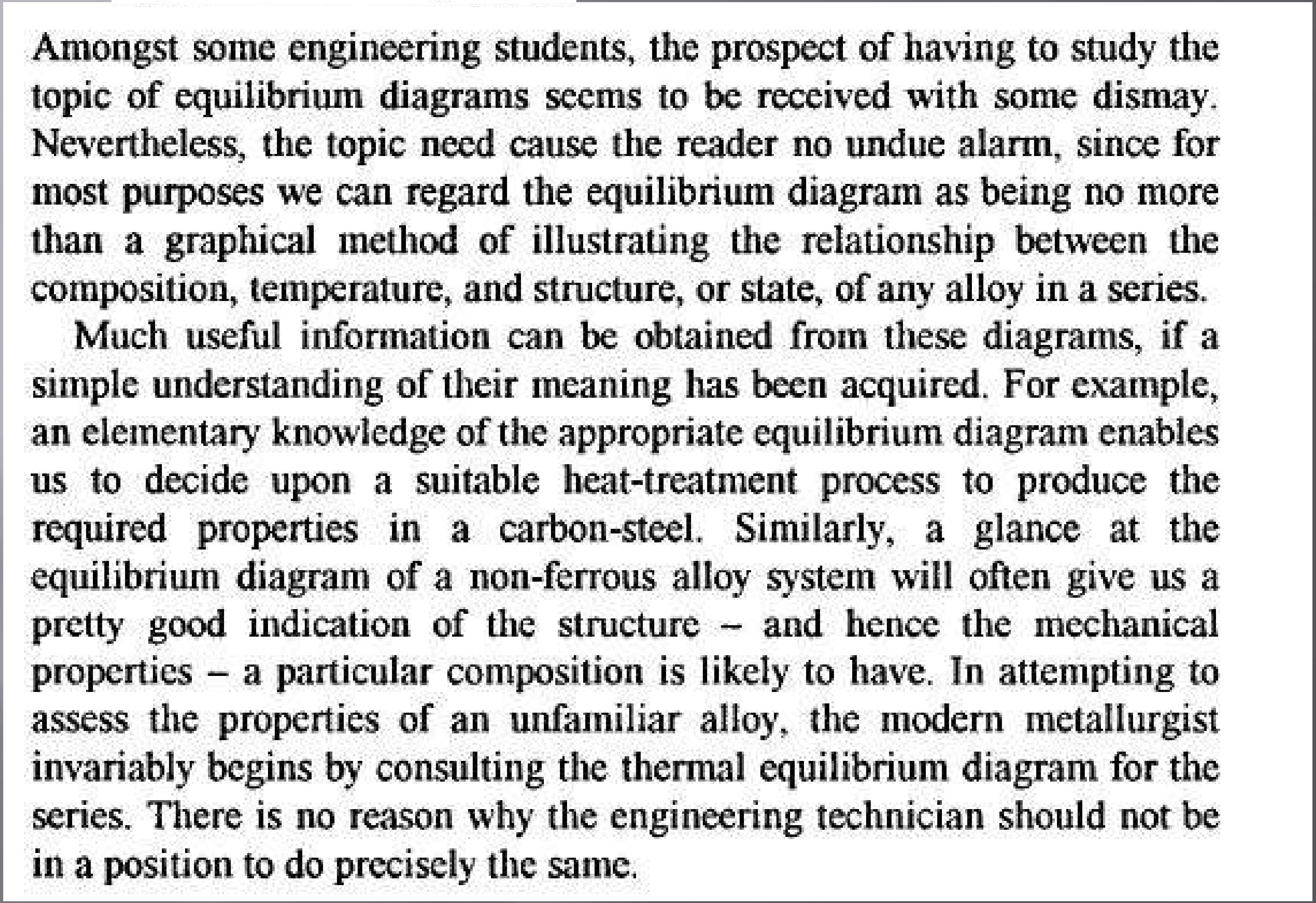
Figure 8.7 *This is the way in which metallurgists believe diffusion takes place in a solid solution. A series of five 'moves' is necessary in order that the 'black' atom (and an accompanying 'vacant site') can go forward by one space.*

Intermetallic compounds



When heated, many metals combine with oxygen to form compounds we call oxides, whilst some metals are attacked by sulphur gases in furnace atmospheres to form sulphides. This is a general pattern in which metals as positive ions combine with non-metals as negative ions to form ionic compounds which usually bear no physical resemblance to the elements from which they are formed. Thus, the very reactive sodium (which is silvery-white in appearance and gives positive ions) combines with the very reactive gas chlorine (which is greenish in colour and forms negative ions) to form sodium chloride, i.e. table-salt. Metallic oxides, sulphides and chlorides are examples of ionic compounds formed by the attraction between positive and negative ions. However, sometimes two metals when melted together will combine to form a chemical compound called an *intermetallic compound*. This often happens when one of the two metals has strongly positive ions and the other weakly positive ions.

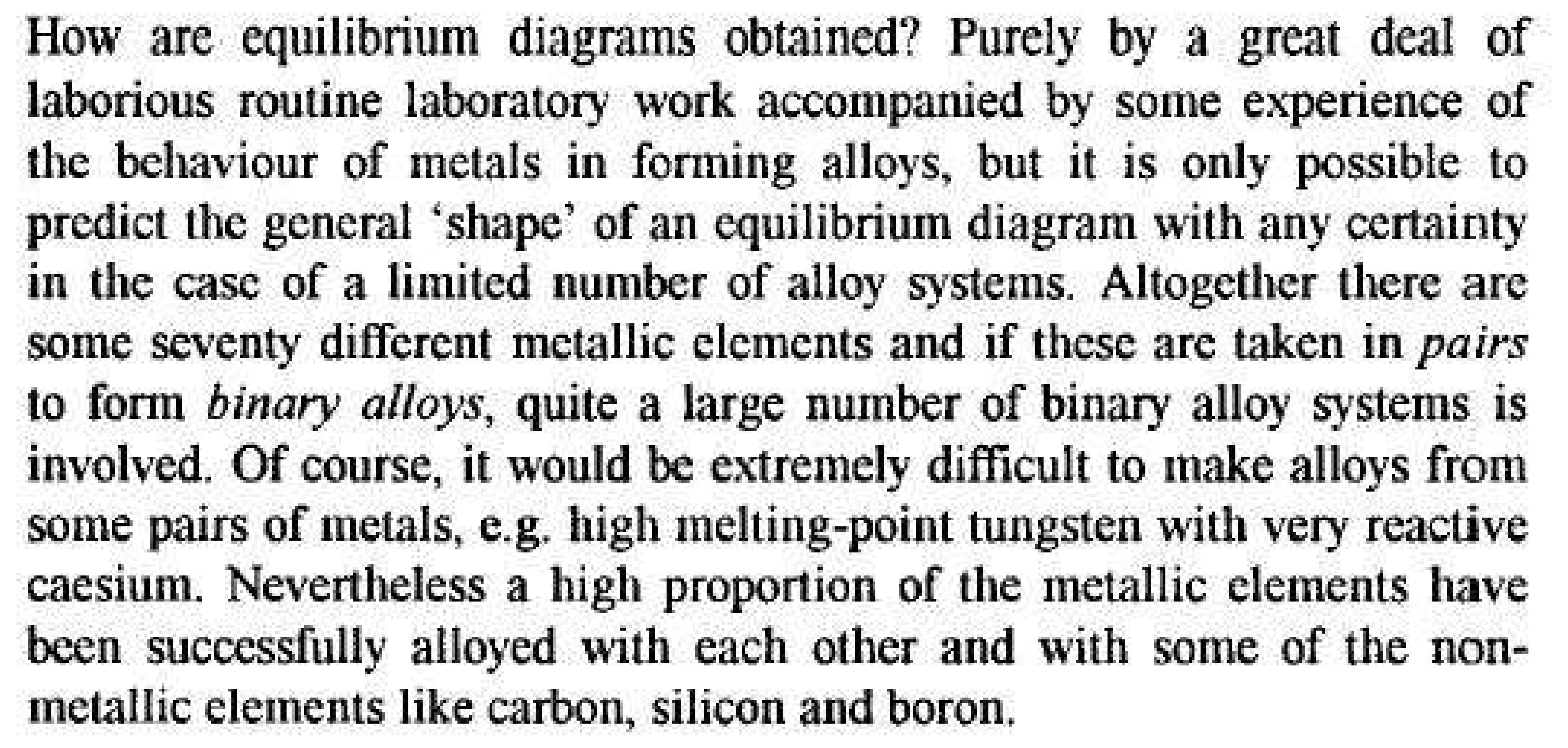
Equilibrium diagrams



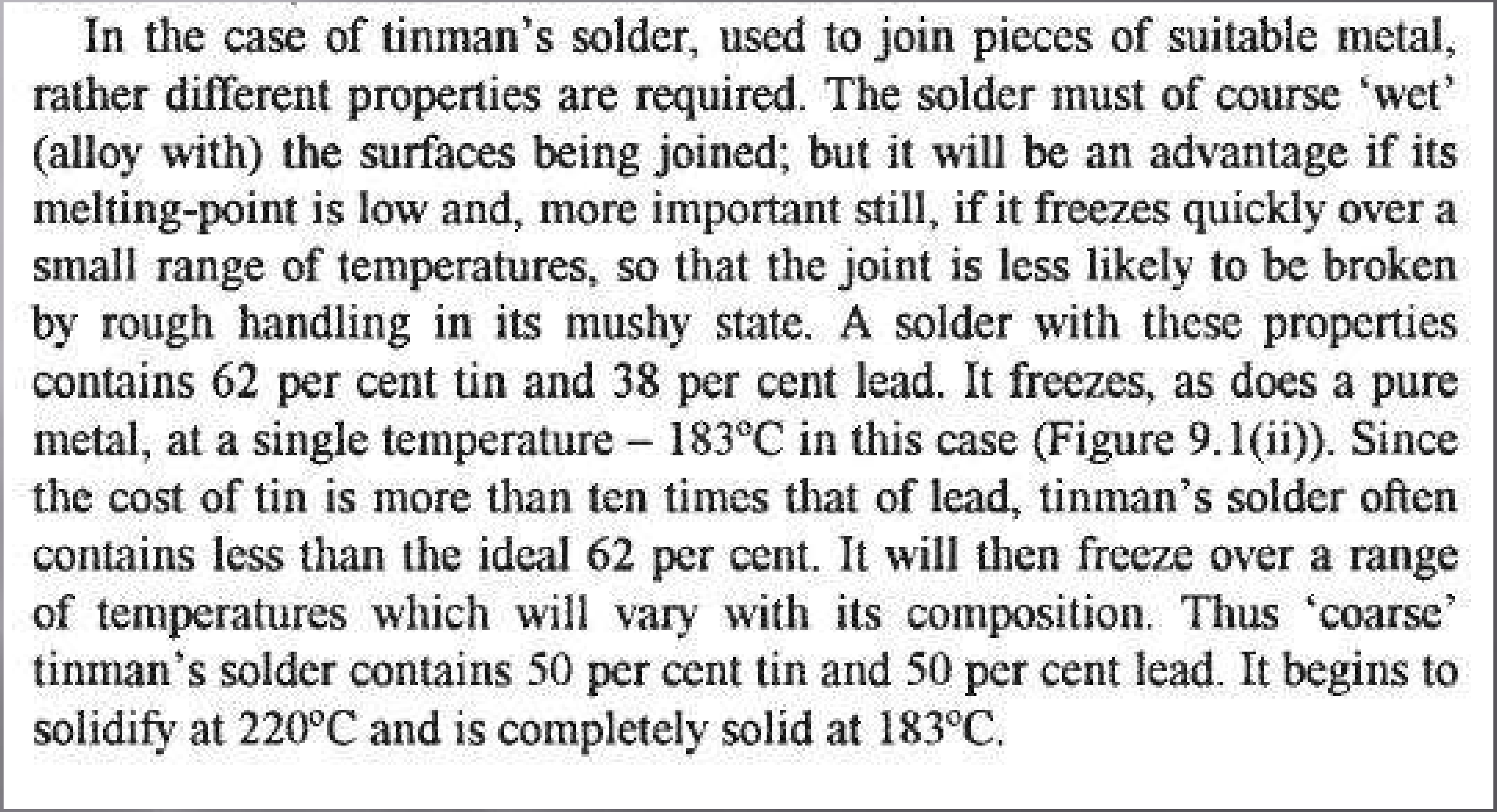
Amongst some engineering students, the prospect of having to study the topic of equilibrium diagrams seems to be received with some dismay. Nevertheless, the topic need cause the reader no undue alarm, since for most purposes we can regard the equilibrium diagram as being no more than a graphical method of illustrating the relationship between the composition, temperature, and structure, or state, of any alloy in a series.

Much useful information can be obtained from these diagrams, if a simple understanding of their meaning has been acquired. For example, an elementary knowledge of the appropriate equilibrium diagram enables us to decide upon a suitable heat-treatment process to produce the required properties in a carbon-steel. Similarly, a glance at the equilibrium diagram of a non-ferrous alloy system will often give us a pretty good indication of the structure – and hence the mechanical properties – a particular composition is likely to have. In attempting to assess the properties of an unfamiliar alloy, the modern metallurgist invariably begins by consulting the thermal equilibrium diagram for the series. There is no reason why the engineering technician should not be in a position to do precisely the same.

Obtaining equilibrium diagrams



How are equilibrium diagrams obtained? Purely by a great deal of laborious routine laboratory work accompanied by some experience of the behaviour of metals in forming alloys, but it is only possible to predict the general 'shape' of an equilibrium diagram with any certainty in the case of a limited number of alloy systems. Altogether there are some seventy different metallic elements and if these are taken in *pairs* to form *binary alloys*, quite a large number of binary alloy systems is involved. Of course, it would be extremely difficult to make alloys from some pairs of metals, e.g. high melting-point tungsten with very reactive caesium. Nevertheless a high proportion of the metallic elements have been successfully alloyed with each other and with some of the non-metallic elements like carbon, silicon and boron.



In the case of tinman's solder, used to join pieces of suitable metal, rather different properties are required. The solder must of course 'wet' (alloy with) the surfaces being joined; but it will be an advantage if its melting-point is low and, more important still, if it freezes quickly over a small range of temperatures, so that the joint is less likely to be broken by rough handling in its mushy state. A solder with these properties contains 62 per cent tin and 38 per cent lead. It freezes, as does a pure metal, at a single temperature – 183°C in this case (Figure 9.1(ii)). Since the cost of tin is more than ten times that of lead, tinman's solder often contains less than the ideal 62 per cent. It will then freeze over a range of temperatures which will vary with its composition. Thus 'coarse' tinman's solder contains 50 per cent tin and 50 per cent lead. It begins to solidify at 220°C and is completely solid at 183°C.

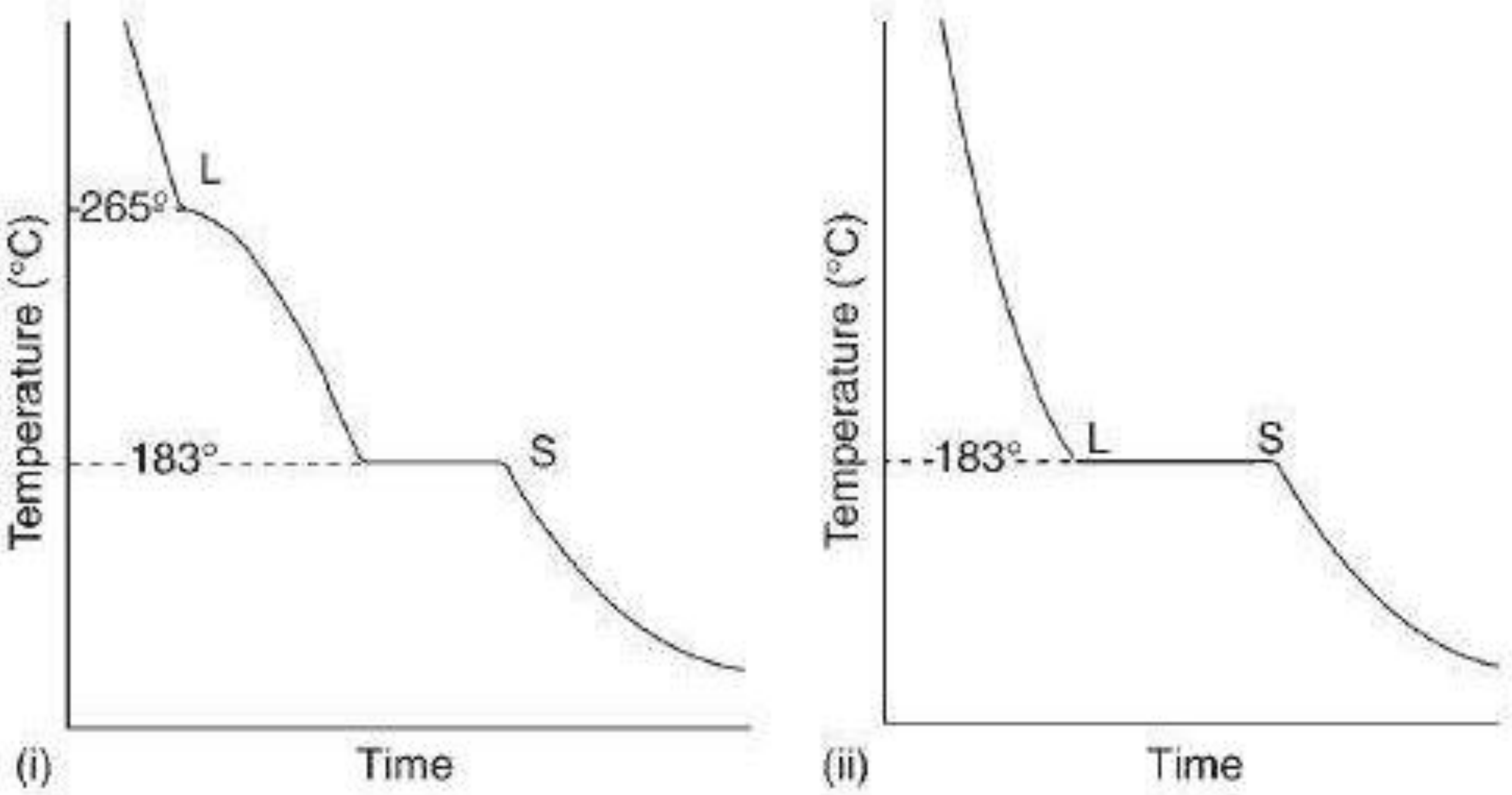


Figure 9.1 *Cooling curves for plumber's solder and for tinman's solder.*

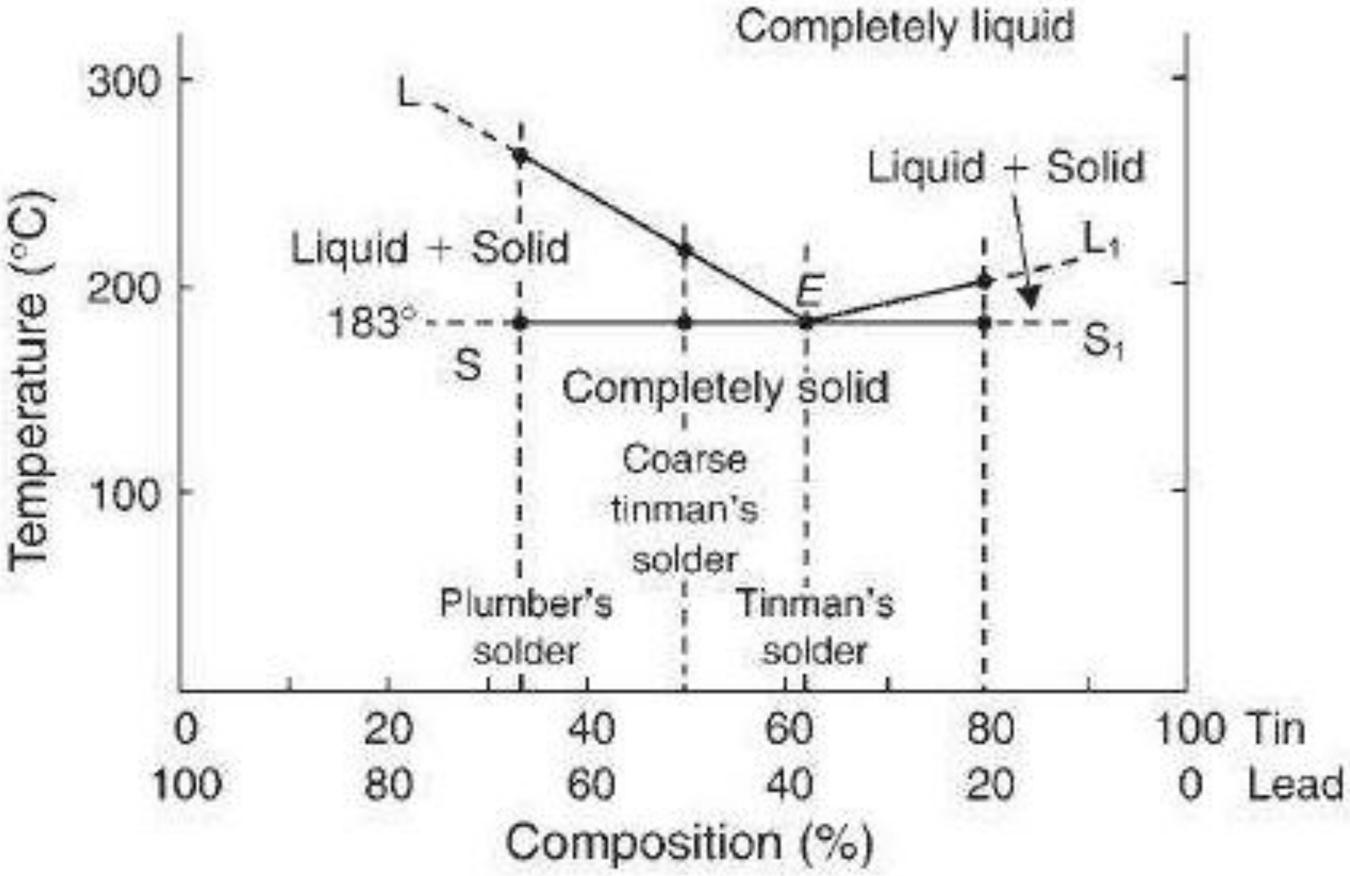
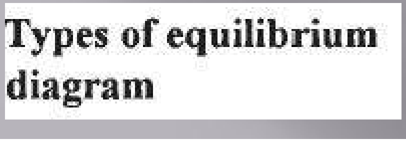
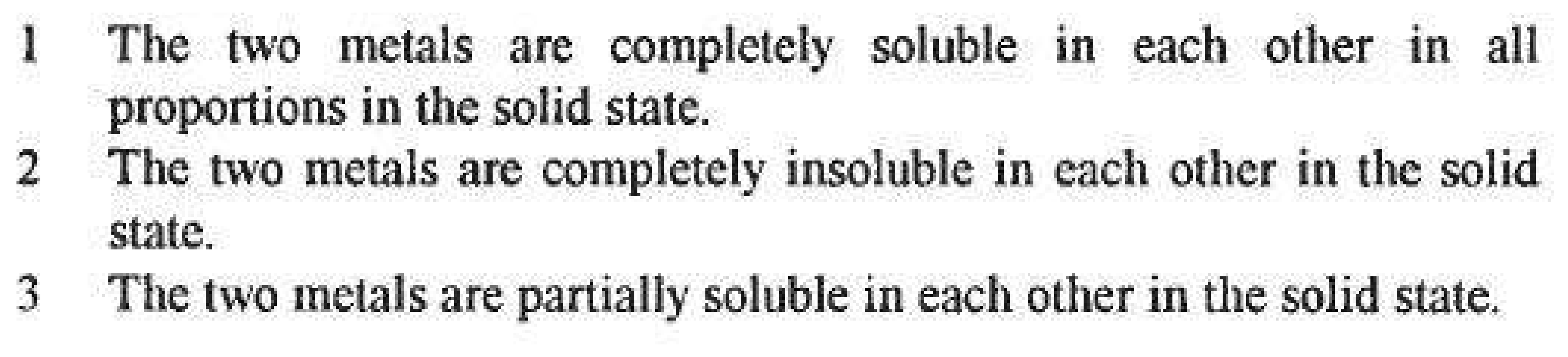


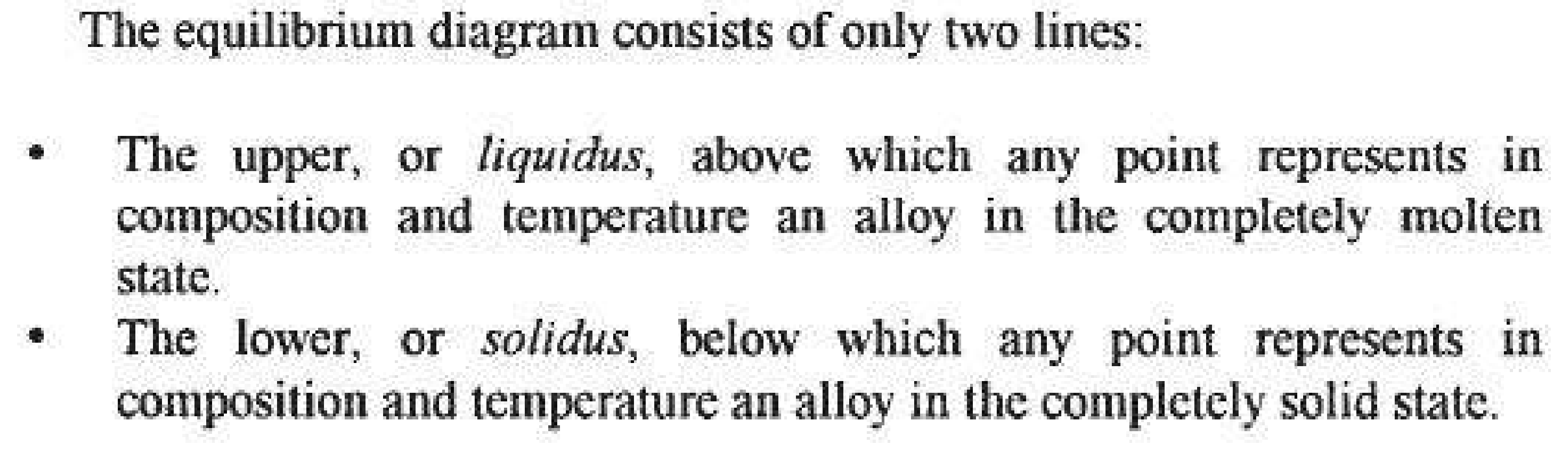
Figure 9.3 *Part of the lead-tin equilibrium diagram. The limited information obtained from the cooling curves mentioned enables us to construct only so much of the diagram.*



Types of equilibrium diagram



1 The two metals are completely soluble in each other in all proportions in the solid state.
2 The two metals are completely insoluble in each other in the solid state.
3 The two metals are partially soluble in each other in the solid state.



The equilibrium diagram consists of only two lines:

- The upper, or *liquidus*, above which any point represents in composition and temperature an alloy in the completely molten state.
- The lower, or *solidus*, below which any point represents in composition and temperature an alloy in the completely solid state.

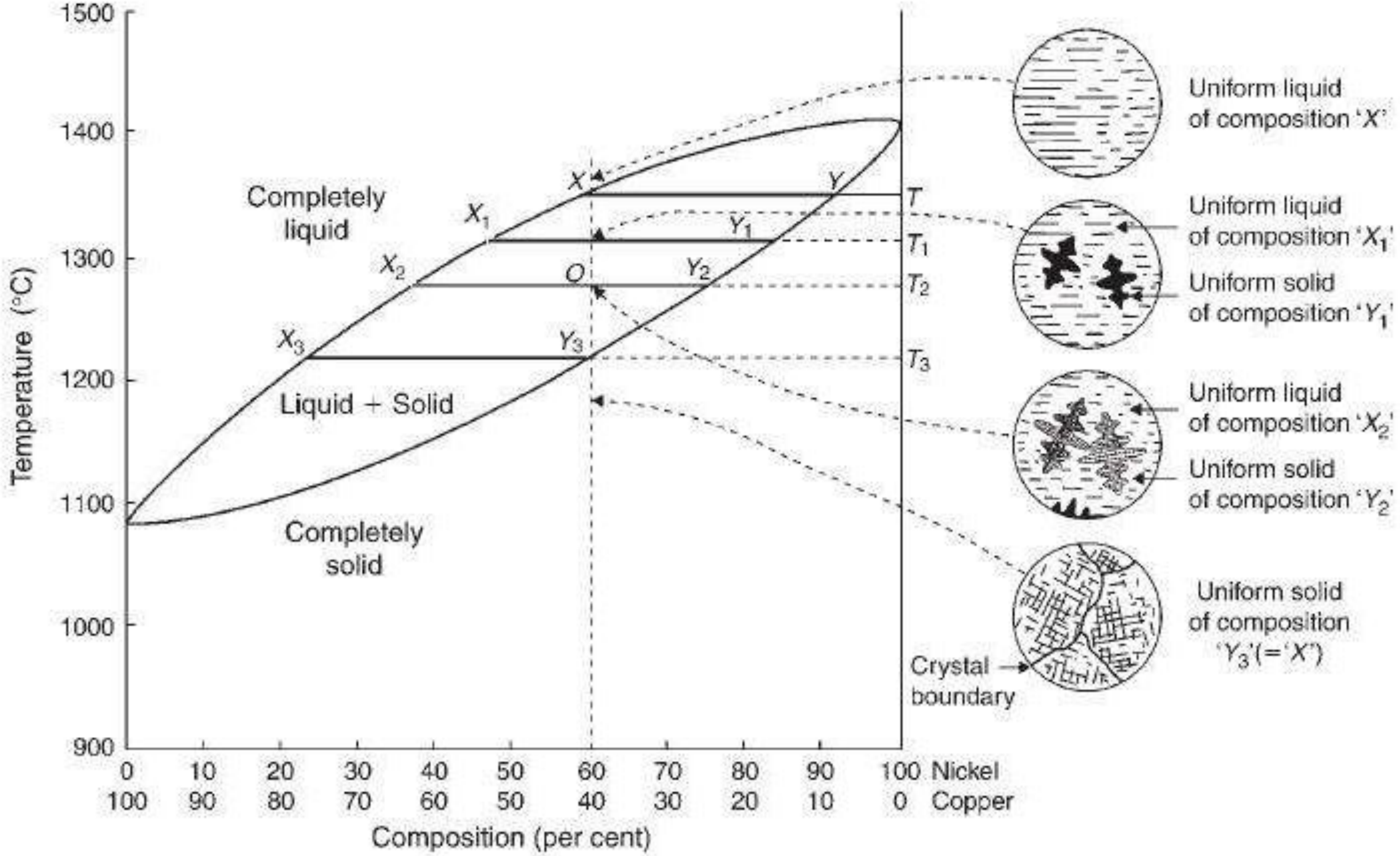
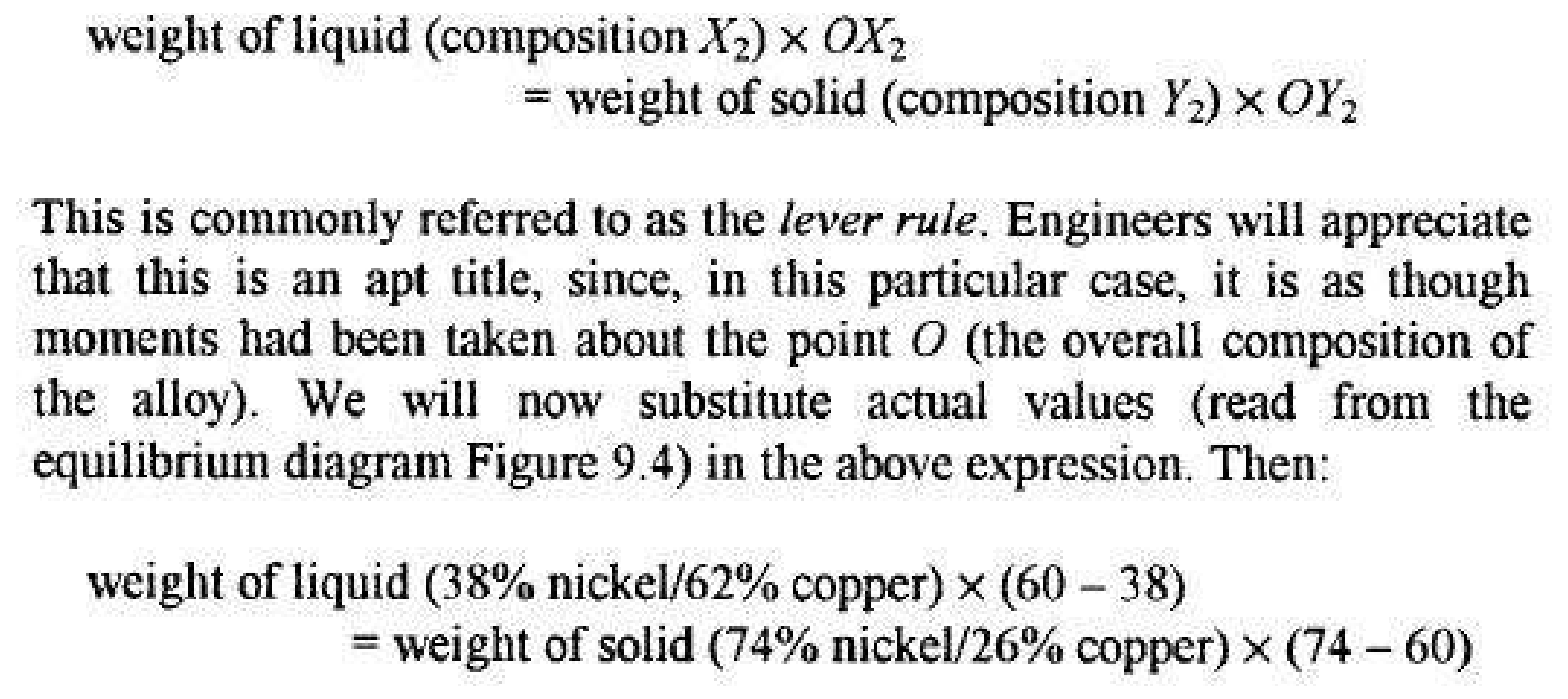


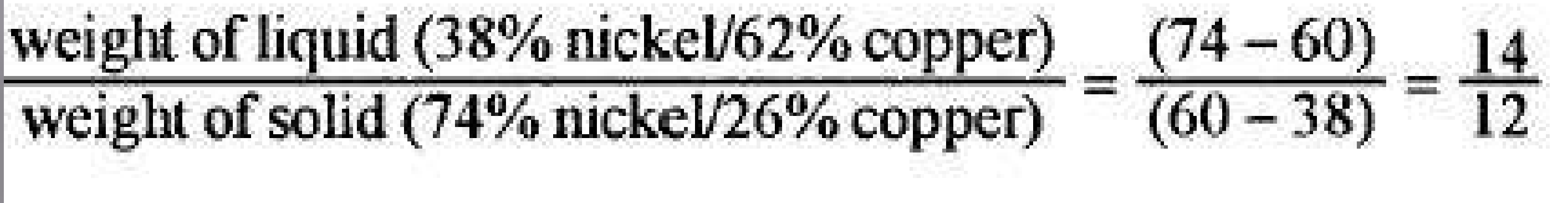
Figure 9.4 *The nickel-copper thermal equilibrium diagram. The solidification of an alloy under conditions of equilibrium (slow cooling) is illustrated.*



$$\text{weight of liquid (composition } X_2) \times OX_2 = \text{weight of solid (composition } Y_2) \times OY_2$$

This is commonly referred to as the *lever rule*. Engineers will appreciate that this is an apt title, since, in this particular case, it is as though moments had been taken about the point O (the overall composition of the alloy). We will now substitute actual values (read from the equilibrium diagram Figure 9.4) in the above expression. Then:

$$\text{weight of liquid (38\% nickel/62\% copper)} \times (60 - 38) = \text{weight of solid (74\% nickel/26\% copper)} \times (74 - 60)$$



$$\frac{\text{weight of liquid (38\% nickel/62\% copper)}}{\text{weight of solid (74\% nickel/26\% copper)}} = \frac{(74 - 60)}{(60 - 38)} = \frac{14}{12}$$

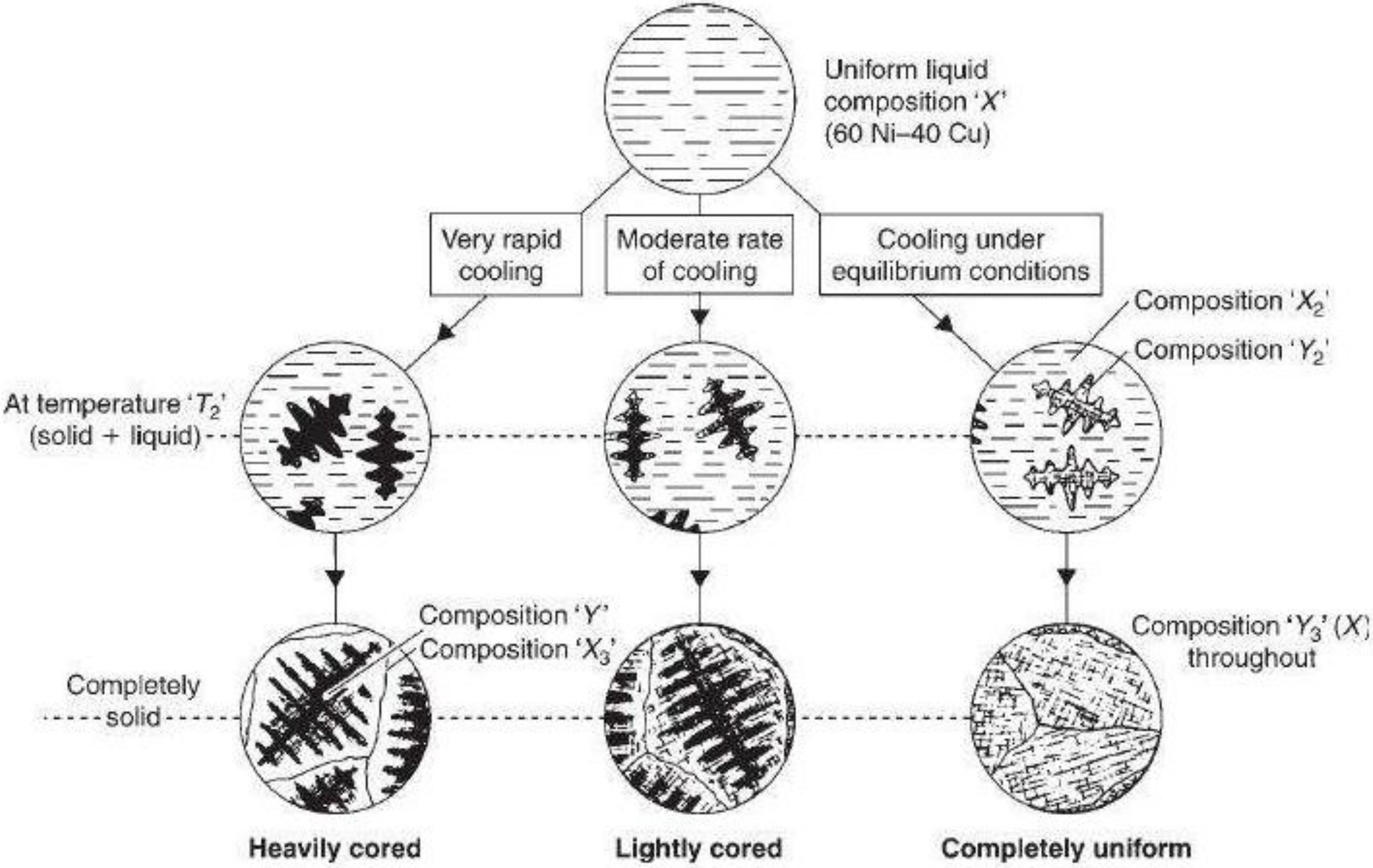


Figure 9.5 *Illustrating the effects of cooling-rate on the extent of coring in the 60 per cent nickel/40 per cent copper alloy dealt with above.*

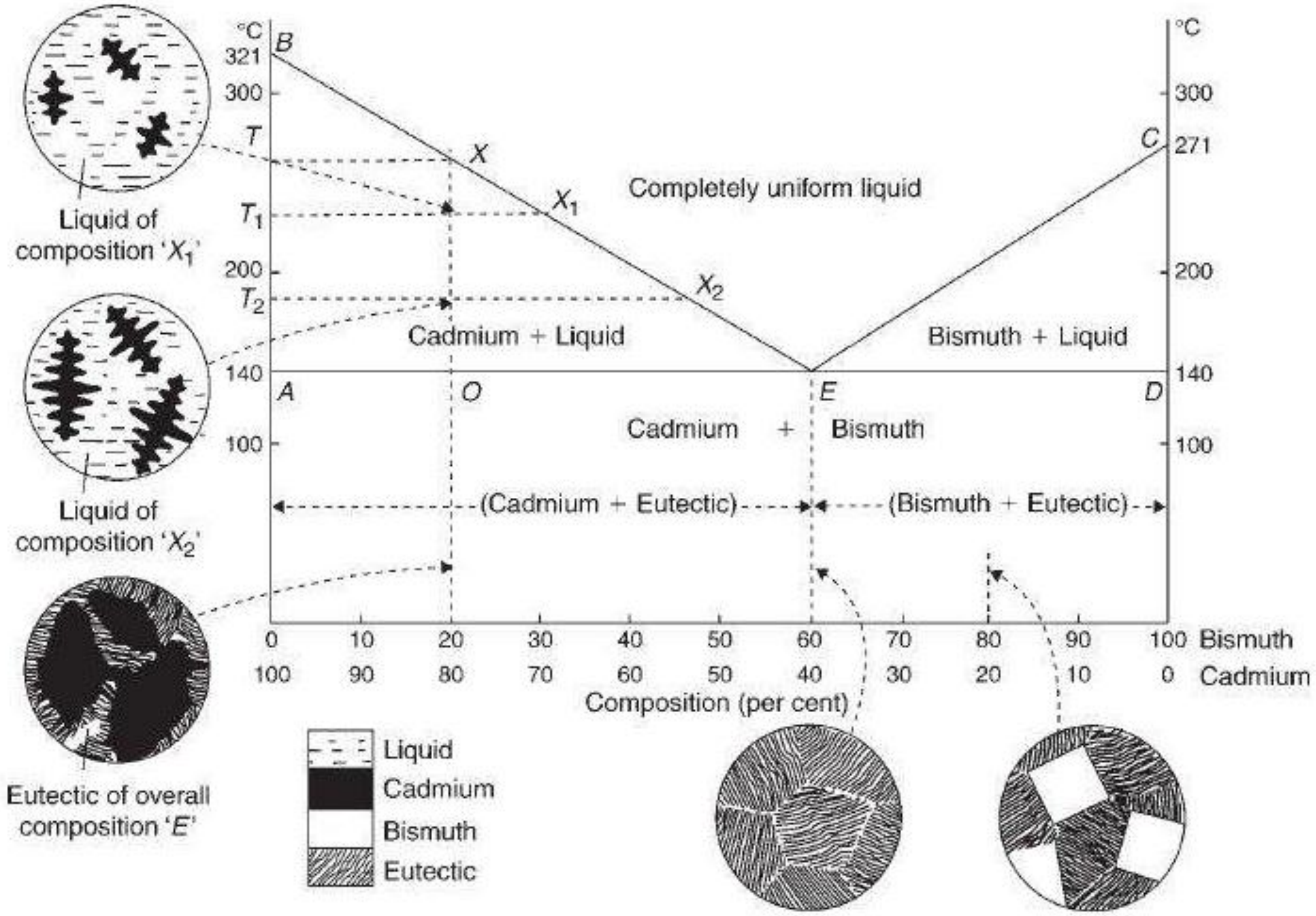
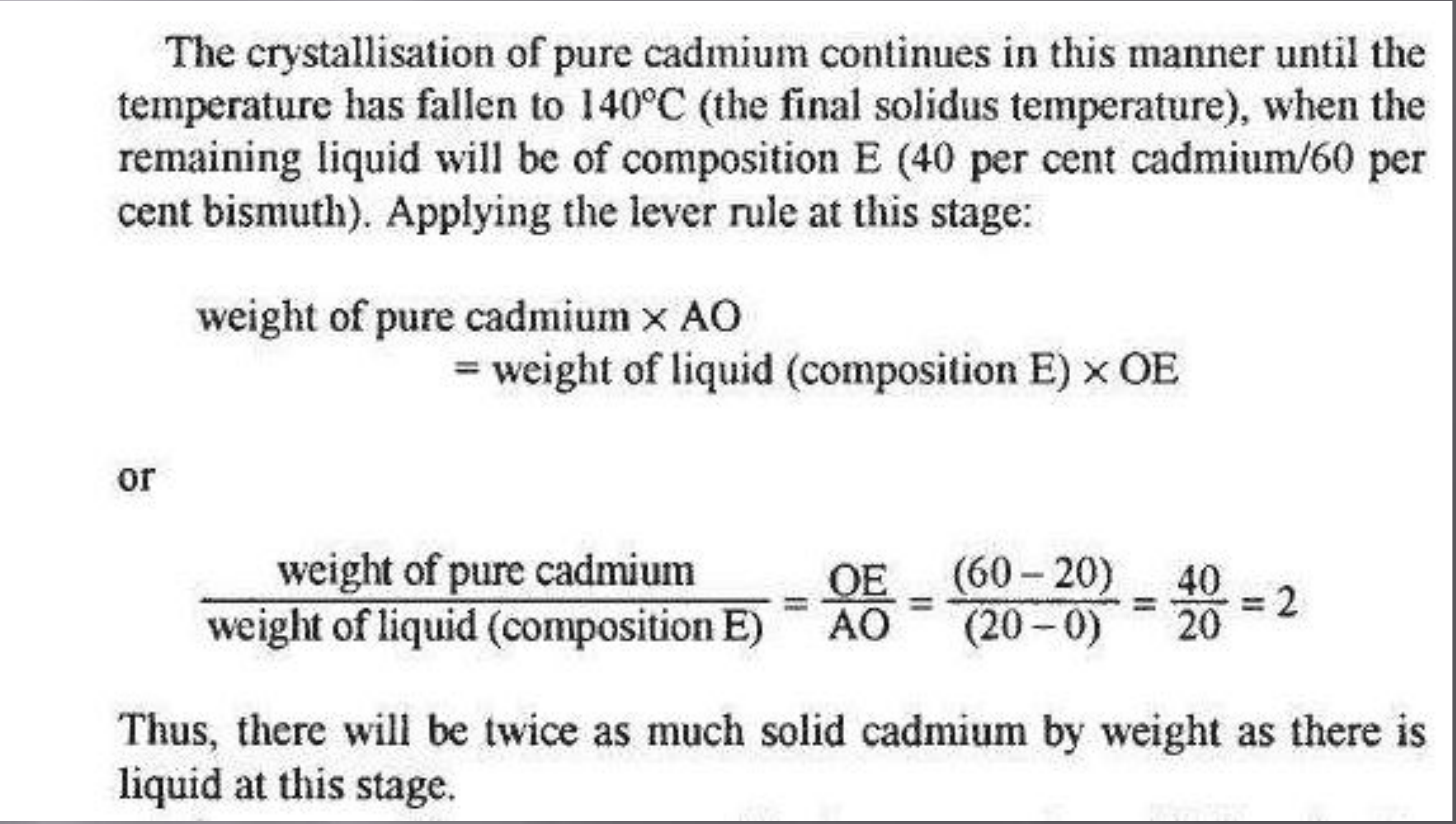


Figure 9.6 *The cadmium-bismuth thermal equilibrium diagram.*



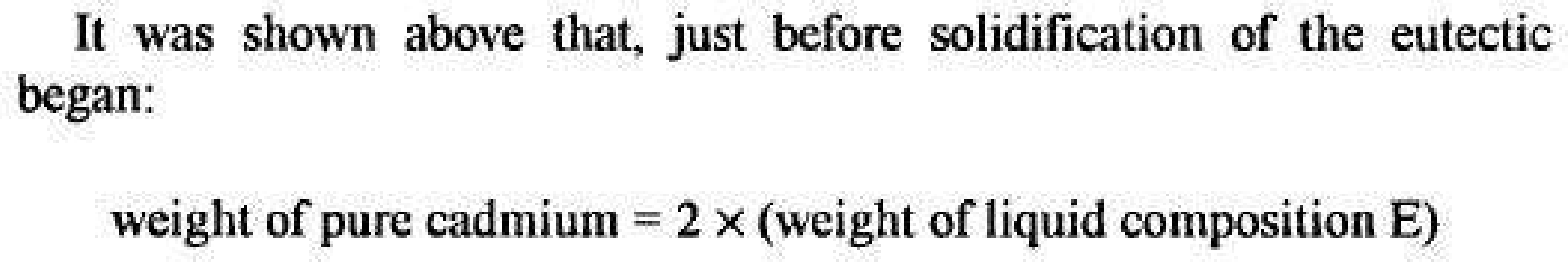
The crystallisation of pure cadmium continues in this manner until the temperature has fallen to 140°C (the final solidus temperature), when the remaining liquid will be of composition E (40 per cent cadmium/60 per cent bismuth). Applying the lever rule at this stage:

$$\text{weight of pure cadmium} \times \text{AO} = \text{weight of liquid (composition E)} \times \text{OE}$$

or

$$\frac{\text{weight of pure cadmium}}{\text{weight of liquid (composition E)}} = \frac{\text{OE}}{\text{AO}} = \frac{(60-20)}{(20-0)} = \frac{40}{20} = 2$$

Thus, there will be twice as much solid cadmium by weight as there is liquid at this stage.



It was shown above that, just before solidification of the eutectic began:

$$\text{weight of pure cadmium} = 2 \times (\text{weight of liquid composition E})$$

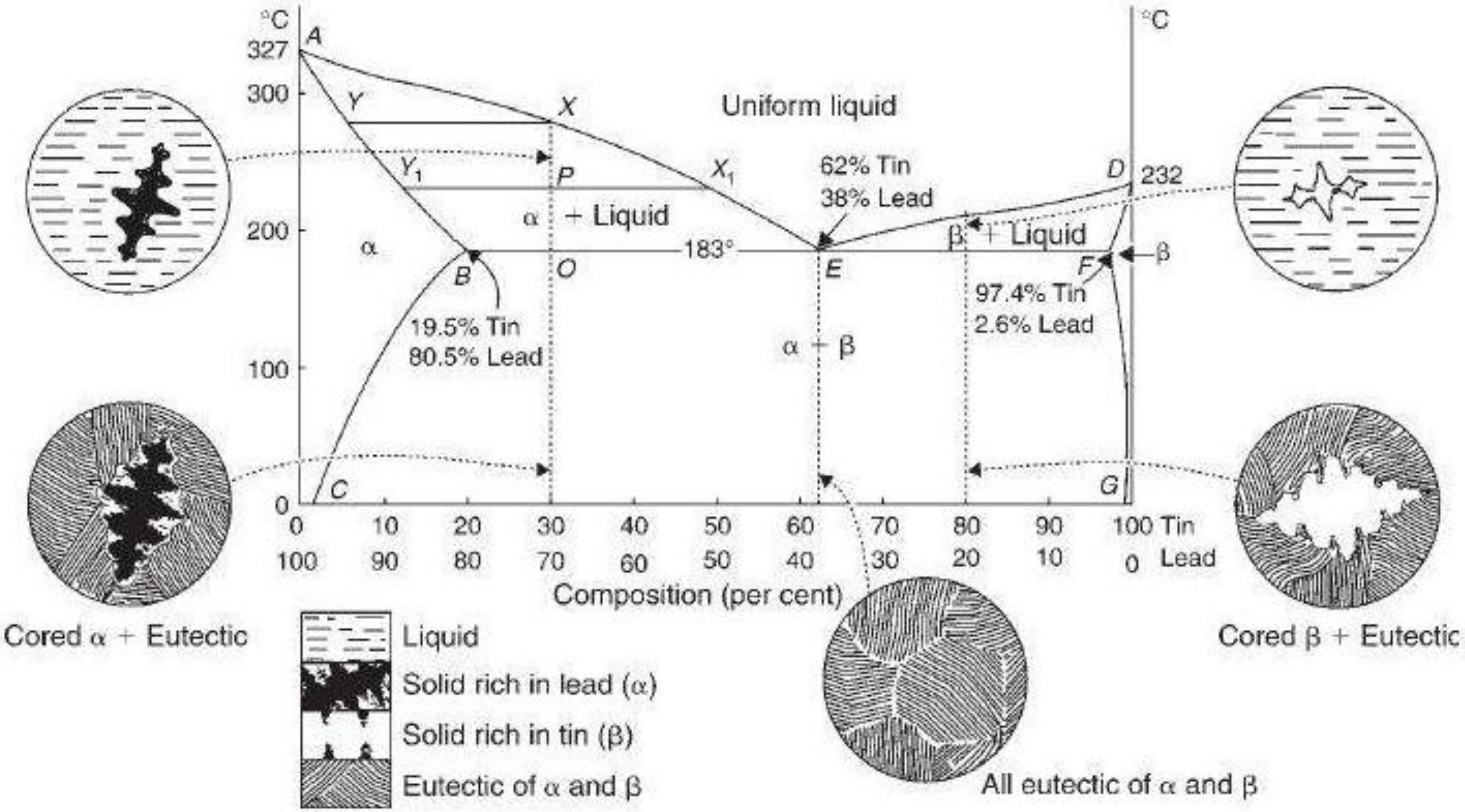


Figure 9.7 *The lead-tin thermal equilibrium diagram, showing the effects of rapid cooling on representative microstructures.*

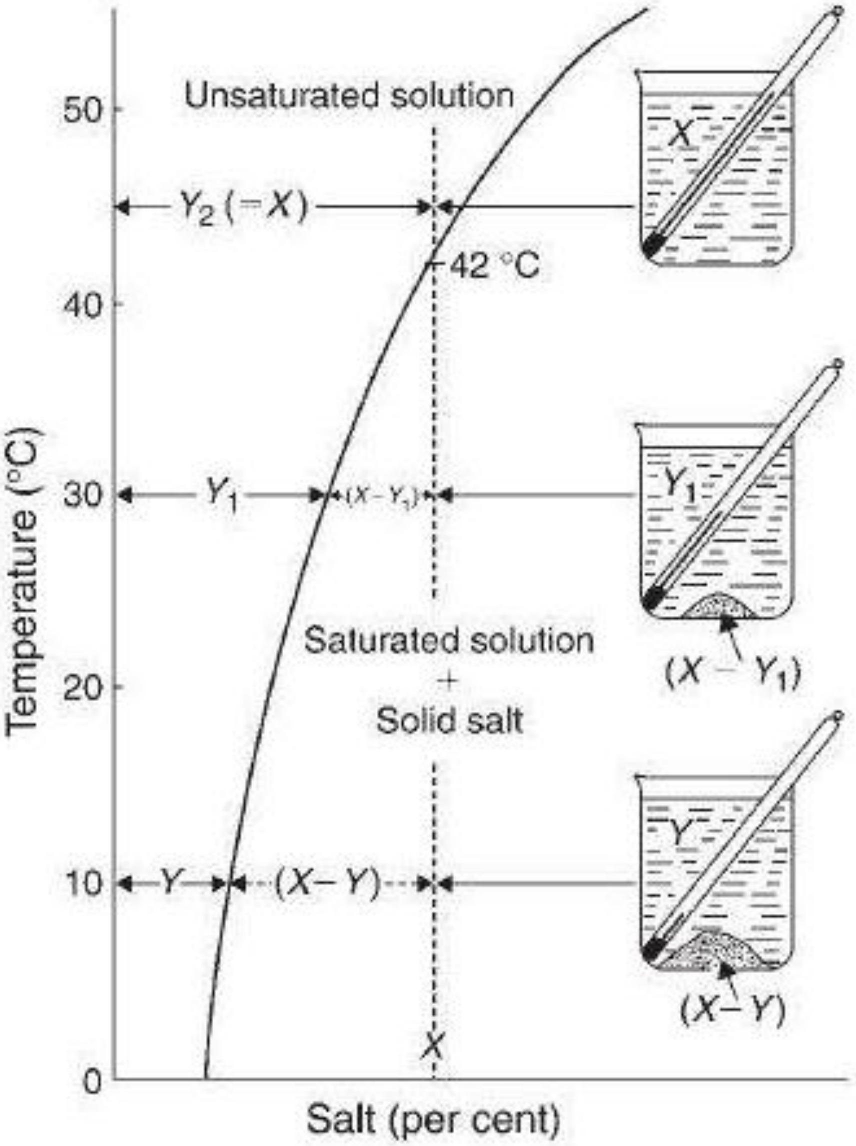


Figure 9.8 *The solubility curve for salt in water. Solubility increases as the temperature increases.*

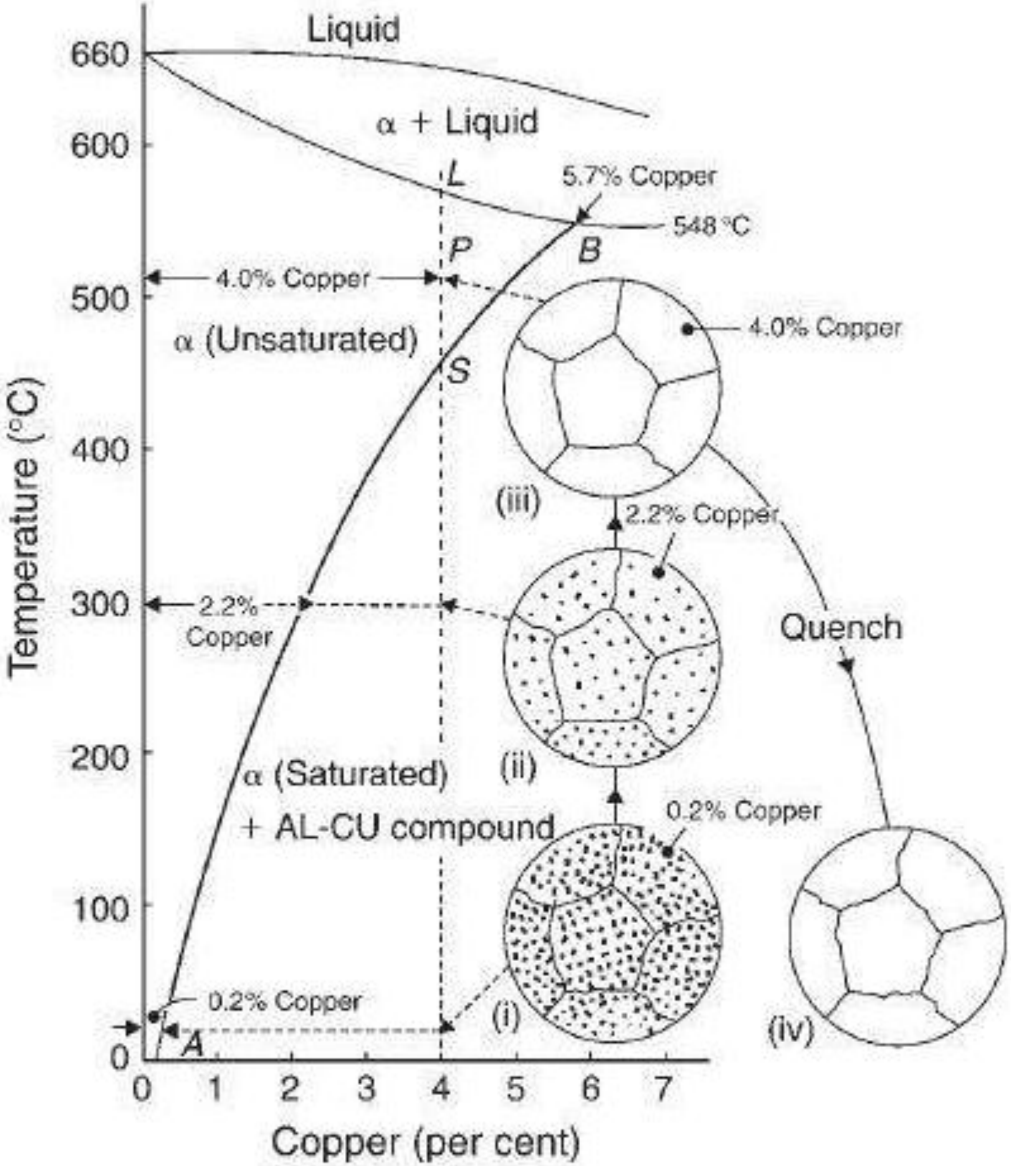


Figure 9.9 *The solubility curve for copper in aluminium. This is the aluminium-rich end of the aluminium-copper thermal equilibrium diagram.*

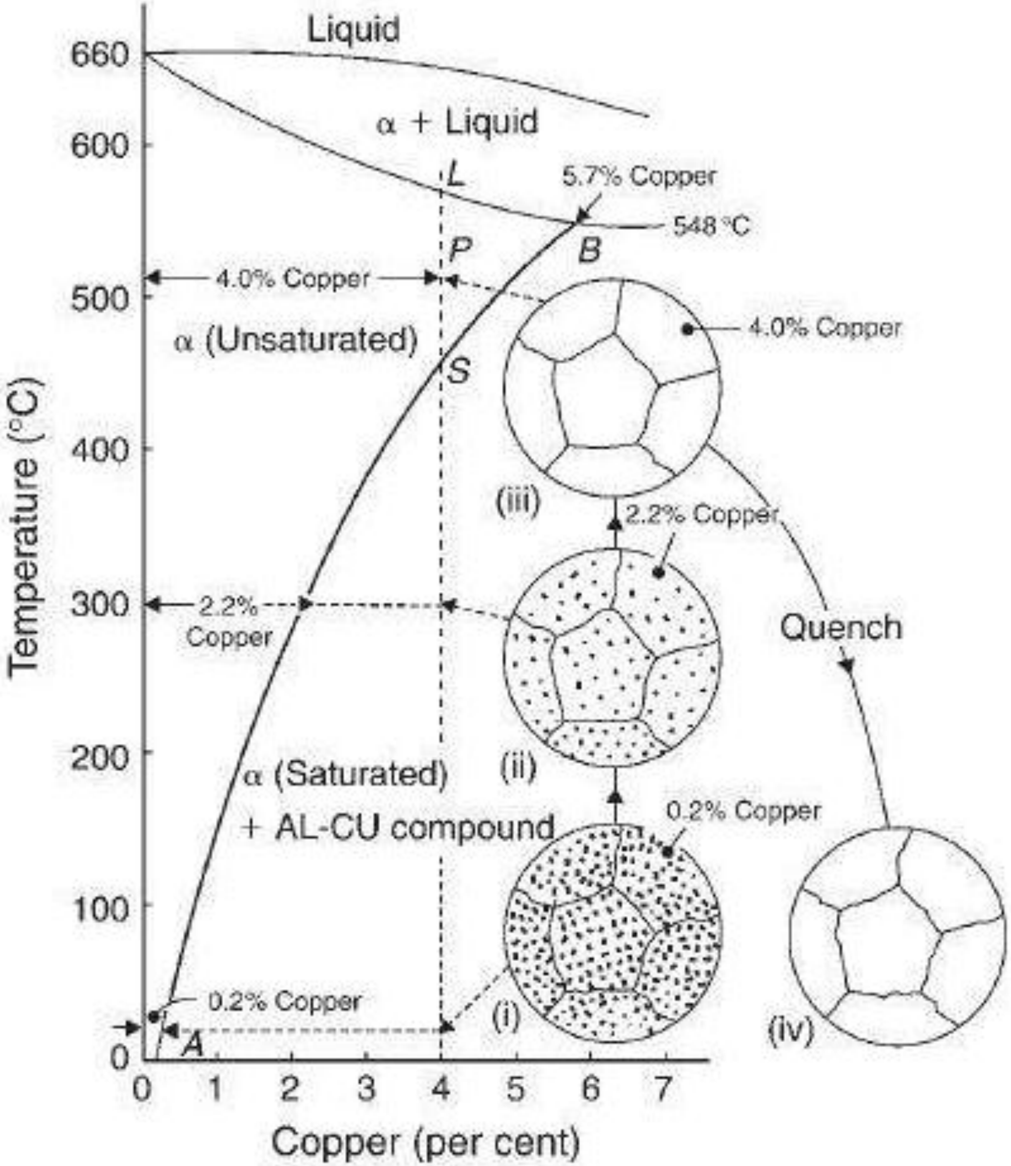


Figure 9.9 *The solubility curve for copper in aluminium. This is the aluminium-rich end of the aluminium-copper thermal equilibrium diagram.*

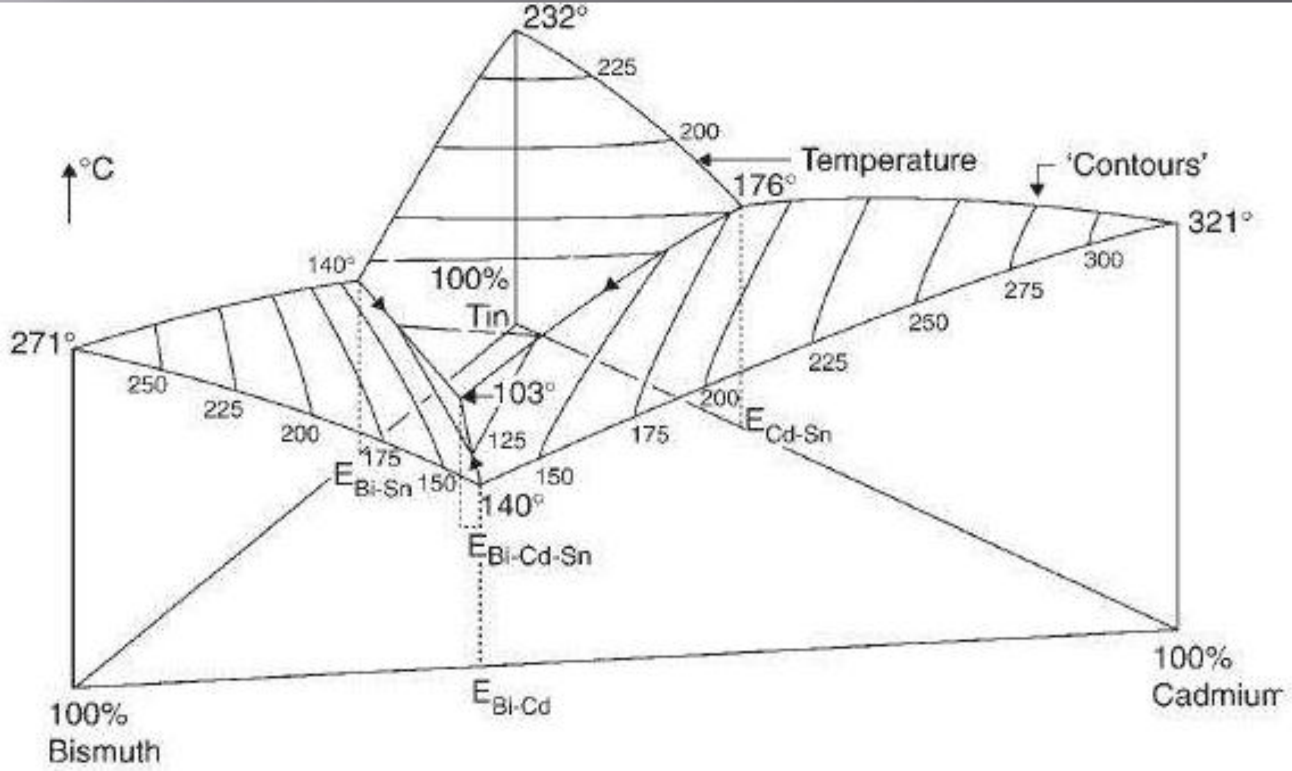
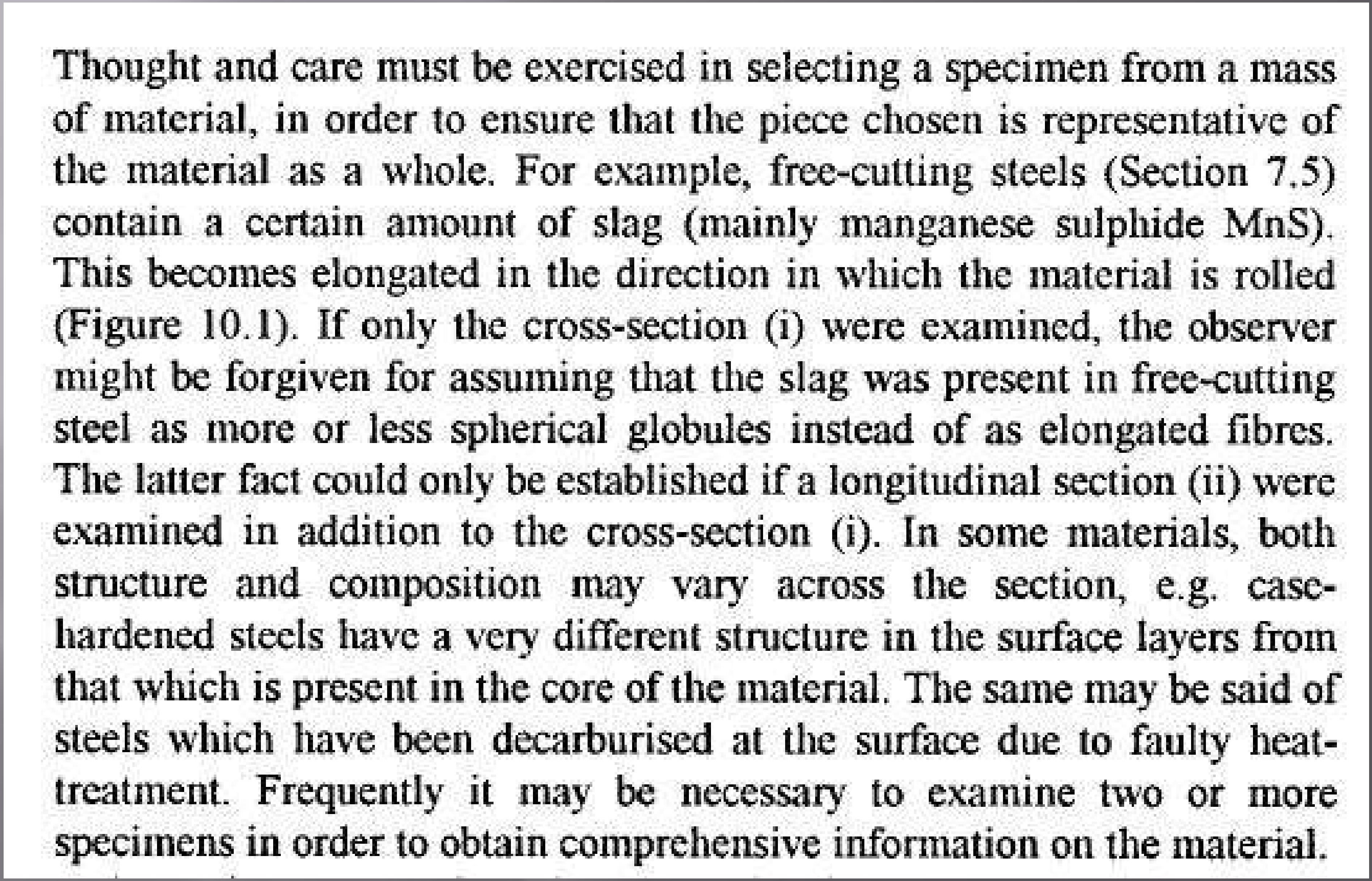


Figure 9.10 *The bismuth-cadmium-tin thermal equilibrium diagram. This is of course a ternary diagram. The three 'valleys' drain down to the ternary (or 'triple') eutectic point at 103°C. This alloy contains 53.9 per cent bismuth, 25.9 per cent tin and 20.3 per cent cadmium. The 'temperature contours' are at 25°C intervals. The ternary eutectic would melt at a temperature just above that of boiling water.*



Thought and care must be exercised in selecting a specimen from a mass of material, in order to ensure that the piece chosen is representative of the material as a whole. For example, free-cutting steels (Section 7.5) contain a certain amount of slag (mainly manganese sulphide MnS). This becomes elongated in the direction in which the material is rolled (Figure 10.1). If only the cross-section (i) were examined, the observer might be forgiven for assuming that the slag was present in free-cutting steel as more or less spherical globules instead of as elongated fibres. The latter fact could only be established if a longitudinal section (ii) were examined in addition to the cross-section (i). In some materials, both structure and composition may vary across the section, e.g. case-hardened steels have a very different structure in the surface layers from that which is present in the core of the material. The same may be said of steels which have been decarburised at the surface due to faulty heat-treatment. Frequently it may be necessary to examine two or more specimens in order to obtain comprehensive information on the material.

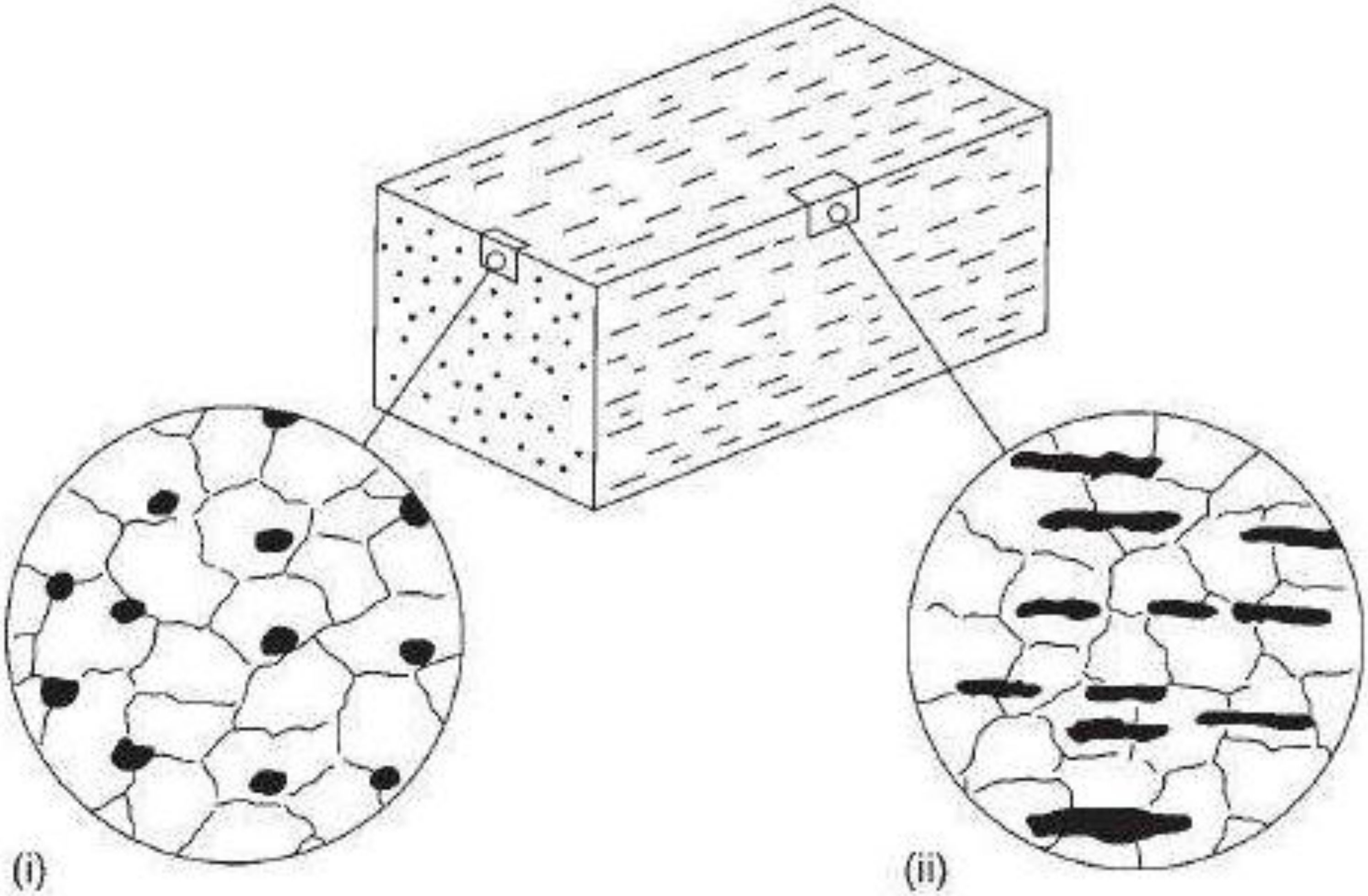
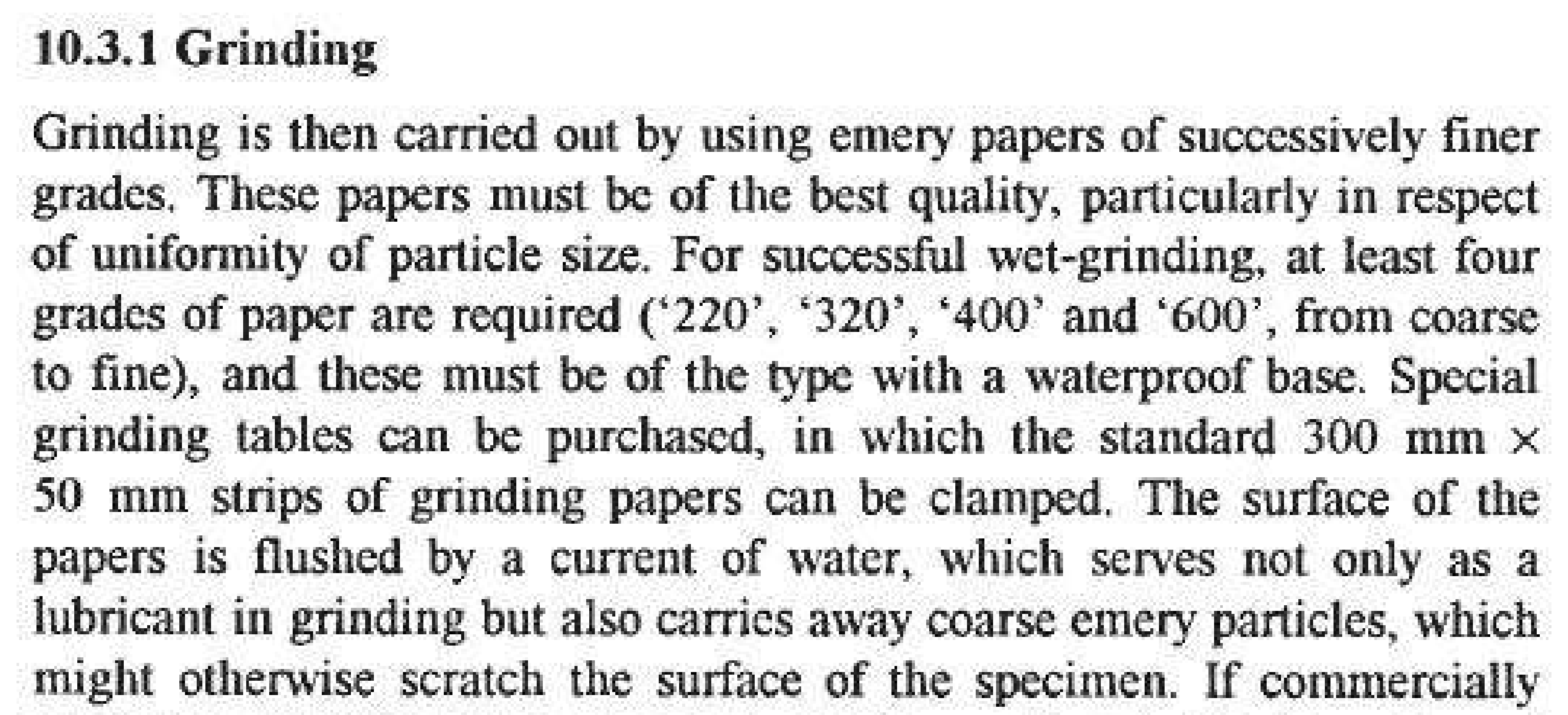


Figure 10.1 *At least two specimens are necessary to represent adequately the microstructure of a free-cutting steel.*



10.3.1 Grinding

Grinding is then carried out by using emery papers of successively finer grades. These papers must be of the best quality, particularly in respect of uniformity of particle size. For successful wet-grinding, at least four grades of paper are required ('220', '320', '400' and '600', from coarse to fine), and these must be of the type with a waterproof base. Special grinding tables can be purchased, in which the standard 300 mm × 50 mm strips of grinding papers can be clamped. The surface of the papers is flushed by a current of water, which serves not only as a lubricant in grinding but also carries away coarse emery particles, which might otherwise scratch the surface of the specimen. If commercially

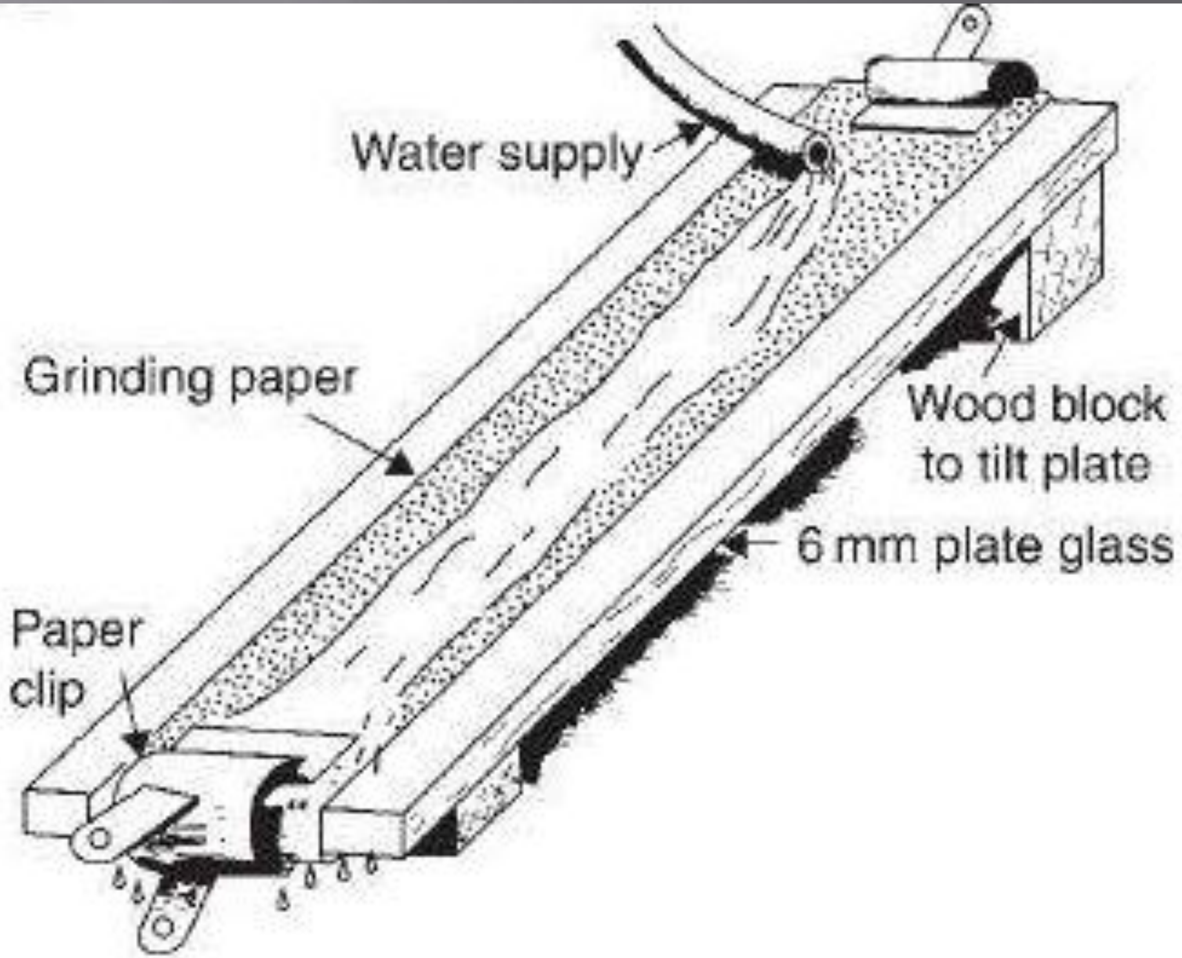
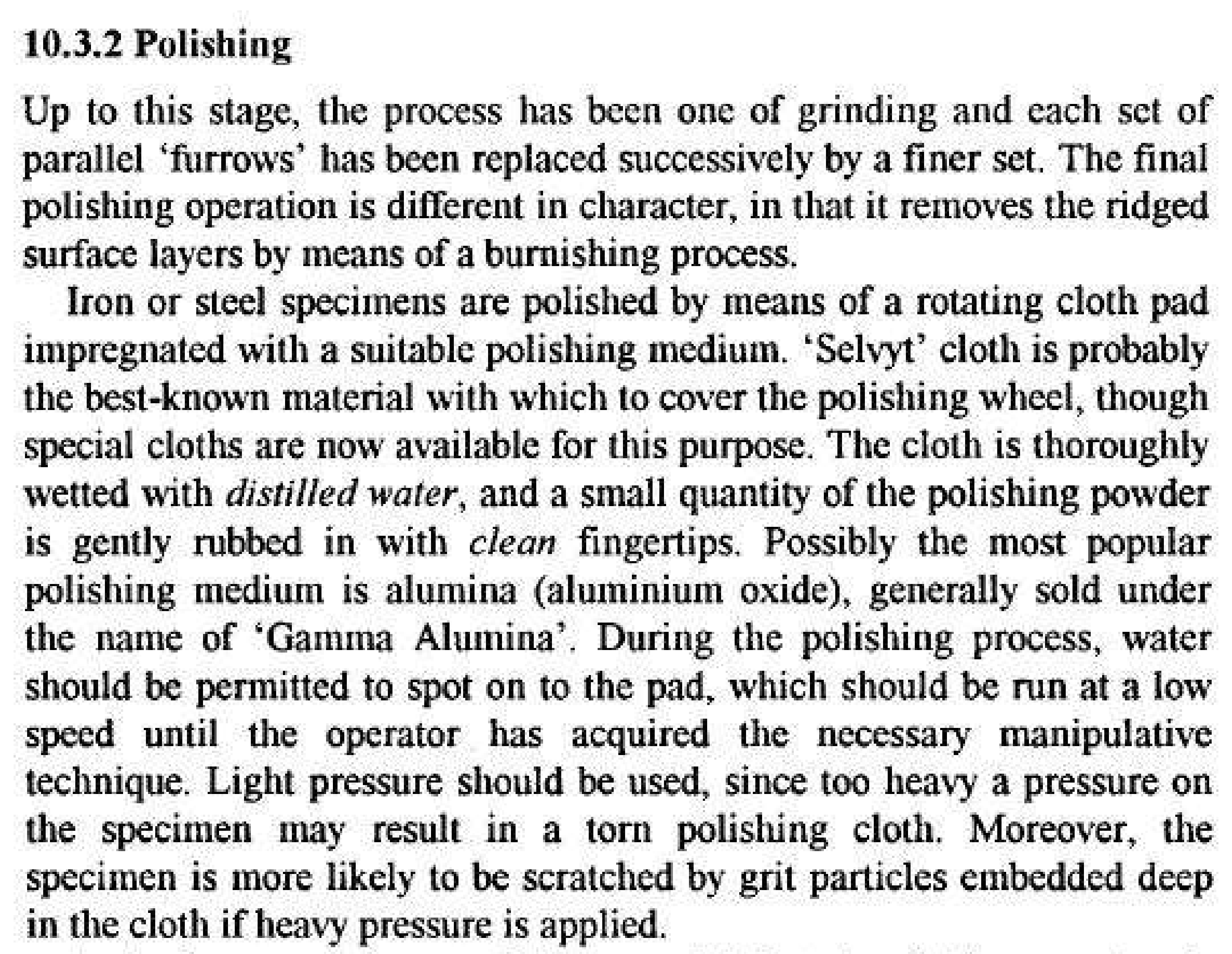


Figure 10.3 *A simple grinding table adapted from odds and ends.*

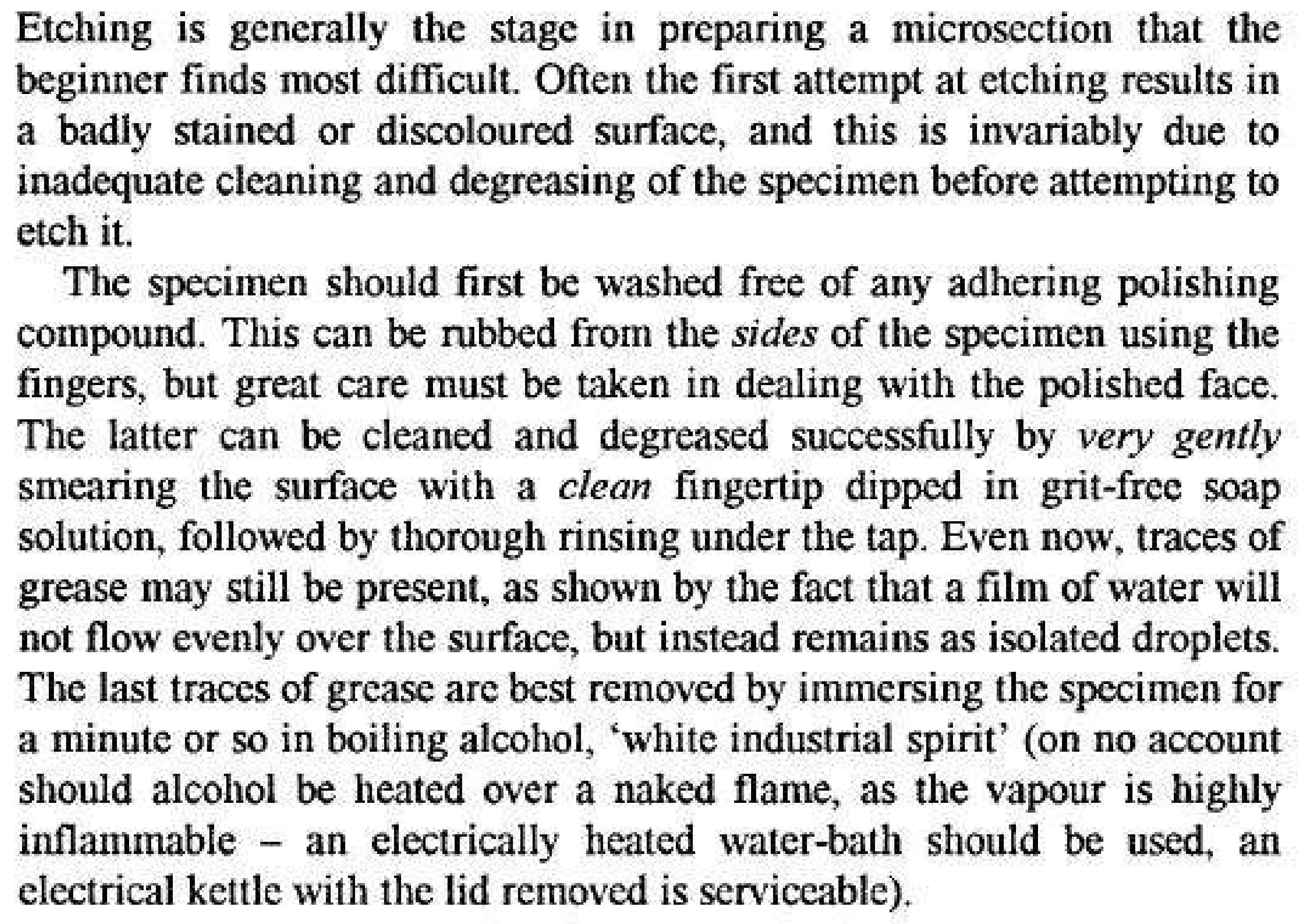


10.3.2 Polishing

Up to this stage, the process has been one of grinding and each set of parallel 'furrows' has been replaced successively by a finer set. The final polishing operation is different in character, in that it removes the ridged surface layers by means of a burnishing process.

Iron or steel specimens are polished by means of a rotating cloth pad impregnated with a suitable polishing medium. 'Selvyt' cloth is probably the best-known material with which to cover the polishing wheel, though special cloths are now available for this purpose. The cloth is thoroughly wetted with *distilled water*, and a small quantity of the polishing powder is gently rubbed in with *clean* fingertips. Possibly the most popular polishing medium is alumina (aluminium oxide), generally sold under the name of 'Gamma Alumina'. During the polishing process, water should be permitted to spot on to the pad, which should be run at a low speed until the operator has acquired the necessary manipulative technique. Light pressure should be used, since too heavy a pressure on the specimen may result in a torn polishing cloth. Moreover, the specimen is more likely to be scratched by grit particles embedded deep in the cloth if heavy pressure is applied.

Etching the specimen



Etching is generally the stage in preparing a microsection that the beginner finds most difficult. Often the first attempt at etching results in a badly stained or discoloured surface, and this is invariably due to inadequate cleaning and degreasing of the specimen before attempting to etch it.

The specimen should first be washed free of any adhering polishing compound. This can be rubbed from the *sides* of the specimen using the fingers, but great care must be taken in dealing with the polished face. The latter can be cleaned and degreased successfully by *very gently* smearing the surface with a *clean* fingertip dipped in grit-free soap solution, followed by thorough rinsing under the tap. Even now, traces of grease may still be present, as shown by the fact that a film of water will not flow evenly over the surface, but instead remains as isolated droplets. The last traces of grease are best removed by immersing the specimen for a minute or so in boiling alcohol, 'white industrial spirit' (on no account should alcohol be heated over a naked flame, as the vapour is highly inflammable – an electrically heated water-bath should be used, an electrical kettle with the lid removed is serviceable).

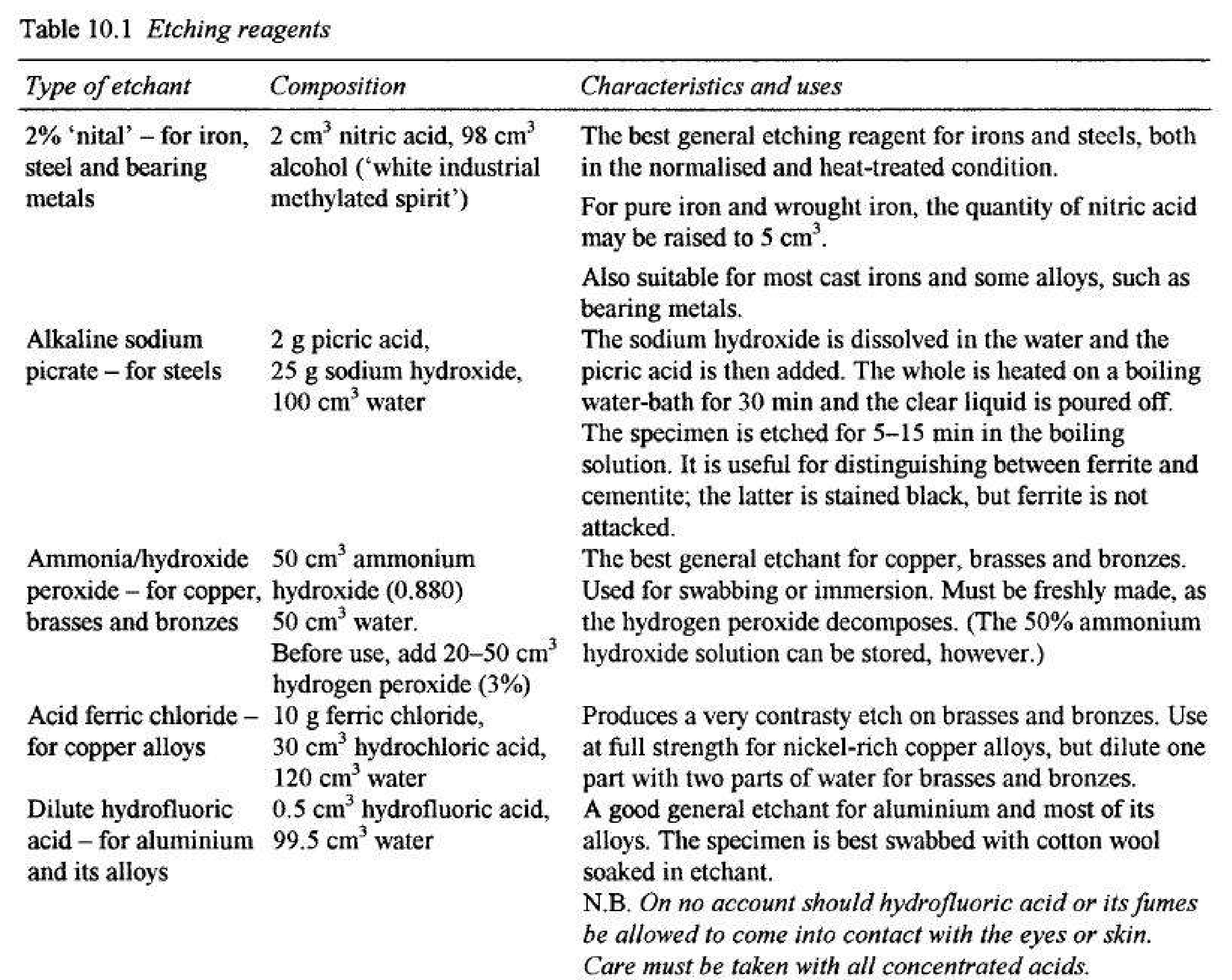
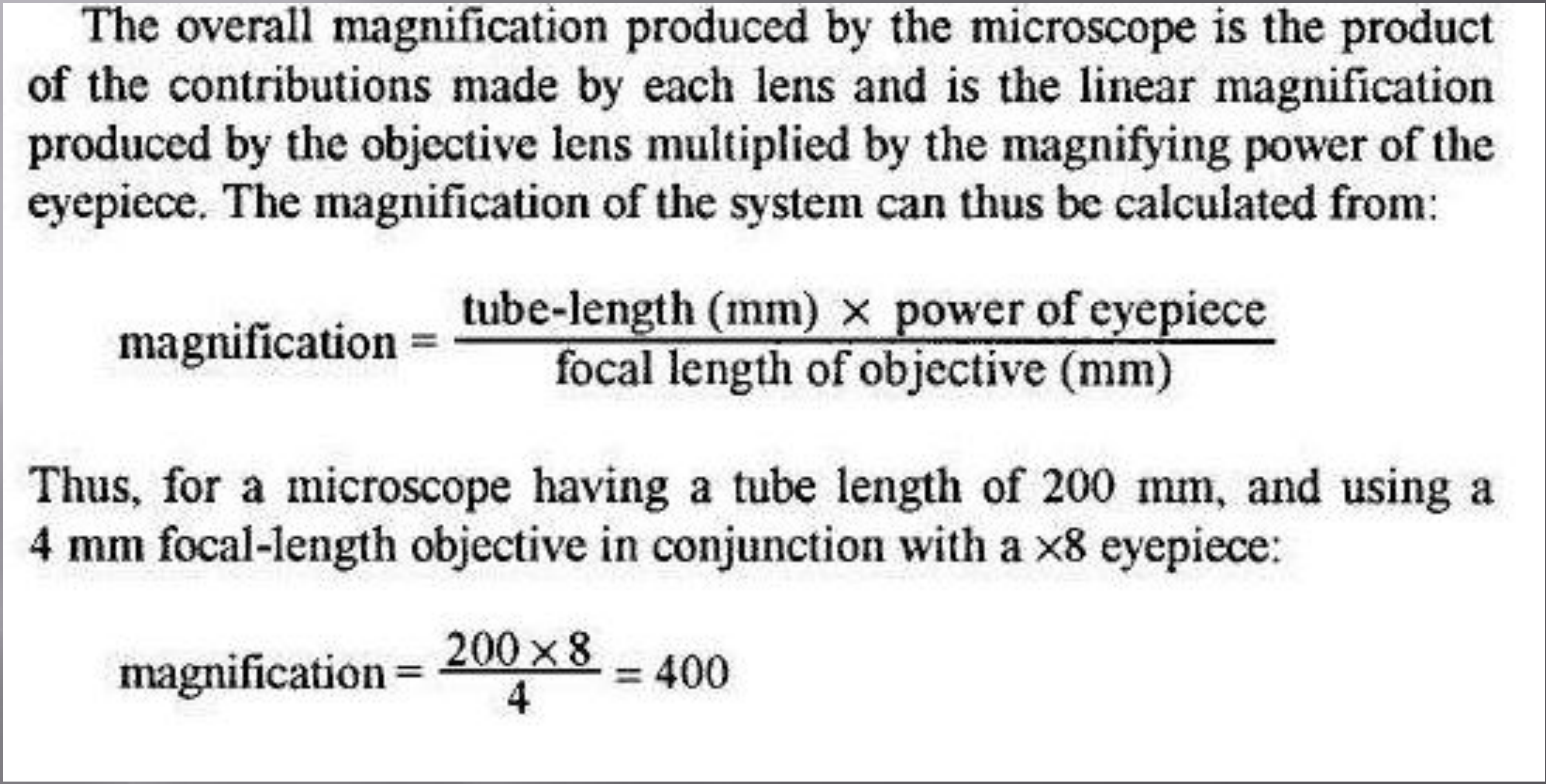


Table 10.1 *Etching reagents*

Type of etchant	*Composition*	*Characteristics and uses*
2% 'nital' – for iron, steel and bearing metals	2 cm^3 nitric acid, 98 cm^3 alcohol ('white industrial methylated spirit')	The best general etching reagent for irons and steels, both in the normalised and heat-treated condition. For pure iron and wrought iron, the quantity of nitric acid may be raised to 5 cm^3. Also suitable for most cast irons and some alloys, such as bearing metals.
Alkaline sodium picrate – for steels	2 g picric acid, 25 g sodium hydroxide, 100 cm^3 water	The sodium hydroxide is dissolved in the water and the picric acid is then added. The whole is heated on a boiling water-bath for 30 min and the clear liquid is poured off. The specimen is etched for 5–15 min in the boiling solution. It is useful for distinguishing between ferrite and cementite; the latter is stained black, but ferrite is not attacked.
Ammonia/hydroxide peroxide – for copper, brasses and bronzes	50 cm^3 ammonium hydroxide (0.880) 50 cm^3 water. Before use, add 20–50 cm^3 hydrogen peroxide (3%)	The best general etchant for copper, brasses and bronzes. Used for swabbing or immersion. Must be freshly made, as the hydrogen peroxide decomposes. (The 50% ammonium hydroxide solution can be stored, however.)
Acid ferric chloride – for copper alloys	10 g ferric chloride, 30 cm^3 hydrochloric acid, 120 cm^3 water	Produces a very contrasty etch on brasses and bronzes. Use at full strength for nickel-rich copper alloys, but dilute one part with two parts of water for brasses and bronzes.
Dilute hydrofluoric acid – for aluminium and its alloys	0.5 cm^3 hydrofluoric acid, 99.5 cm^3 water	A good general etchant for aluminium and most of its alloys. The specimen is best swabbed with cotton wool soaked in etchant. N.B. *On no account should hydrofluoric acid or its fumes be allowed to come into contact with the eyes or skin. Care must be taken with all concentrated acids.*



The overall magnification produced by the microscope is the product of the contributions made by each lens and is the linear magnification produced by the objective lens multiplied by the magnifying power of the eyepiece. The magnification of the system can thus be calculated from:

$$\text{magnification} = \frac{\text{tube-length (mm)} \times \text{power of eyepiece}}{\text{focal length of objective (mm)}}$$

Thus, for a microscope having a tube length of 200 mm, and using a 4 mm focal-length objective in conjunction with a ×8 eyepiece:

$$\text{magnification} = \frac{200 \times 8}{4} = 400$$

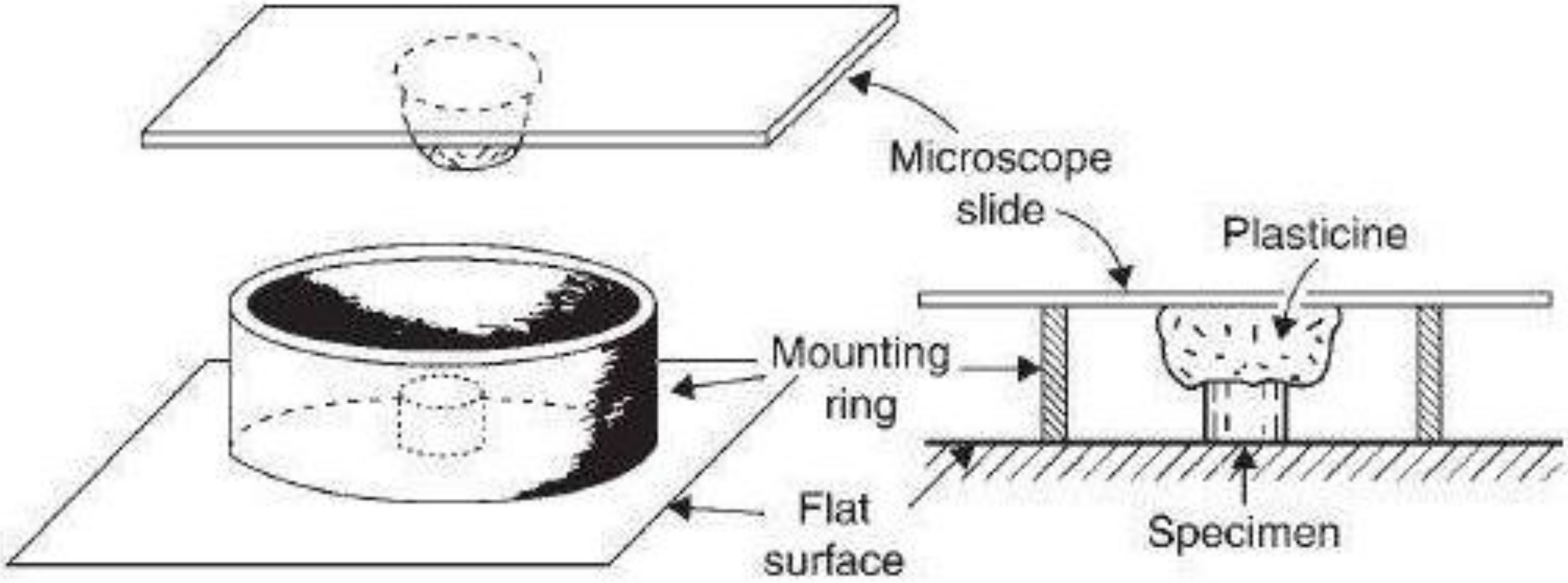


Figure 10.6 *Mounting a specimen so that its surface is normal to the axis of the microscope.*

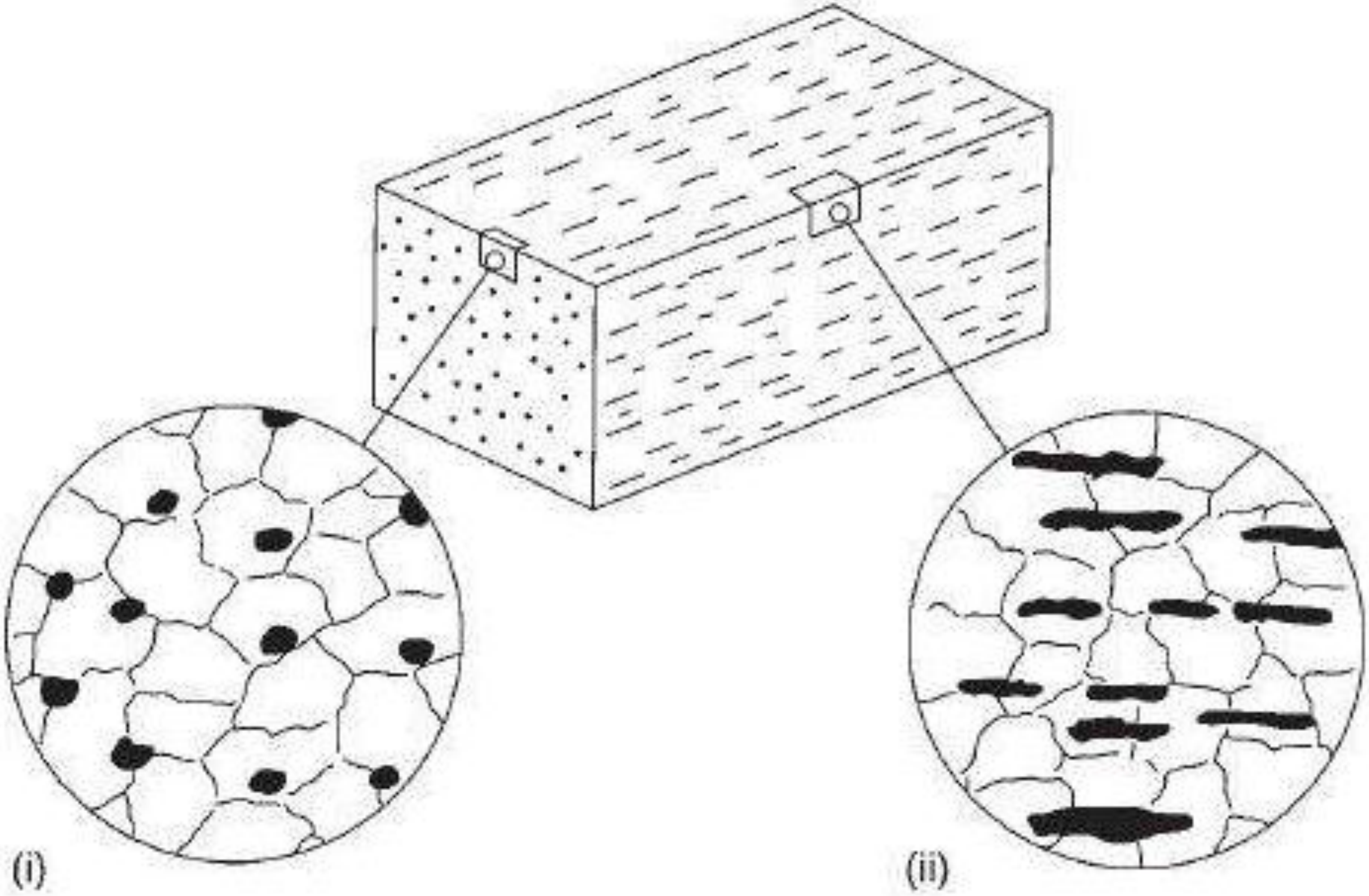


Figure 10.1 *At least two specimens are necessary to represent adequately the microstructure of a free-cutting steel.*

Specimens can also be mounted using thermoplastic or thermosetting materials in conjunction with a mould capable of being electrically heated and a suitable press. The advantage of using a thermosetting material, such as Bakelite, is that it is less likely to be dissolved by organic degreasing agents such as acetone or warm alcohol.

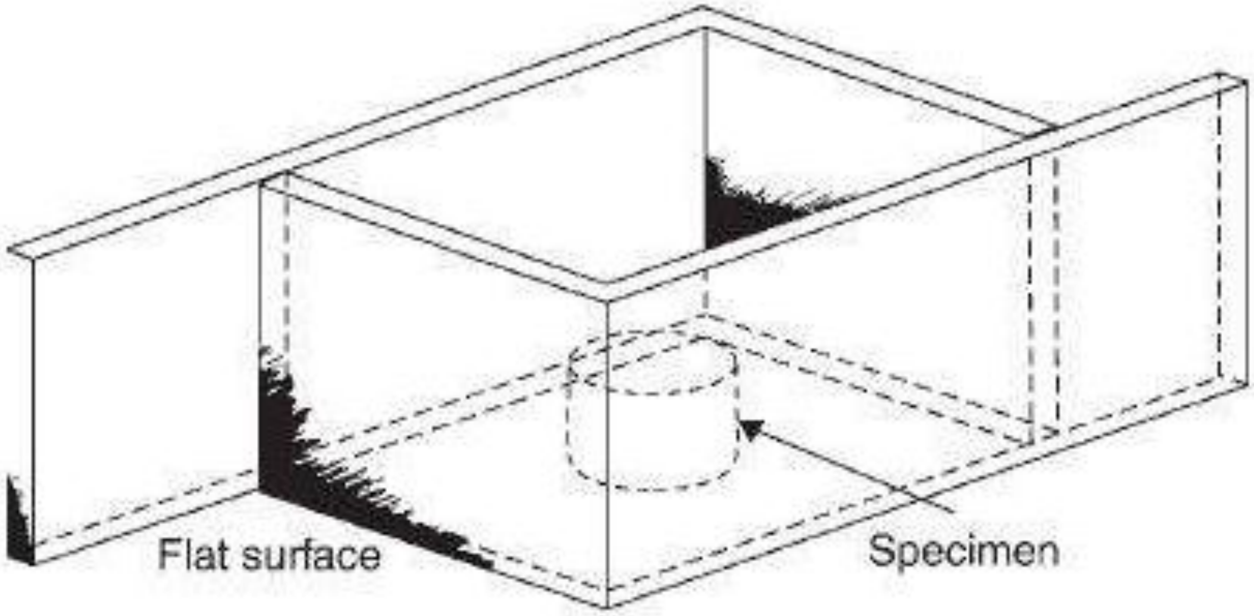
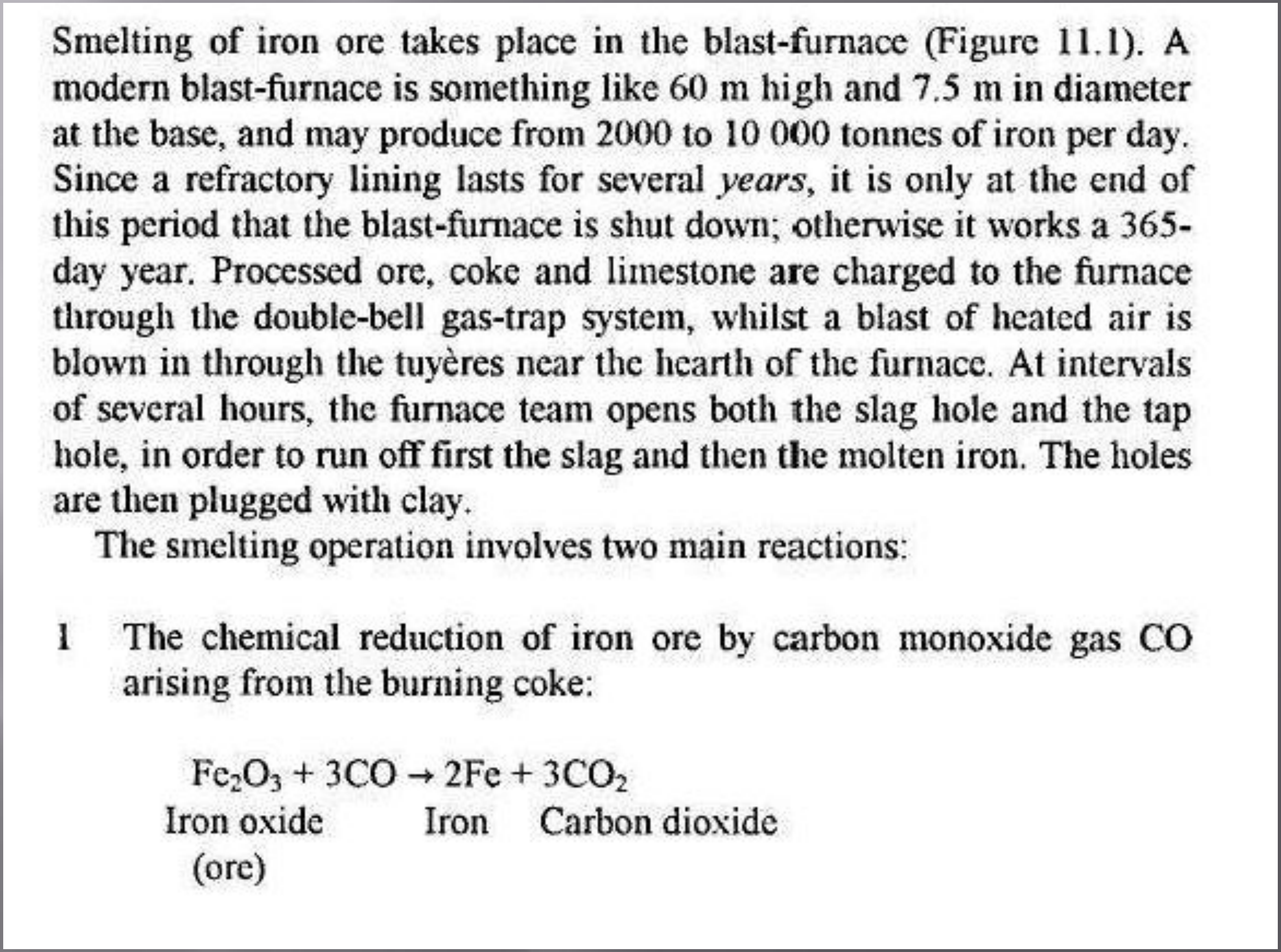


Figure 10.2 *A method of mounting a specimen in a cold-setting plastic material. No pressure is required.*



Smelting of iron ore takes place in the blast-furnace (Figure 11.1). A modern blast-furnace is something like 60 m high and 7.5 m in diameter at the base, and may produce from 2000 to 10 000 tonnes of iron per day. Since a refractory lining lasts for several *years*, it is only at the end of this period that the blast-furnace is shut down; otherwise it works a 365-day year. Processed ore, coke and limestone are charged to the furnace through the double-bell gas-trap system, whilst a blast of heated air is blown in through the tuyères near the hearth of the furnace. At intervals of several hours, the furnace team opens both the slag hole and the tap hole, in order to run off first the slag and then the molten iron. The holes are then plugged with clay.

The smelting operation involves two main reactions:

1 The chemical reduction of iron ore by carbon monoxide gas CO arising from the burning coke:

$$\underset{\text{(ore)}}{\underset{\text{Iron oxide}}{Fe_2O_3}} + 3CO \rightarrow \underset{\text{Iron}}{2Fe} + \underset{\text{Carbon dioxide}}{3CO_2}$$

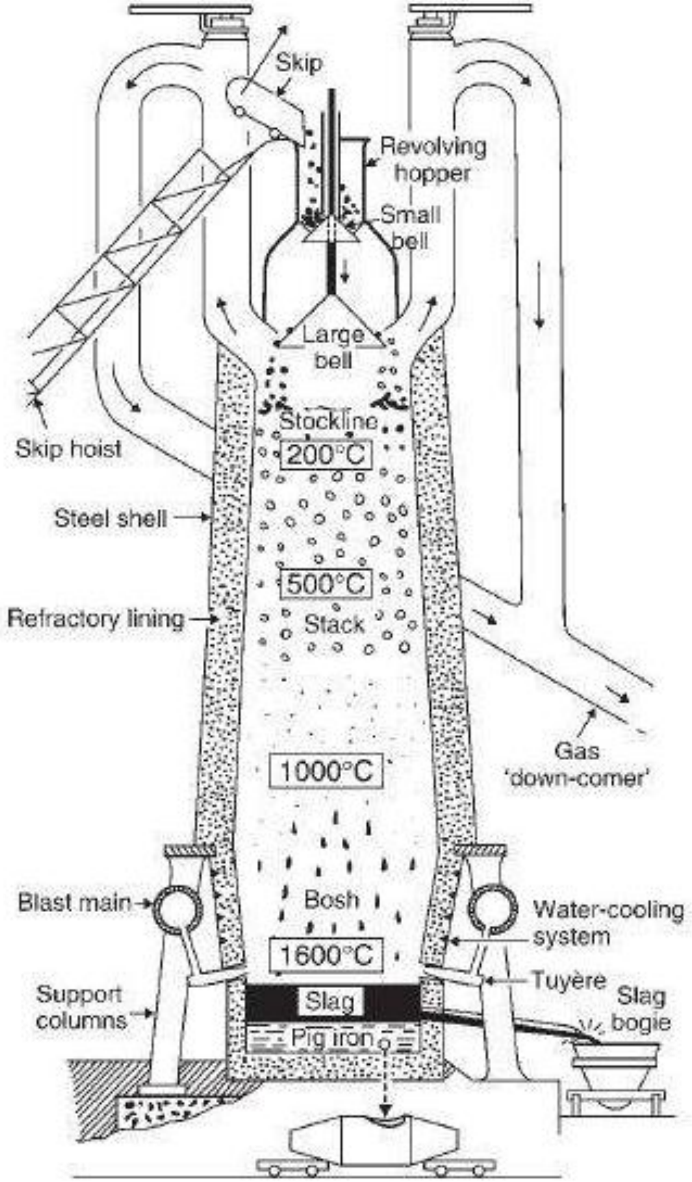
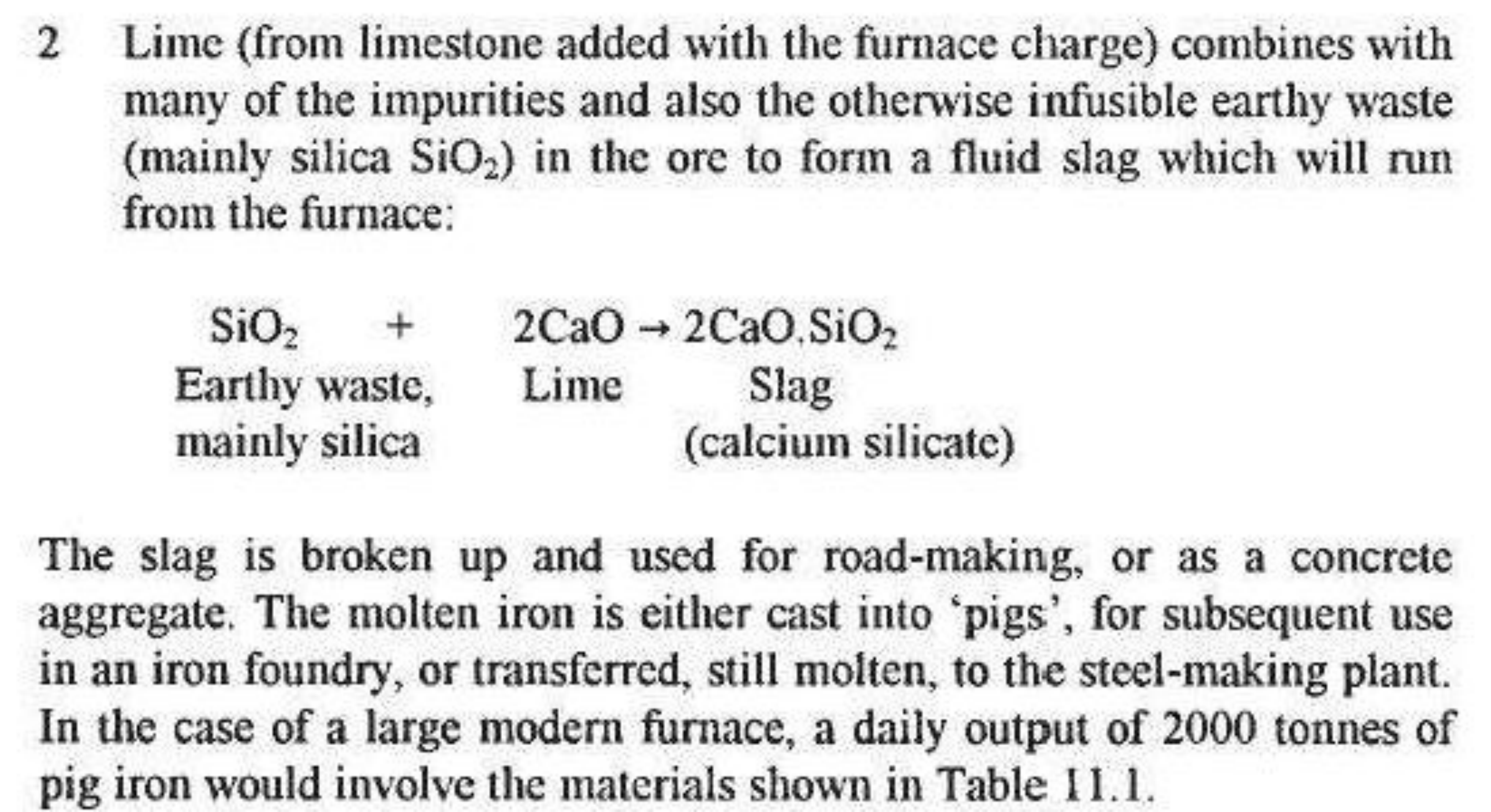


Figure 11.1 *A modern blast-furnace.*

Table 11.1 *Materials involved with a daily output of 2000 tonnes of pig iron*

Charge	*Amount, tonnes*
Ore, say 50% iron	4 000
Limestone	800
Coke	1 800
Air	8 000
Total	14 600
Products	
Pig iron	2 000
Slag	1 600
Dust	200
Furnace gas	10 800
Total	14 600

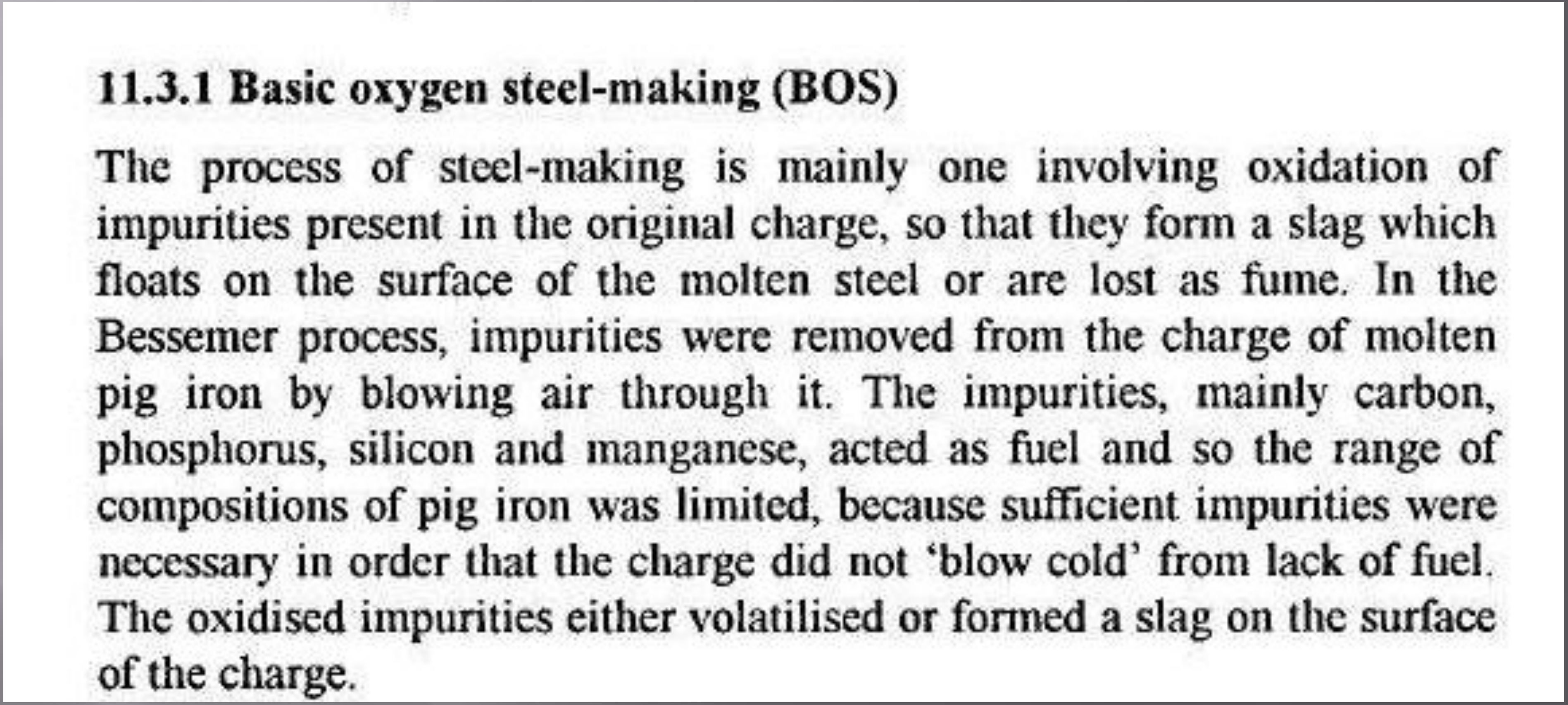


2 Lime (from limestone added with the furnace charge) combines with many of the impurities and also the otherwise infusible earthy waste (mainly silica SiO_2) in the ore to form a fluid slag which will run from the furnace:

$$SiO_2 \quad + \quad 2CaO \rightarrow 2CaO.SiO_2$$

SiO_2	+	2CaO	→	2CaO.SiO_2
Earthy waste, mainly silica		Lime		Slag (calcium silicate)

The slag is broken up and used for road-making, or as a concrete aggregate. The molten iron is either cast into 'pigs', for subsequent use in an iron foundry, or transferred, still molten, to the steel-making plant. In the case of a large modern furnace, a daily output of 2000 tonnes of pig iron would involve the materials shown in Table 11.1.



11.3.1 Basic oxygen steel-making (BOS)

The process of steel-making is mainly one involving oxidation of impurities present in the original charge, so that they form a slag which floats on the surface of the molten steel or are lost as fume. In the Bessemer process, impurities were removed from the charge of molten pig iron by blowing air through it. The impurities, mainly carbon, phosphorus, silicon and manganese, acted as fuel and so the range of compositions of pig iron was limited, because sufficient impurities were necessary in order that the charge did not 'blow cold' from lack of fuel. The oxidised impurities either volatilised or formed a slag on the surface of the charge.

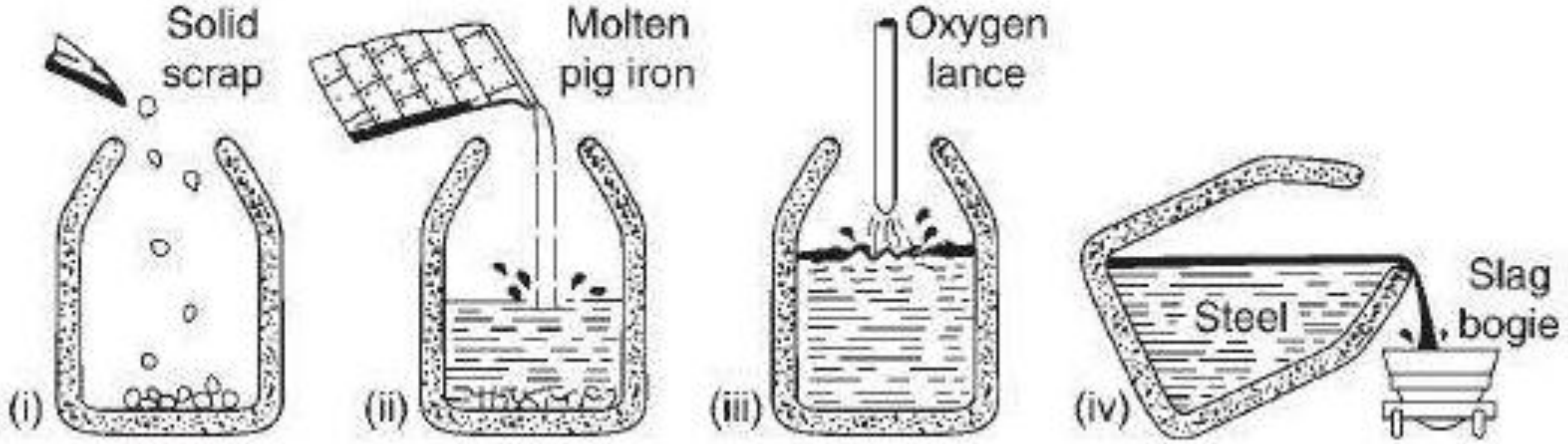
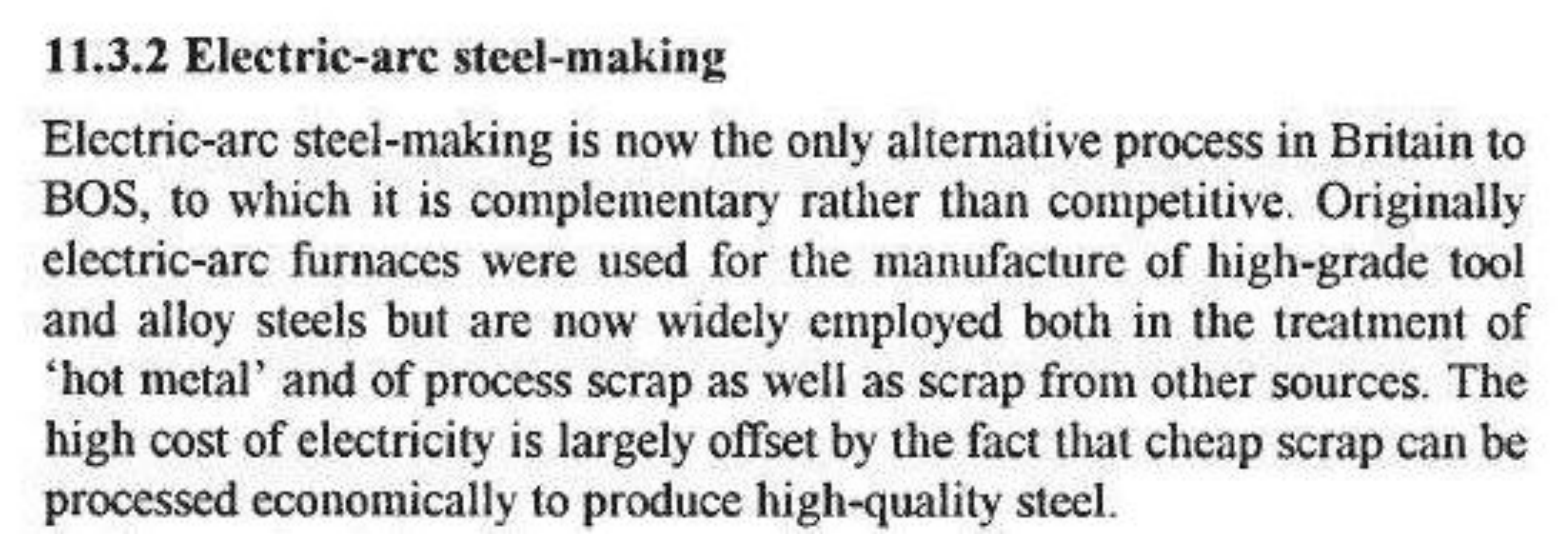


Figure 11.2 *Stages in the manufacture of steel by the basic oxygen process. Steel scrap is added first (i), followed by molten pig iron (ii). At the end of the 'blow', the slag is run off first (iv), before 'teeming' the steel into a ladle.*



11.3.2 Electric-arc steel-making

Electric-arc steel-making is now the only alternative process in Britain to BOS, to which it is complementary rather than competitive. Originally electric-arc furnaces were used for the manufacture of high-grade tool and alloy steels but are now widely employed both in the treatment of 'hot metal' and of process scrap as well as scrap from other sources. The high cost of electricity is largely offset by the fact that cheap scrap can be processed economically to produce high-quality steel.

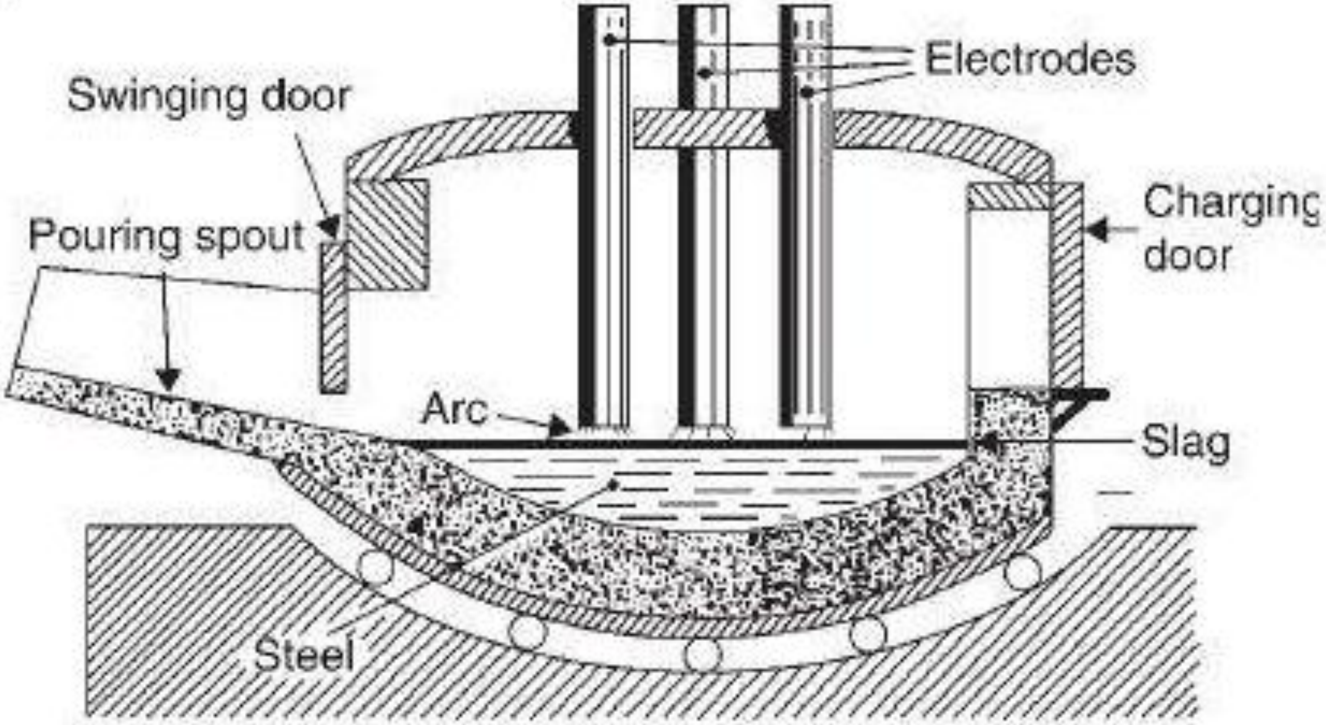
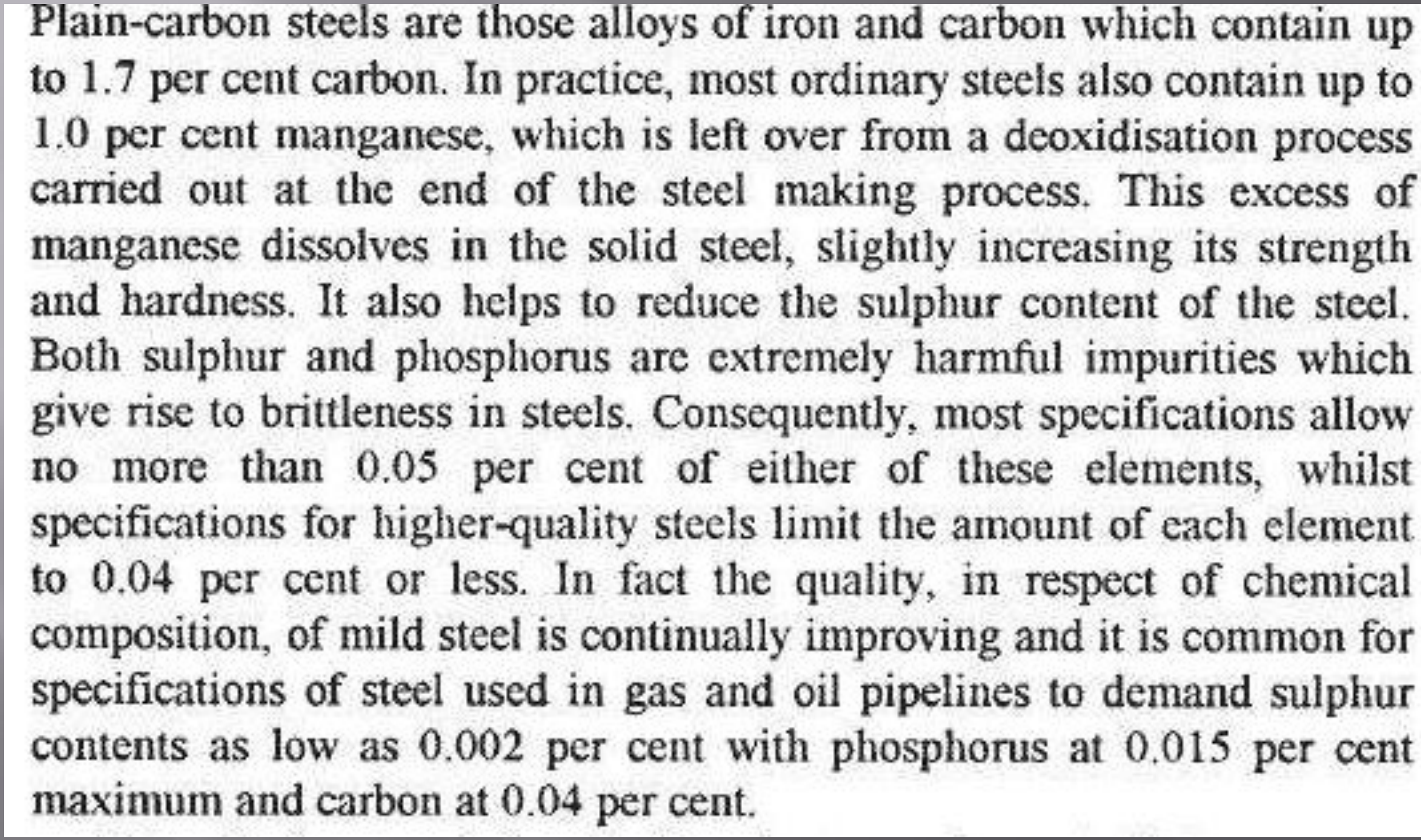


Figure 11.3 *The principles of the electric-arc furnace for steel-making. Modern furnaces have water-cooled panels built into the side walls to protect the refractory lining. Some furnaces lack the pouring spout and the charge is poured from a tap hole in the bottom of the furnace.*



Plain-carbon steels are those alloys of iron and carbon which contain up to 1.7 per cent carbon. In practice, most ordinary steels also contain up to 1.0 per cent manganese, which is left over from a deoxidisation process carried out at the end of the steel making process. This excess of manganese dissolves in the solid steel, slightly increasing its strength and hardness. It also helps to reduce the sulphur content of the steel. Both sulphur and phosphorus are extremely harmful impurities which give rise to brittleness in steels. Consequently, most specifications allow no more than 0.05 per cent of either of these elements, whilst specifications for higher-quality steels limit the amount of each element to 0.04 per cent or less. In fact the quality, in respect of chemical composition, of mild steel is continually improving and it is common for specifications of steel used in gas and oil pipelines to demand sulphur contents as low as 0.002 per cent with phosphorus at 0.015 per cent maximum and carbon at 0.04 per cent.

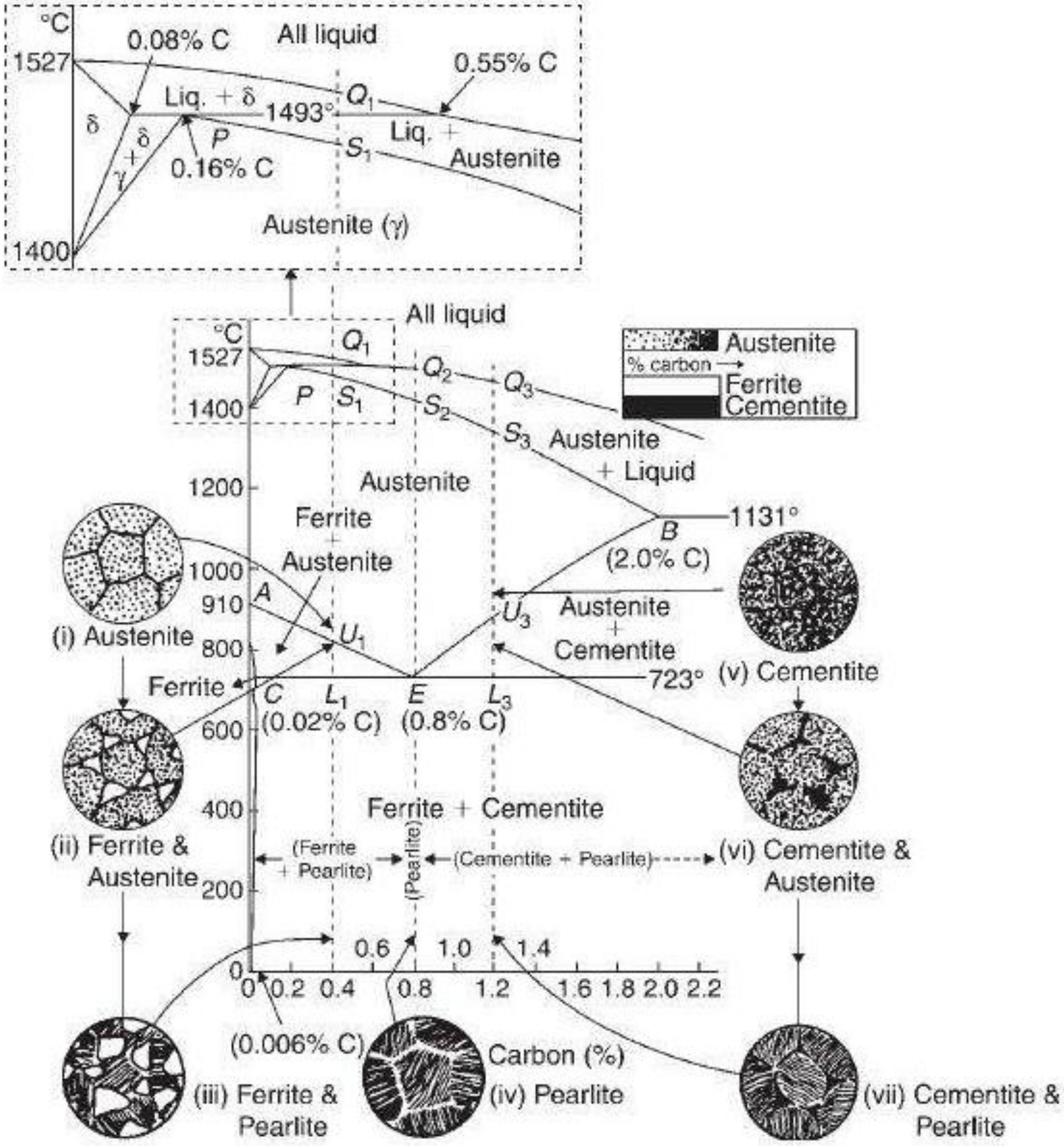
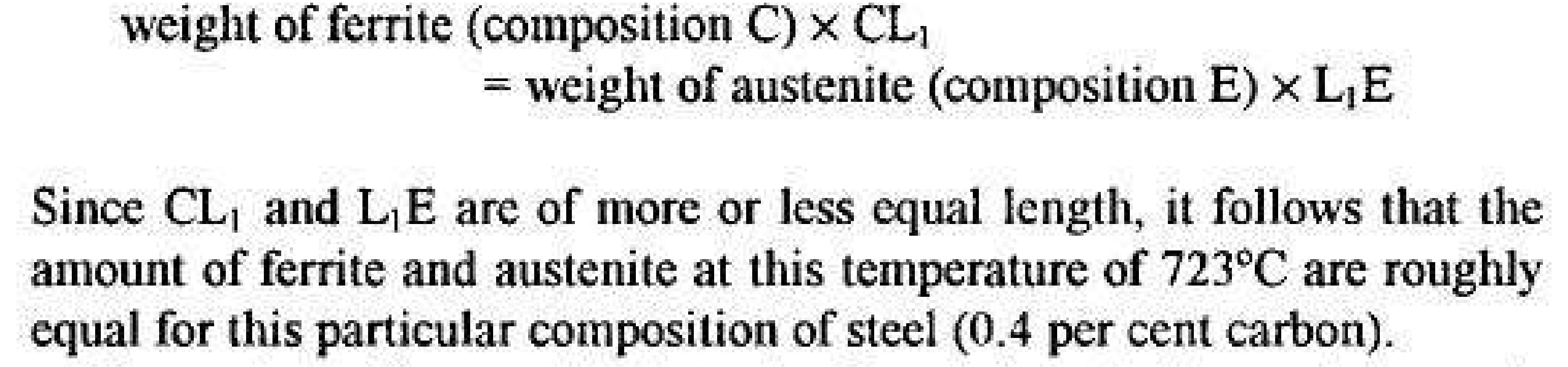


Figure 11.4 *The iron-carbon equilibrium diagram. The small dots in the diagrams depicting structures containing austenite do not represent visible particles of cementite – they are meant to indicate the concentration of carbon atoms dissolved in the austenite and in the real microstructures would of course be invisible. The inset shows the 'peritectic part' of the diagram in greater detail.*



weight of ferrite (composition C) × CL_1
= weight of austenite (composition E) × L_1E

Since CL_1 and L_1E are of more or less equal length, it follows that the amount of ferrite and austenite at this temperature of 723°C are roughly equal for this particular composition of steel (0.4 per cent carbon).

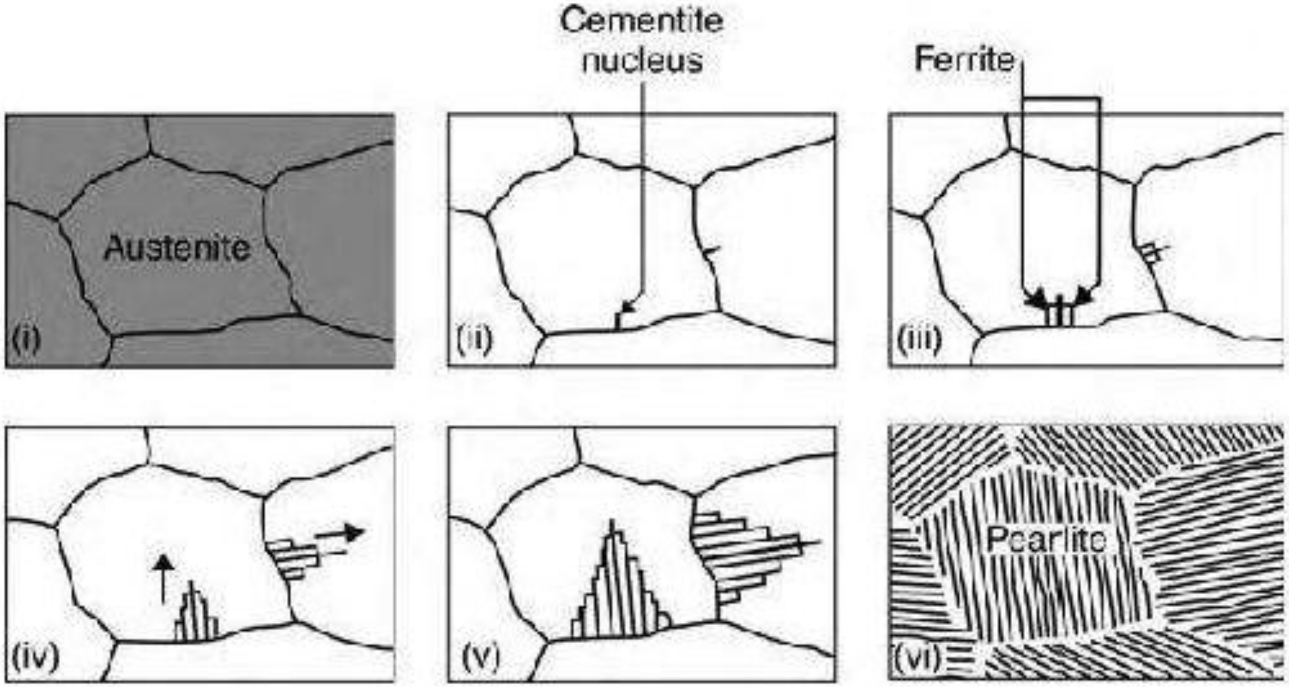
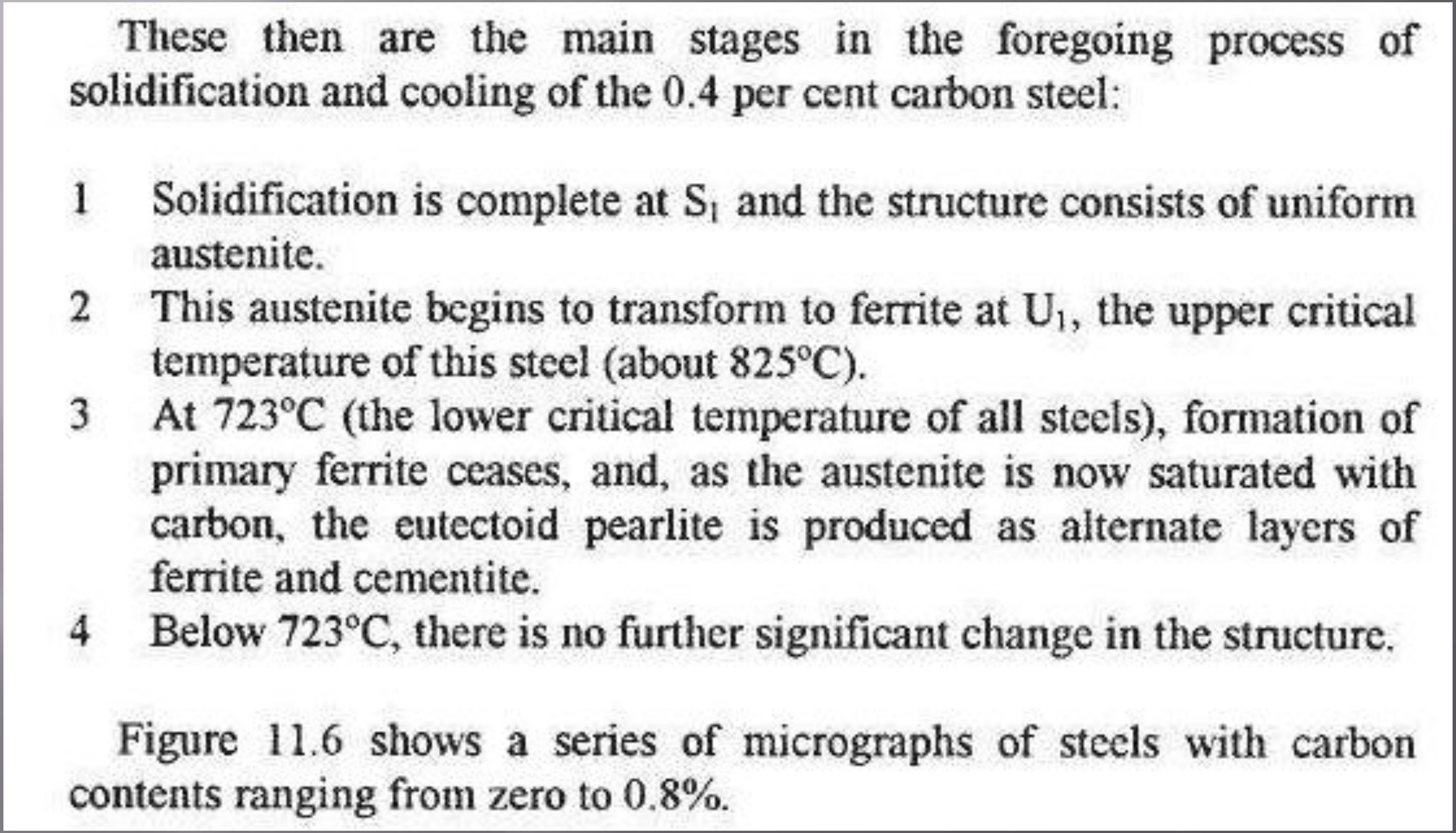


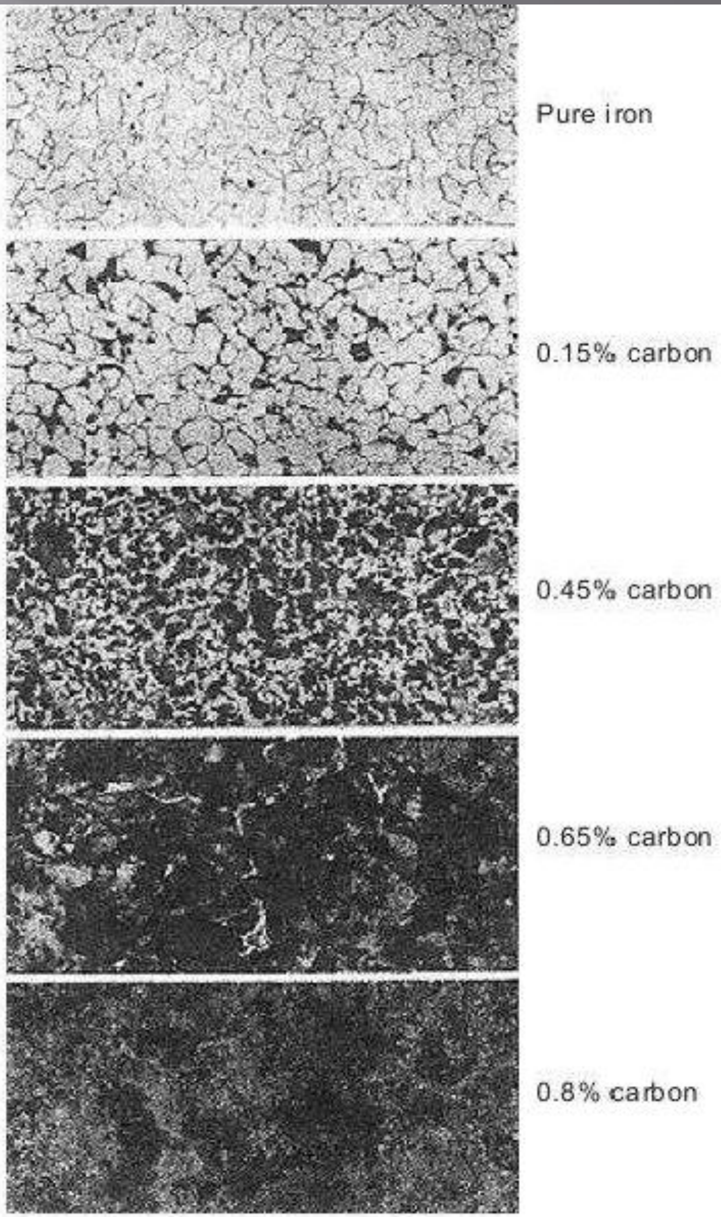
Figure 11.5 *The transformation of austenite to pearlite (in this case in a 0.8 per cent carbon steel).*



These then are the main stages in the foregoing process of solidification and cooling of the 0.4 per cent carbon steel:

1 Solidification is complete at S_1 and the structure consists of uniform austenite.
2 This austenite begins to transform to ferrite at U_1, the upper critical temperature of this steel (about 825°C).
3 At 723°C (the lower critical temperature of all steels), formation of primary ferrite ceases, and, as the austenite is now saturated with carbon, the eutectoid pearlite is produced as alternate layers of ferrite and cementite.
4 Below 723°C, there is no further significant change in the structure.

Figure 11.6 shows a series of micrographs of steels with carbon contents ranging from zero to 0.8%.


Pure iron
0.15% carbon
0.45% carbon
0.65% carbon
0.8% carbon

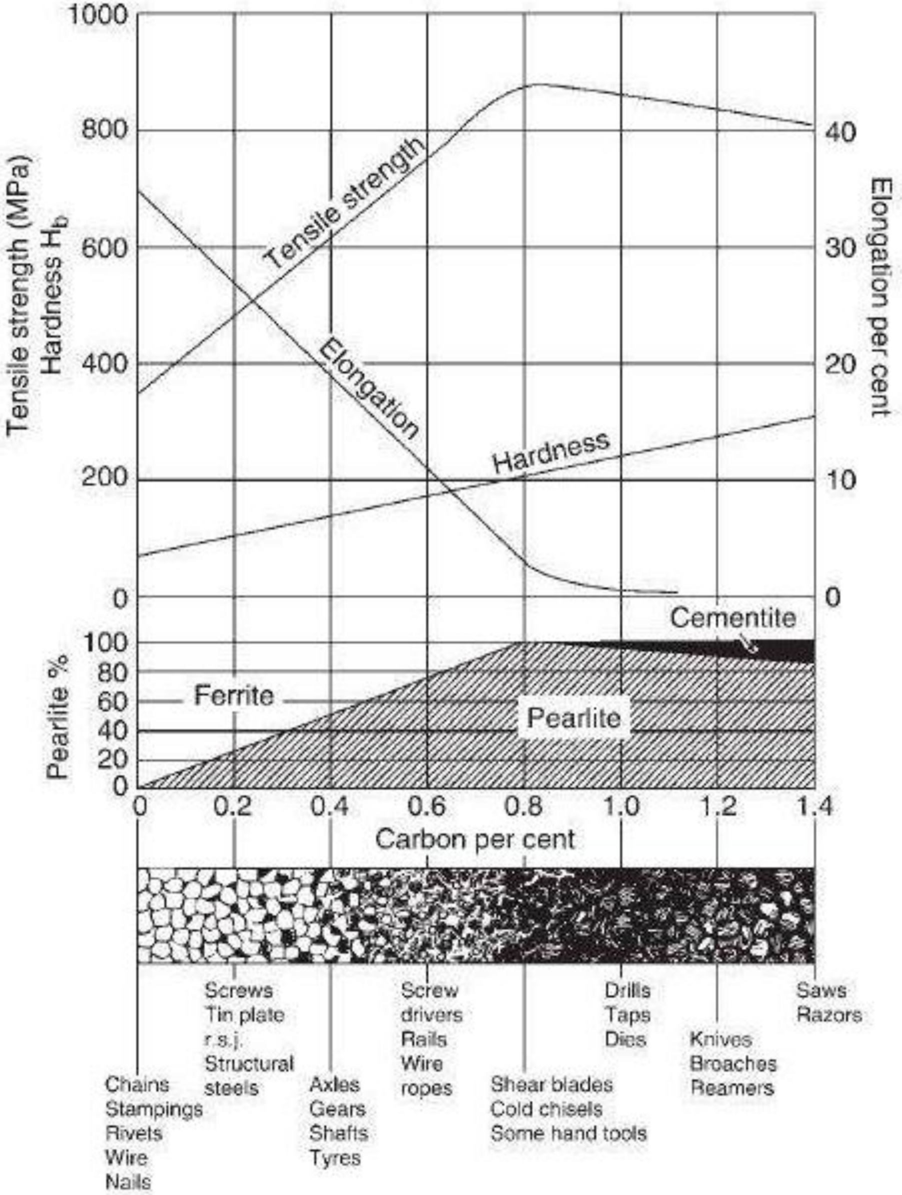


Figure 11.8 *A diagram showing the relationship between carbon content, mechanical properties, and uses of plain-carbon steels which have been slowly cooled from above their upper critical temperatures.*

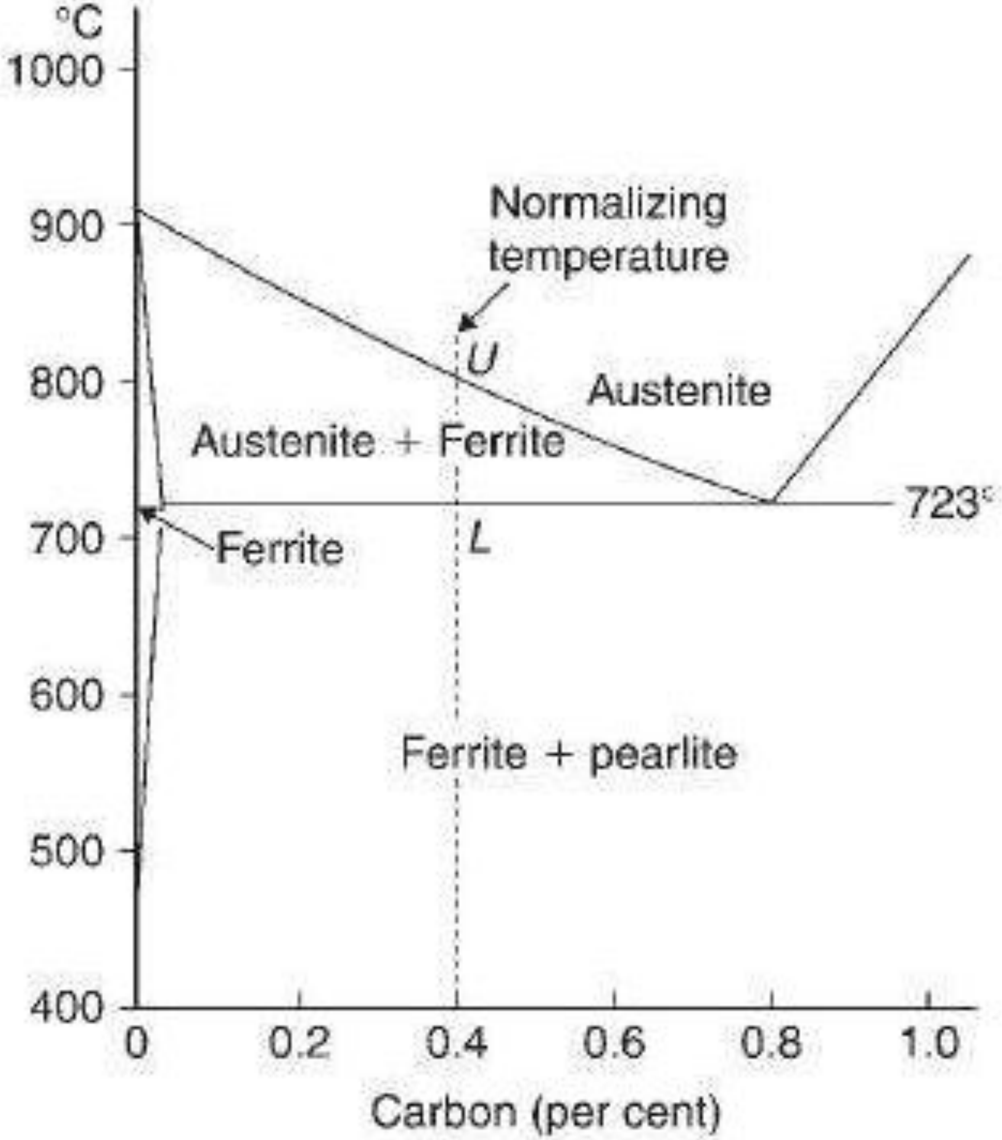
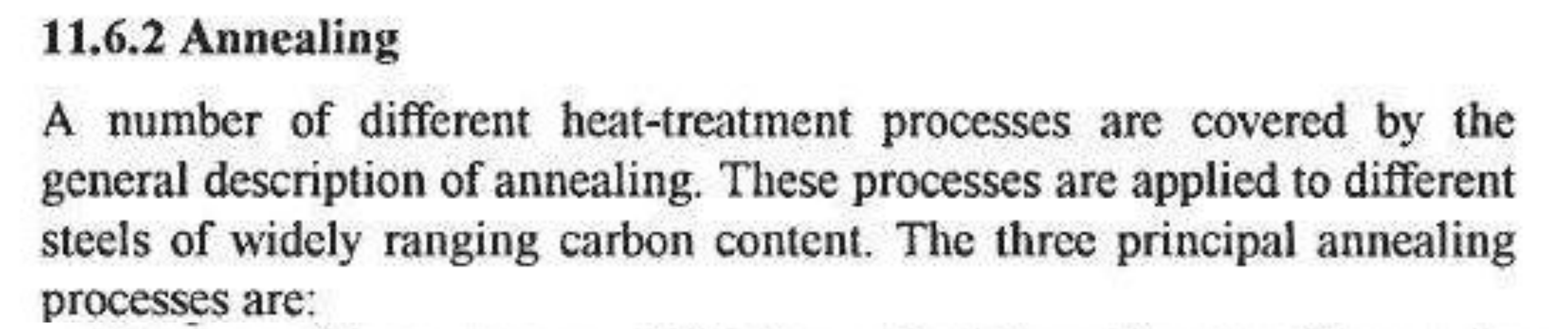
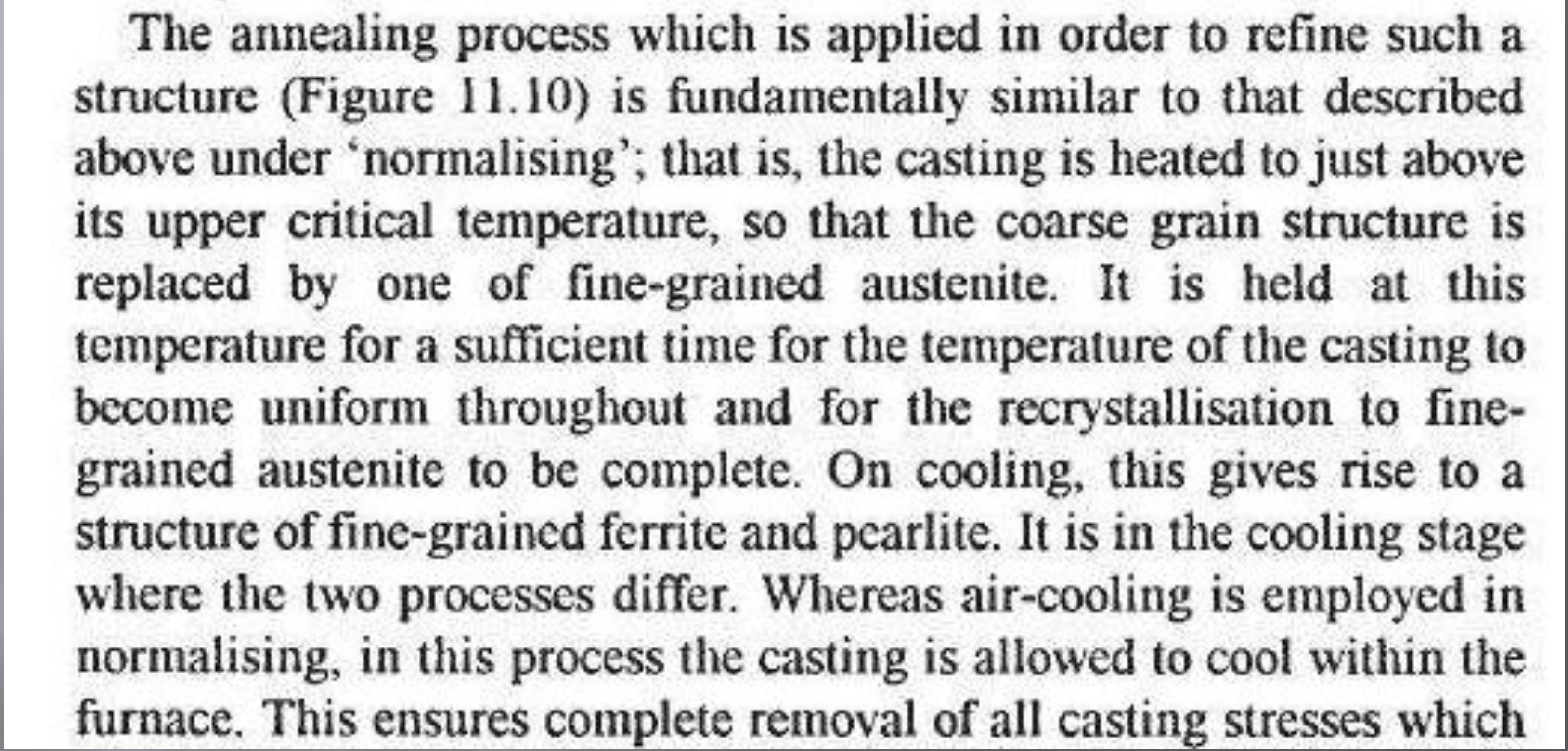


Figure 11.9 *The normalising temperature of a medium-carbon steel in relation to the equilibrium diagram.*

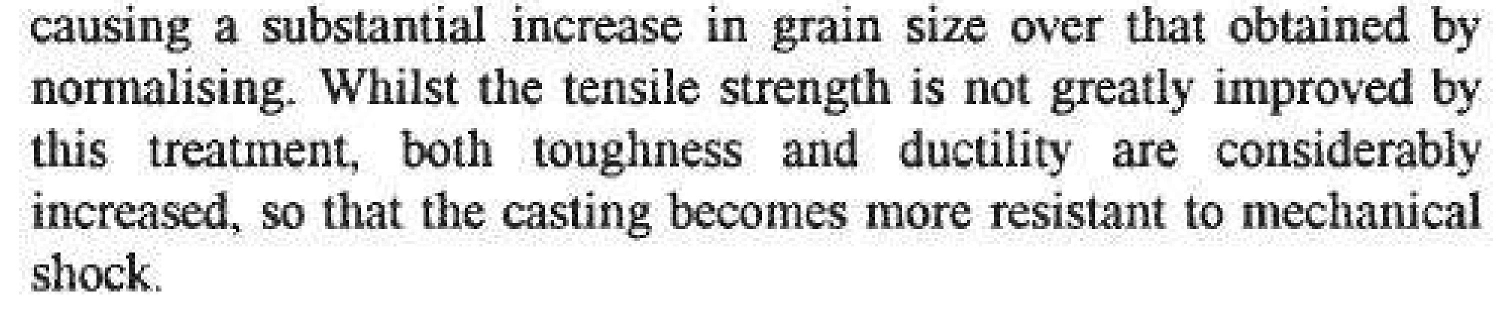


11.6.2 Annealing

A number of different heat-treatment processes are covered by the general description of annealing. These processes are applied to different steels of widely ranging carbon content. The three principal annealing processes are:



The annealing process which is applied in order to refine such a structure (Figure 11.10) is fundamentally similar to that described above under 'normalising'; that is, the casting is heated to just above its upper critical temperature, so that the coarse grain structure is replaced by one of fine-grained austenite. It is held at this temperature for a sufficient time for the temperature of the casting to become uniform throughout and for the recrystallisation to fine-grained austenite to be complete. On cooling, this gives rise to a structure of fine-grained ferrite and pearlite. It is in the cooling stage where the two processes differ. Whereas air-cooling is employed in normalising, in this process the casting is allowed to cool within the furnace. This ensures complete removal of all casting stresses which



causing a substantial increase in grain size over that obtained by normalising. Whilst the tensile strength is not greatly improved by this treatment, both toughness and ductility are considerably increased, so that the casting becomes more resistant to mechanical shock.

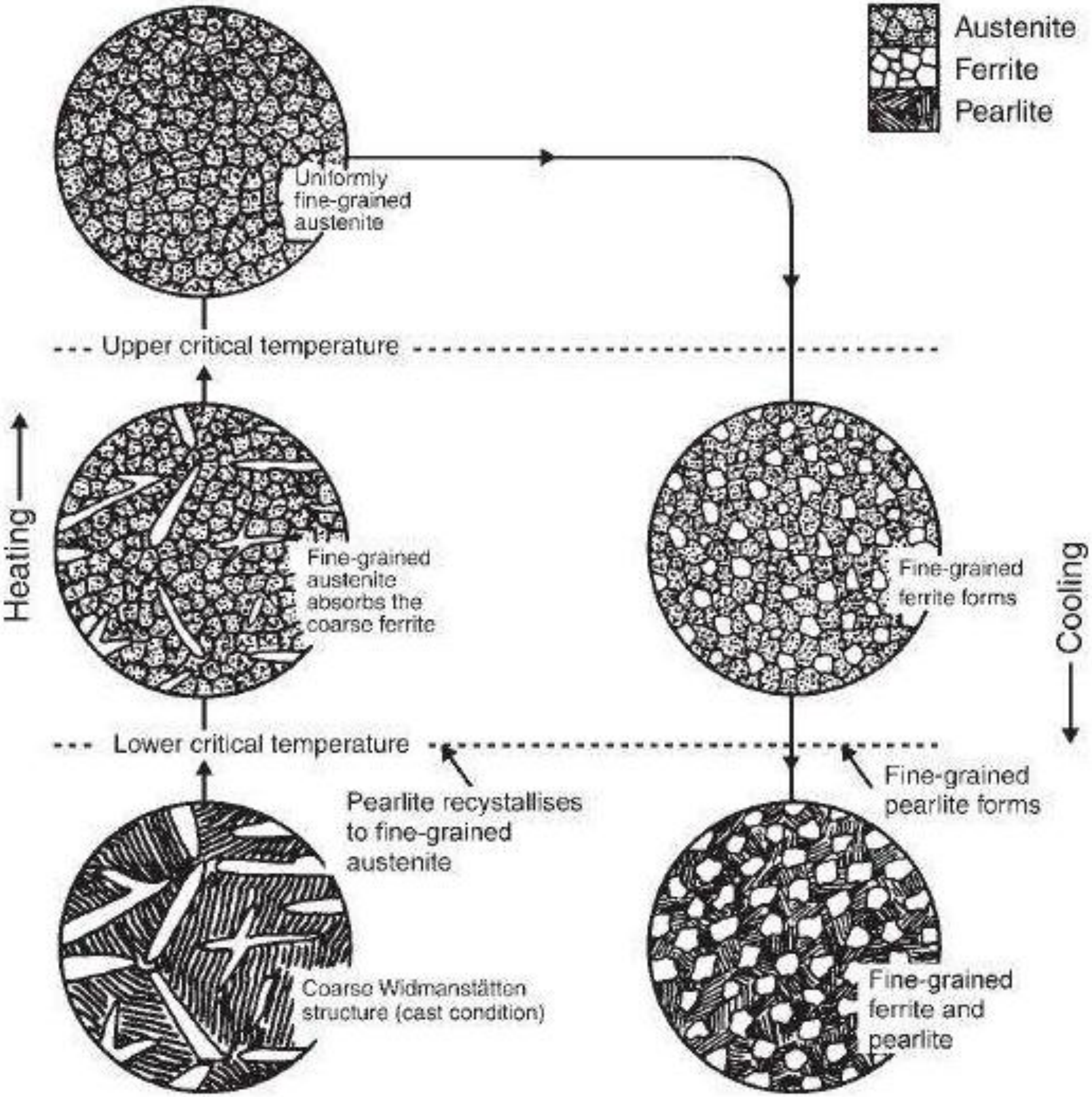


Figure 11.10 *The refinement of grain in a steel casting during a suitable annealing process.*

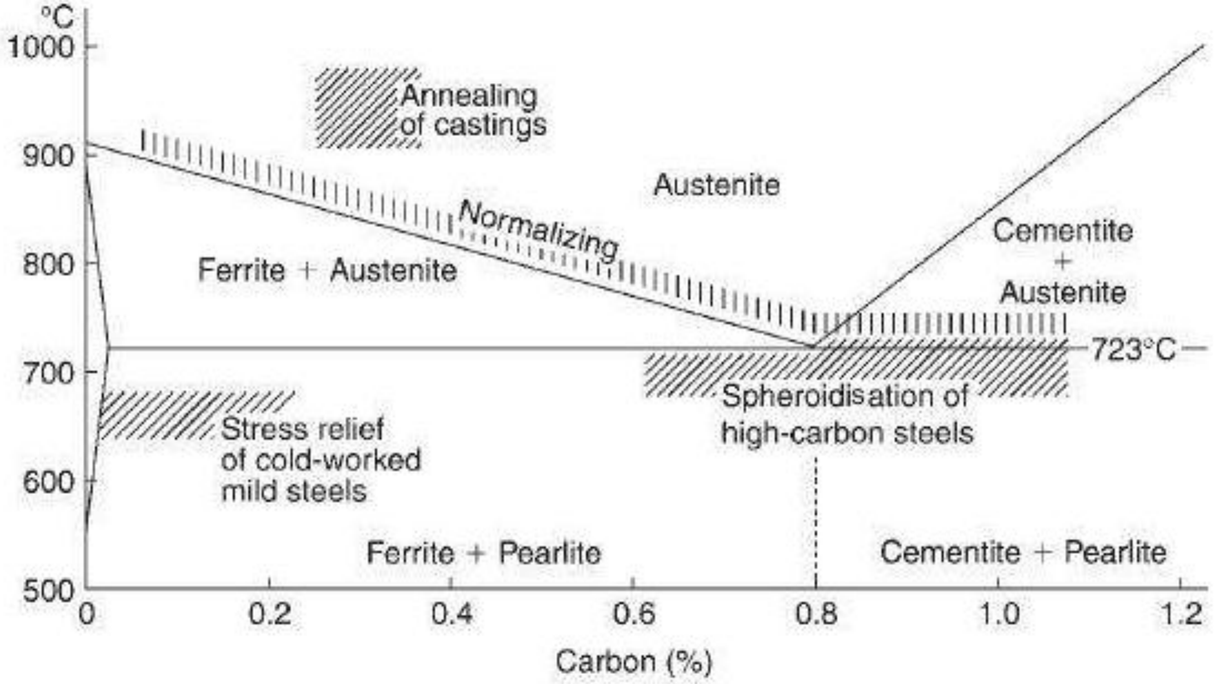
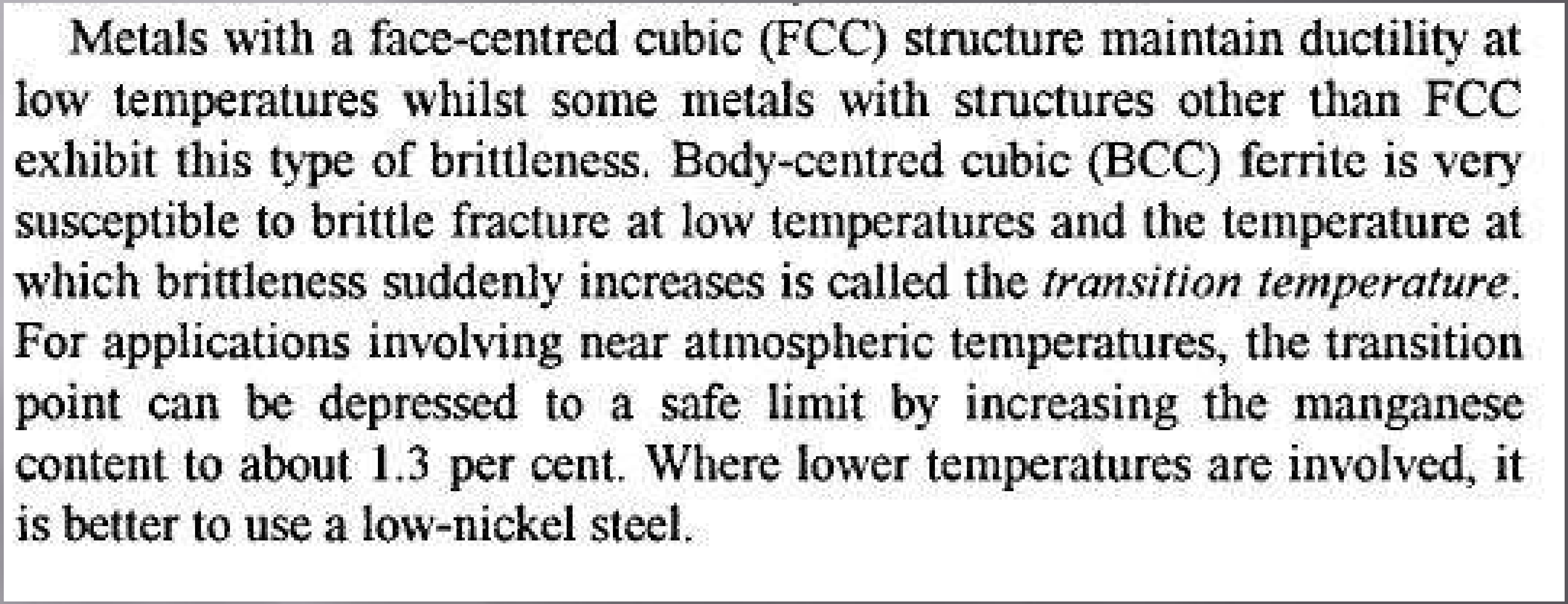


Figure 11.13 *Temperature ranges of various annealing and normalising treatments for carbon steels related to the carbon contents.*

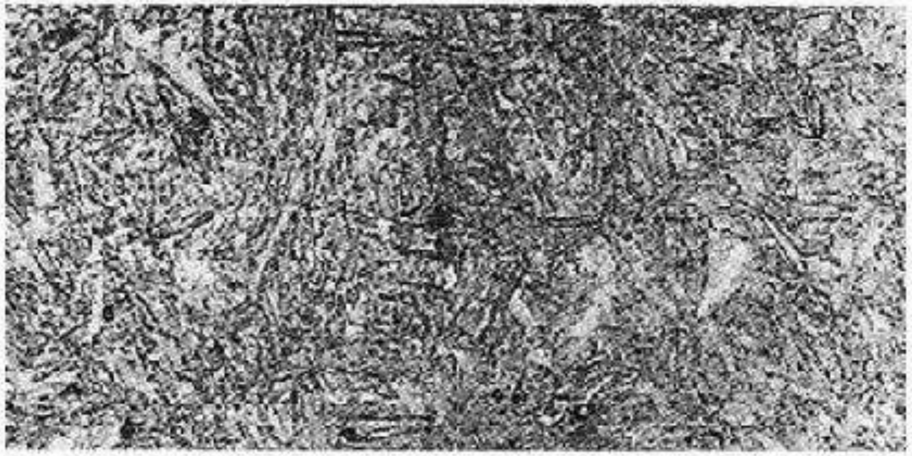
Brittle fracture in steels



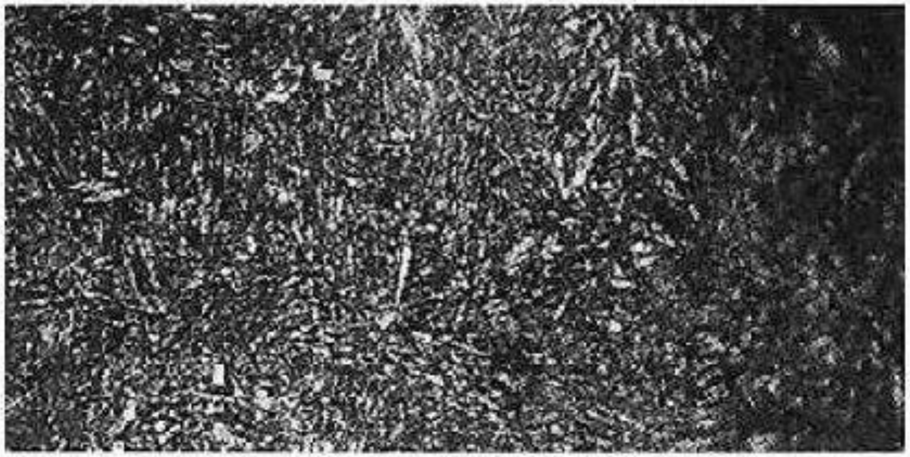
Metals with a face-centred cubic (FCC) structure maintain ductility at low temperatures whilst some metals with structures other than FCC exhibit this type of brittleness. Body-centred cubic (BCC) ferrite is very susceptible to brittle fracture at low temperatures and the temperature at which brittleness suddenly increases is called the *transition temperature*. For applications involving near atmospheric temperatures, the transition point can be depressed to a safe limit by increasing the manganese content to about 1.3 per cent. Where lower temperatures are involved, it is better to use a low-nickel steel.

Principles of hardening

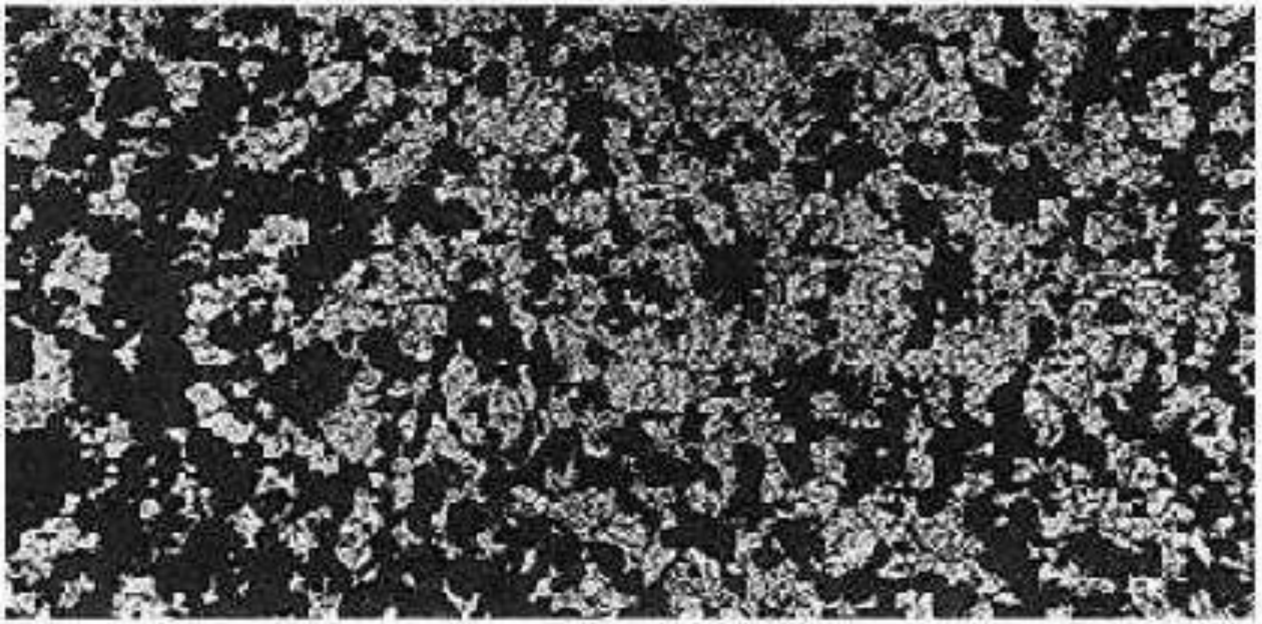
If a piece of steel containing sufficient carbon is heated until its structure is austenitic – that is, until its temperature is above the upper critical temperature – and is then quenched, i.e. cooled quickly, it becomes considerably harder than it would be were it cooled slowly.



(i)



(ii)



(iii)

Figure 12.1 *Representative structures of quenched and tempered specimens of a 0.5 per cent carbon steel: (i) water-quenched from 850°C – martensite which appears as an irregular mass of needle-shaped crystals, but what we see is a cross-section through roughly discus-shaped crystals (×700); (ii) water-quenched from 850°C and tempered at 400°C – tempered martensite, the crystals of which have become darkened by precipitated particles of cementite (×700); (iii) oil-quenched from 850°C – the slower cooling rate during quenching has allowed a mixture of bainite (dark) and martensite (light) to form (×100).*

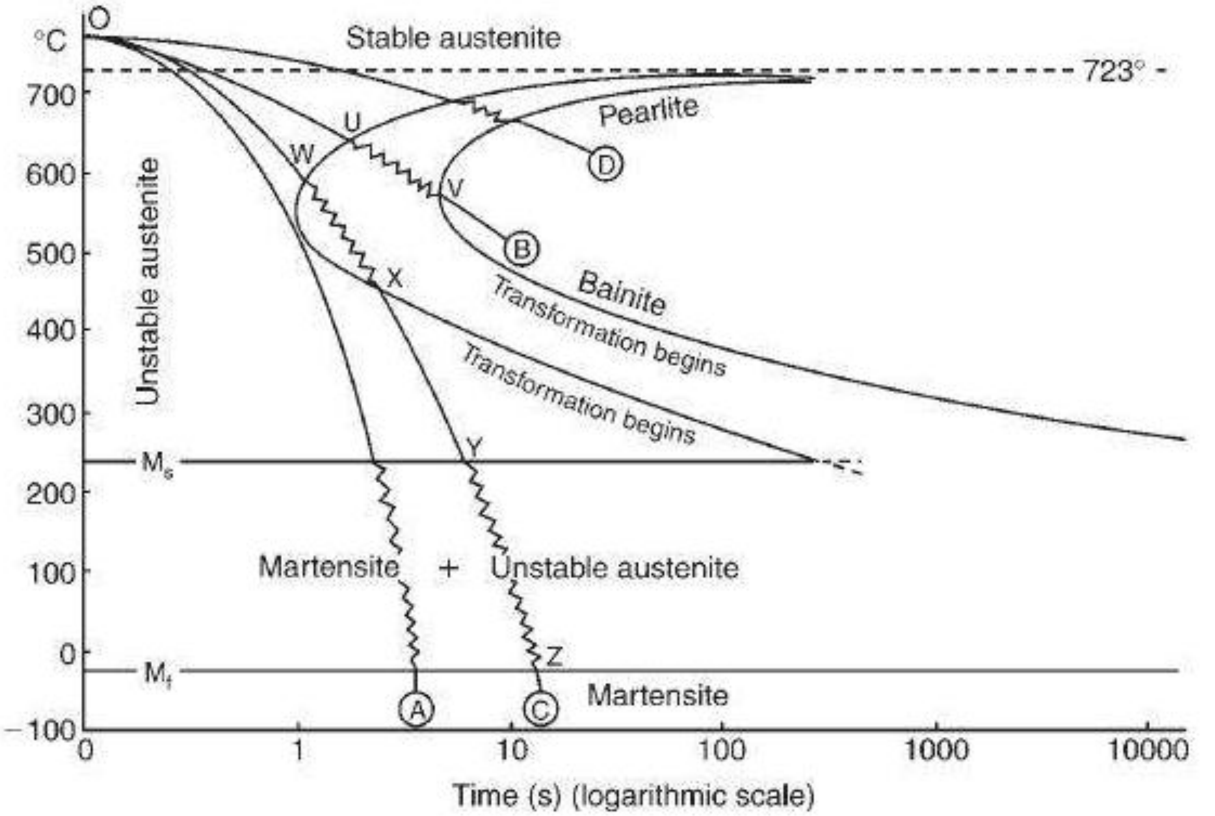


Figure 12.2 *Modified TTT curves for a 0.8 per cent plain carbon steel. Note that a logarithmic scale is used on the horizontal axis in order to compress the right-hand end of the diagram without at the same time cramping the important left-hand side.*

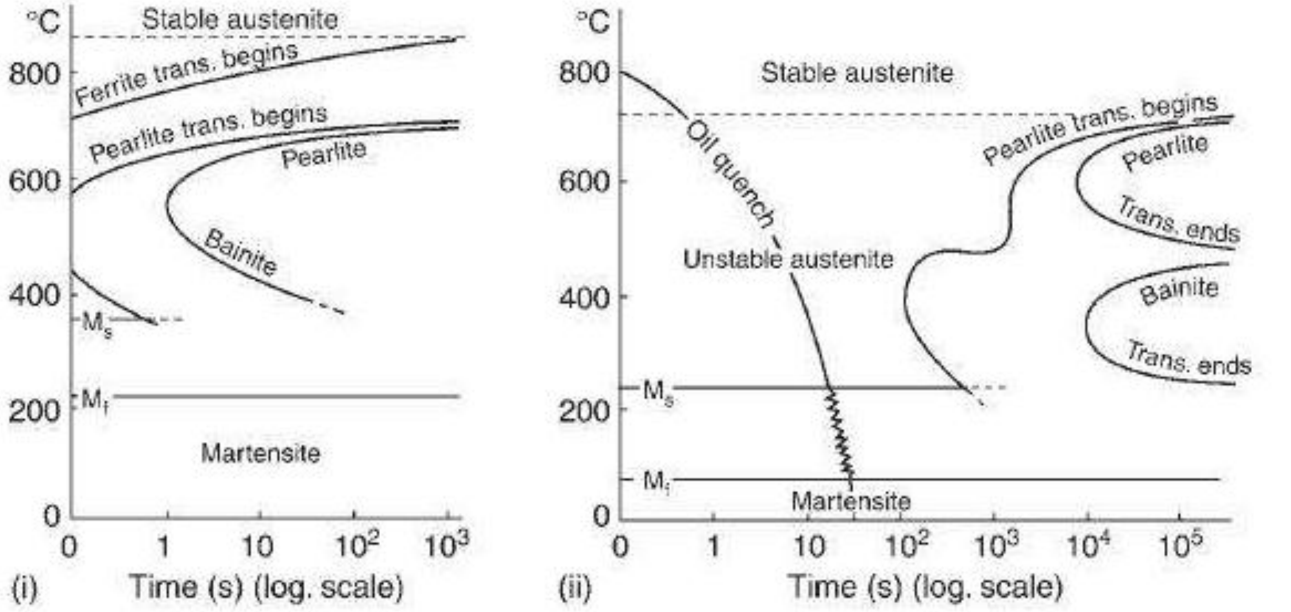


Figure 12.3 *(i) The TTT curves for a 0.35 per cent carbon steel showing that it is virtually impossible to produce a completely martensitic structure by quenching, since however rapid the cooling rate, ferrite separation inevitably begins as the 'ferrite transformation begins' curve is cut. (ii) The TTT curves for an alloy steel containing 0.6 per cent C, 0.6 per cent Mn, 1.8 per cent Ni, 0.6 per cent Cr and 0.3 per cent Mo. This indicates the effects of alloying in slowing transformation rates so that the TTT curves are displaced far to the right. This steel can be oil-quenched to give a martensitic structure.*

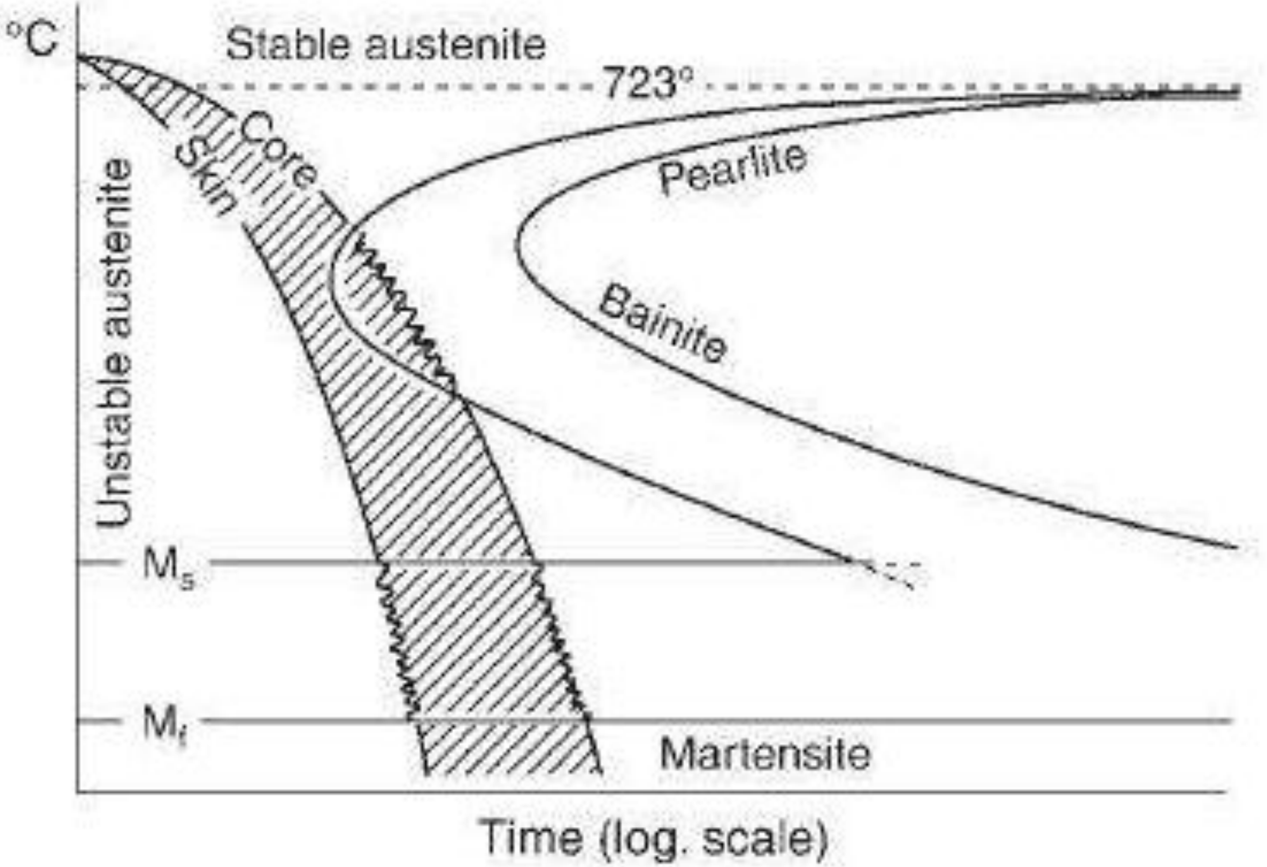
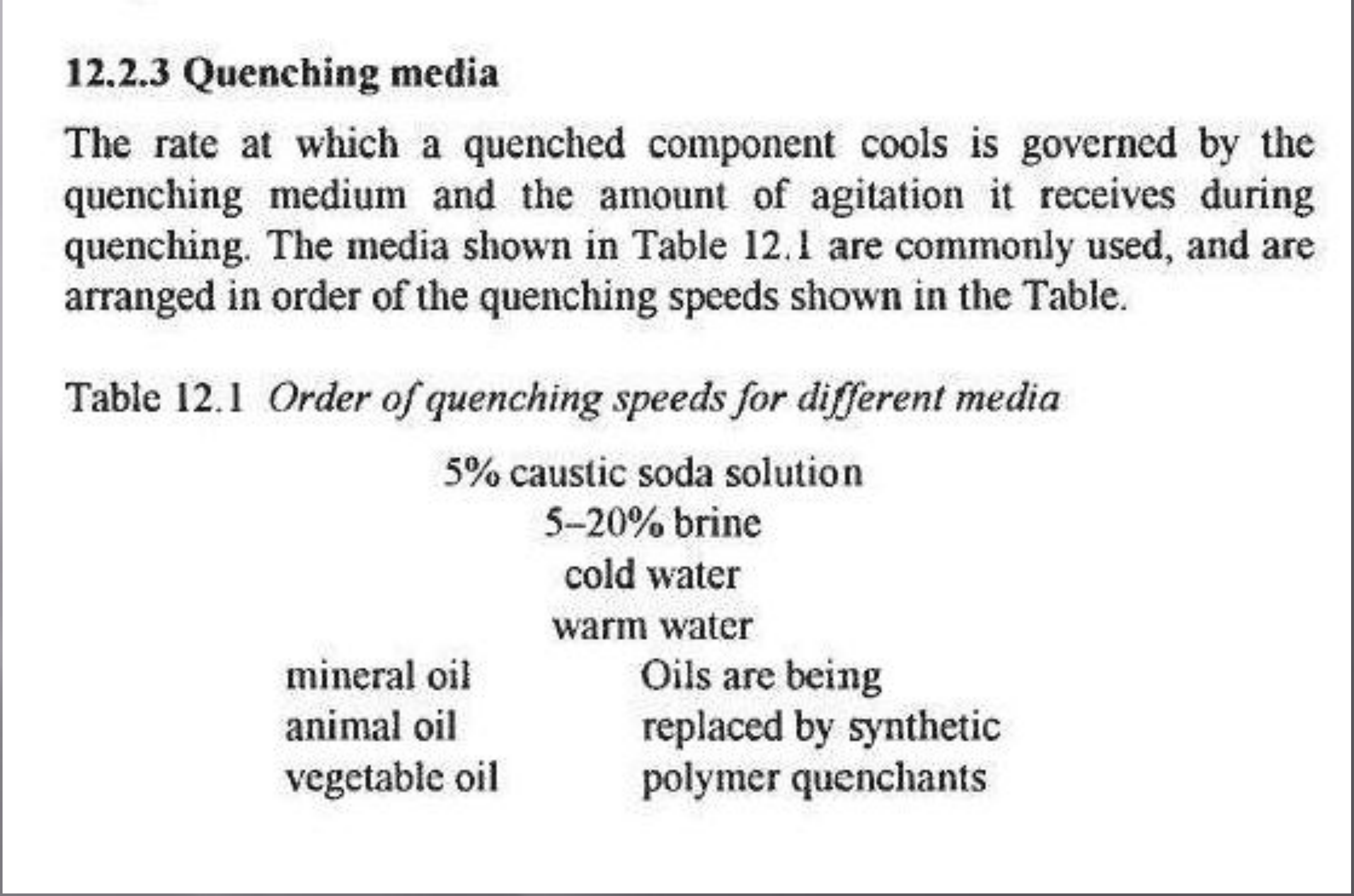


Figure 12.4 *TTT curves for a thick component.*



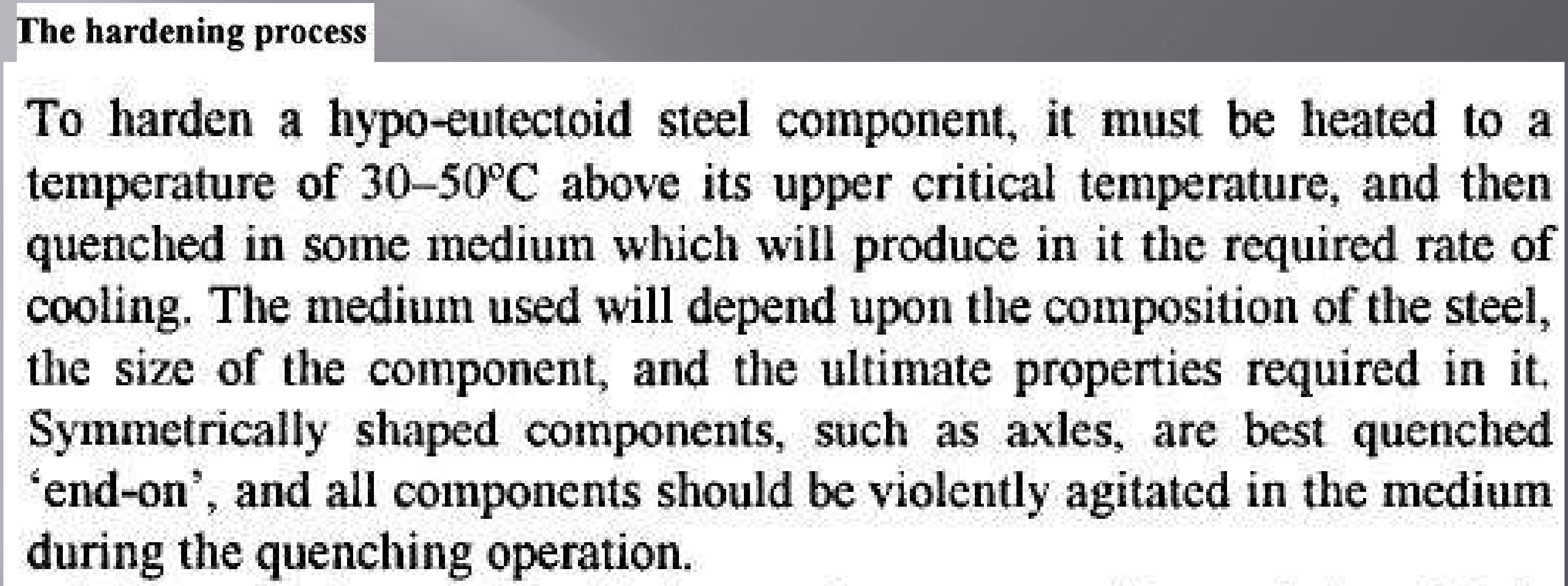
12.2.3 Quenching media

The rate at which a quenched component cools is governed by the quenching medium and the amount of agitation it receives during quenching. The media shown in Table 12.1 are commonly used, and are arranged in order of the quenching speeds shown in the Table.

Table 12.1 *Order of quenching speeds for different media*

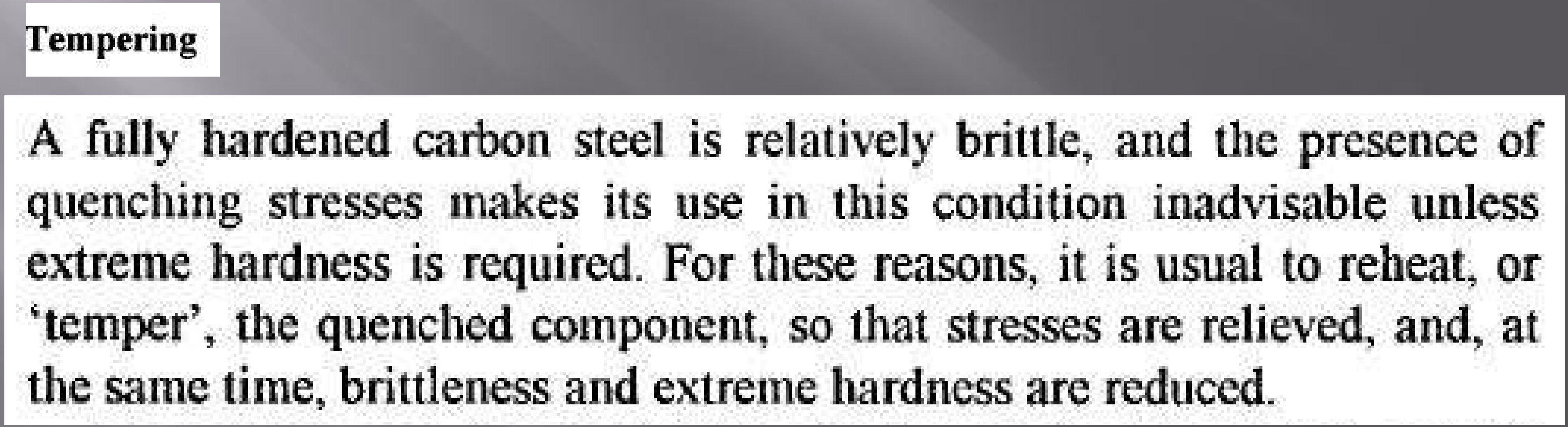
5% caustic soda solution
5–20% brine
cold water
warm water
mineral oil
animal oil
vegetable oil

Oils are being replaced by synthetic polymer quenchants



The hardening process

To harden a hypo-eutectoid steel component, it must be heated to a temperature of 30–50°C above its upper critical temperature, and then quenched in some medium which will produce in it the required rate of cooling. The medium used will depend upon the composition of the steel, the size of the component, and the ultimate properties required in it. Symmetrically shaped components, such as axles, are best quenched ‘end-on’, and all components should be violently agitated in the medium during the quenching operation.



Tempering

A fully hardened carbon steel is relatively brittle, and the presence of quenching stresses makes its use in this condition inadvisable unless extreme hardness is required. For these reasons, it is usual to reheat, or ‘temper’, the quenched component, so that stresses are relieved, and, at the same time, brittleness and extreme hardness are reduced.

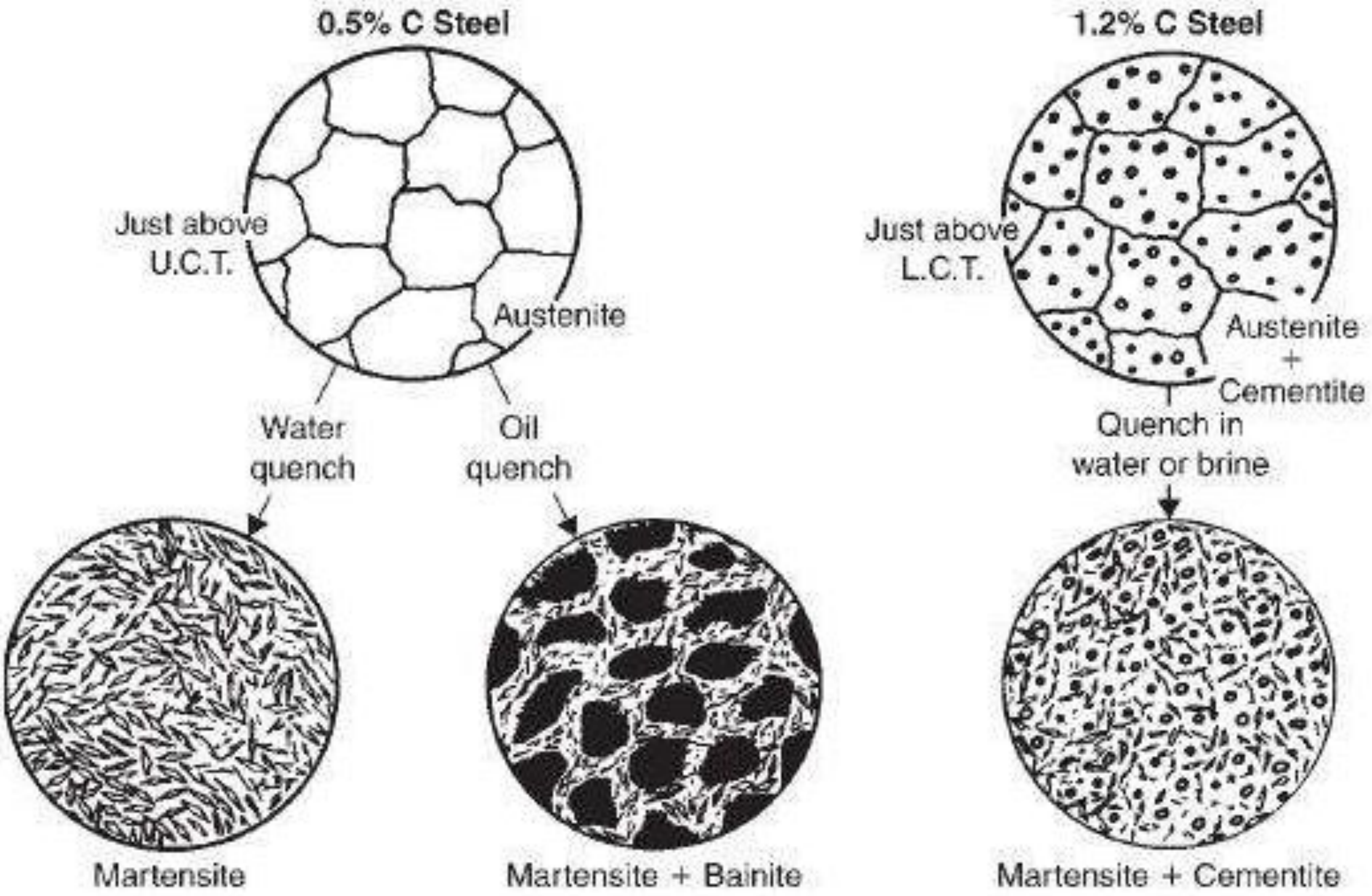


Figure 12.5 *Typical microstructures produced when quenching both medium-carbon and tool steels in their appropriate media.*

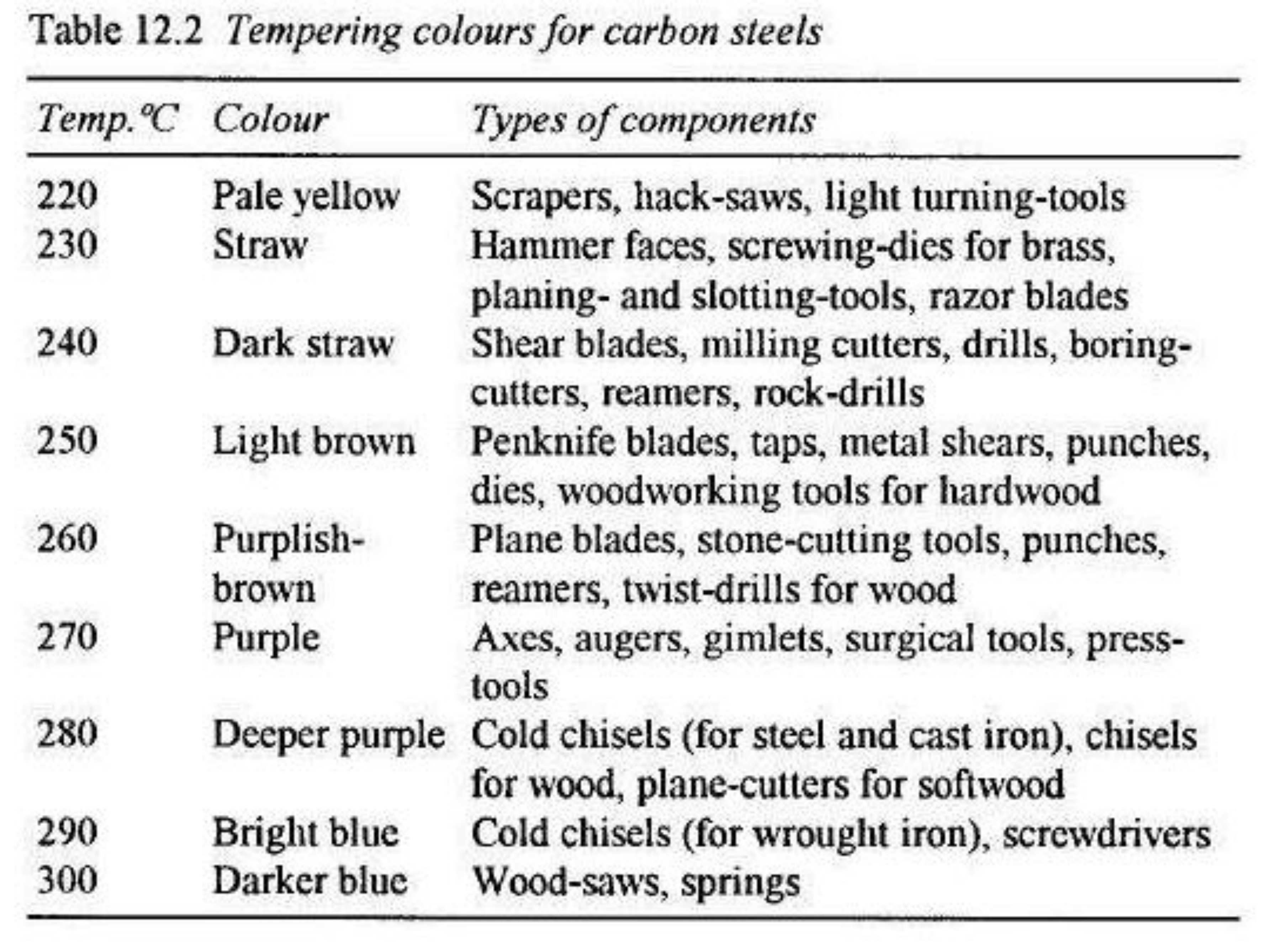


Table 12.2 *Tempering colours for carbon steels*

Temp.°C	*Colour*	*Types of components*
220	Pale yellow	Scrapers, hack-saws, light turning-tools
230	Straw	Hammer faces, screwing-dies for brass, planing- and slotting-tools, razor blades
240	Dark straw	Shear blades, milling cutters, drills, boring-cutters, reamers, rock-drills
250	Light brown	Penknife blades, taps, metal shears, punches, dies, woodworking tools for hardwood
260	Purplish-brown	Plane blades, stone-cutting tools, punches, reamers, twist-drills for wood
270	Purple	Axes, augers, gimlets, surgical tools, press-tools
280	Deeper purple	Cold chisels (for steel and cast iron), chisels for wood, plane-cutters for softwood
290	Bright blue	Cold chisels (for wrought iron), screwdrivers
300	Darker blue	Wood-saws, springs

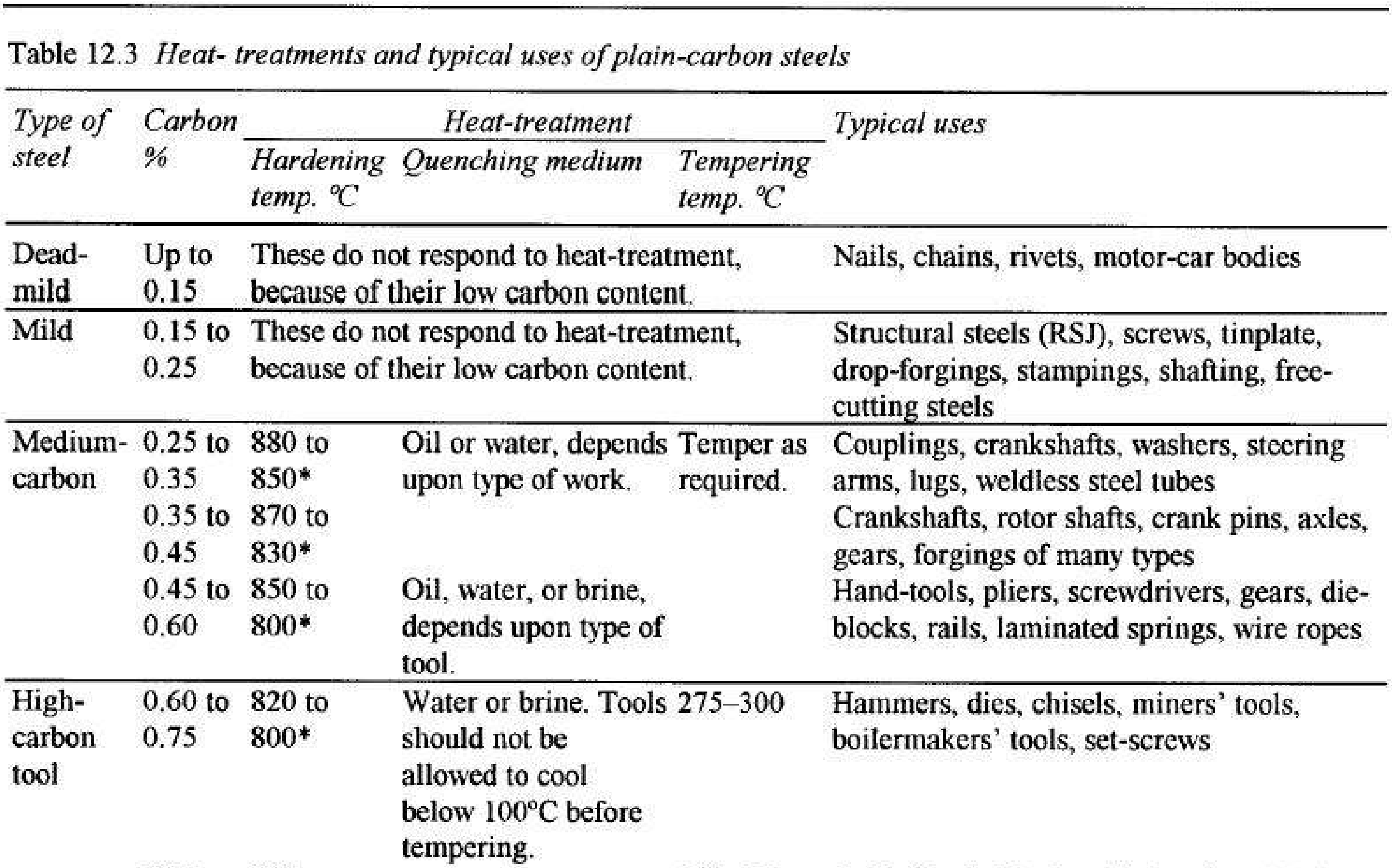
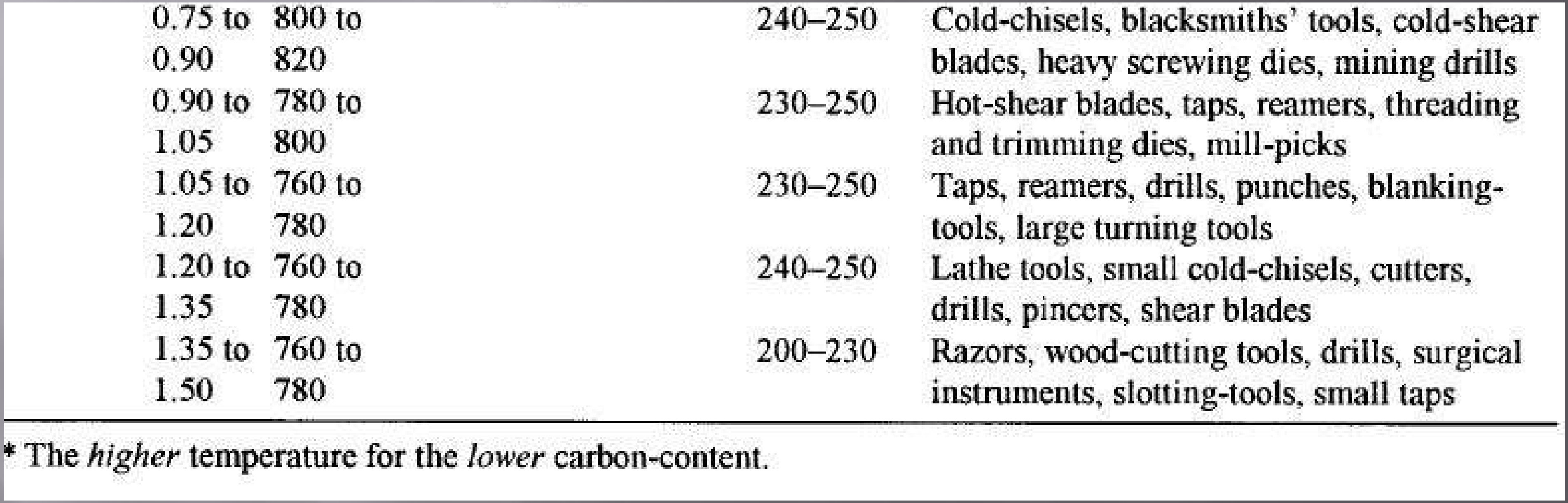


Table 12.3 *Heat- treatments and typical uses of plain-carbon steels*

Type of steel	*Carbon %*	*Heat-treatment*			*Typical uses*
		Hardening temp. °C	*Quenching medium*	*Tempering temp. °C*	
Dead-mild	Up to 0.15	These do not respond to heat-treatment, because of their low carbon content.			Nails, chains, rivets, motor-car bodies
Mild	0.15 to 0.25	These do not respond to heat-treatment, because of their low carbon content.			Structural steels (RSJ), screws, tinplate, drop-forgings, stampings, shafting, free-cutting steels
Medium-carbon	0.25 to 0.35	880 to 850*	Oil or water, depends upon type of work.	Temper as required.	Couplings, crankshafts, washers, steering arms, lugs, weldless steel tubes
	0.35 to 0.45	870 to 830*			Crankshafts, rotor shafts, crank pins, axles, gears, forgings of many types
	0.45 to 0.60	850 to 800*	Oil, water, or brine, depends upon type of tool.		Hand-tools, pliers, screwdrivers, gears, die-blocks, rails, laminated springs, wire ropes
High-carbon tool	0.60 to 0.75	820 to 800*	Water or brine. Tools should not be allowed to cool below 100°C before tempering.	275–300	Hammers, dies, chisels, miners' tools, boilermakers' tools, set-screws



0.75 to 0.90	800 to 820	240–250	Cold-chisels, blacksmiths' tools, cold-shear blades, heavy screwing dies, mining drills
0.90 to 1.05	780 to 800	230–250	Hot-shear blades, taps, reamers, threading and trimming dies, mill-picks
1.05 to 1.20	760 to 780	230–250	Taps, reamers, drills, punches, blanking-tools, large turning tools
1.20 to 1.35	760 to 780	240–250	Lathe tools, small cold-chisels, cutters, drills, pincers, shear blades
1.35 to 1.50	760 to 780	200–230	Razors, wood-cutting tools, drills, surgical instruments, slotting-tools, small taps

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* The *higher* temperature for the *lower* carbon-content.

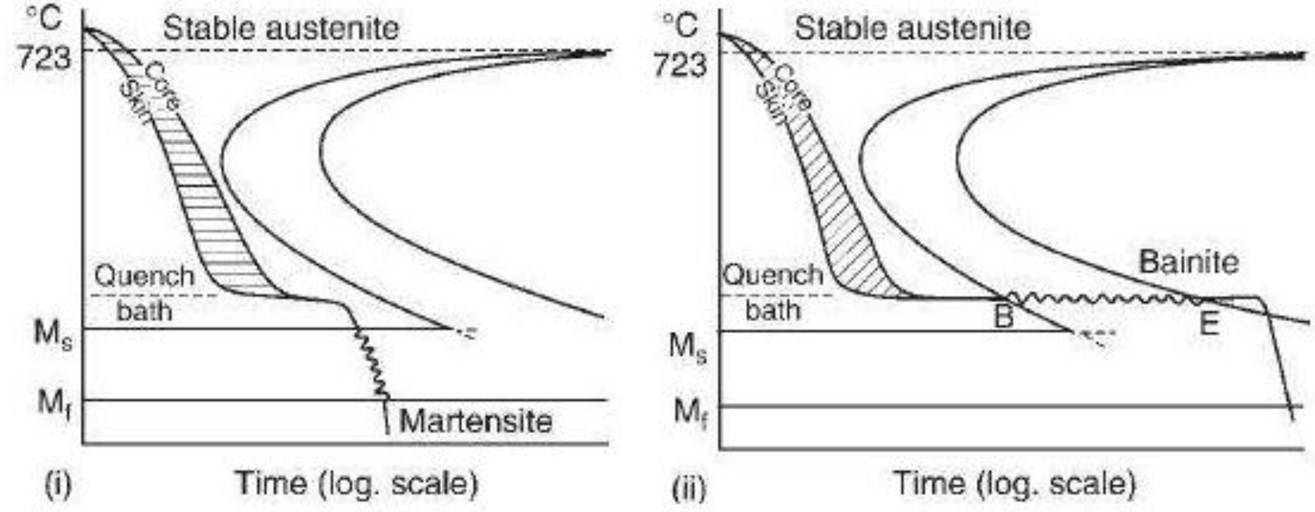


Figure 12.6 *The isothermal treatment of (i) martempering and (ii) austempering.*

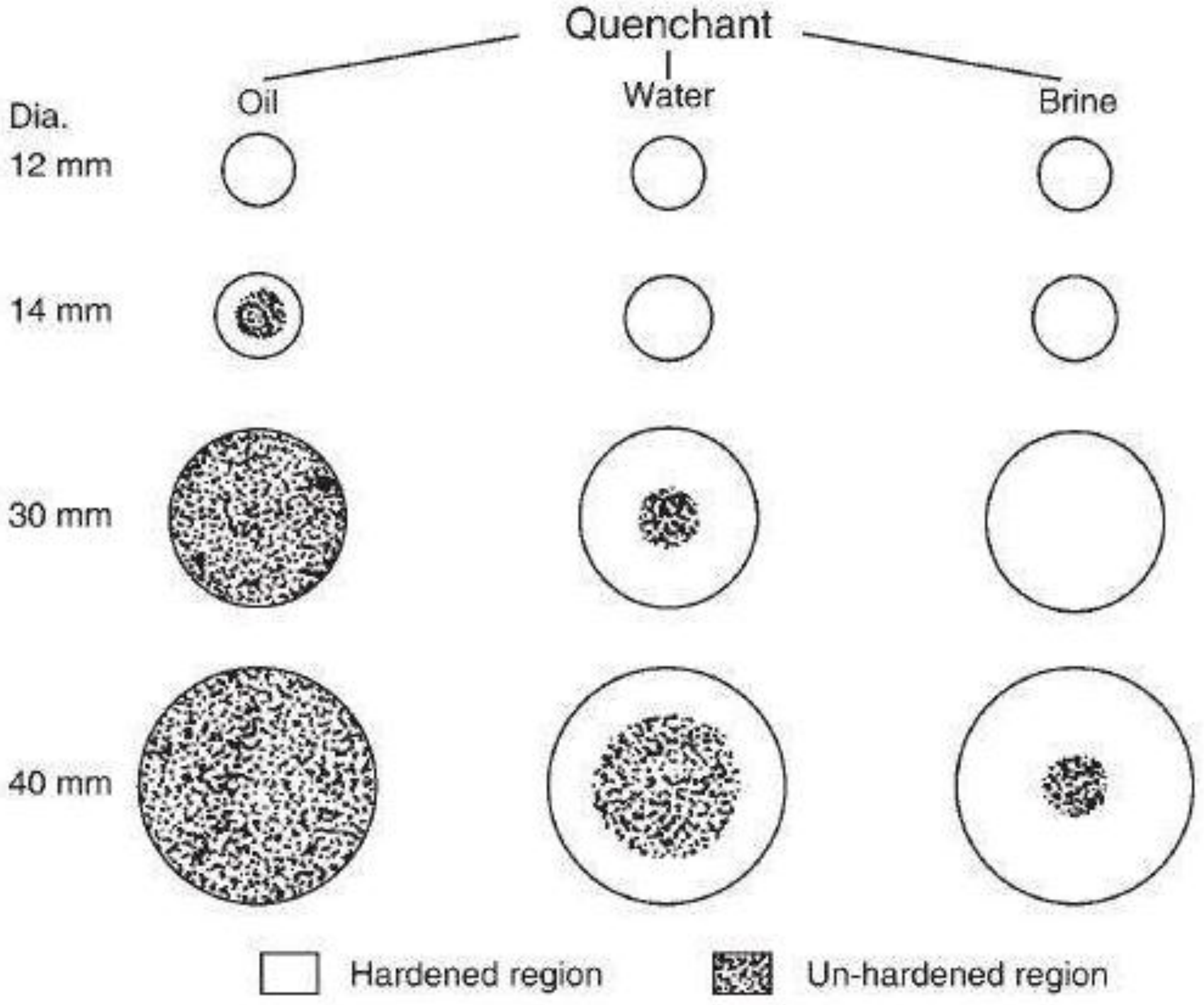
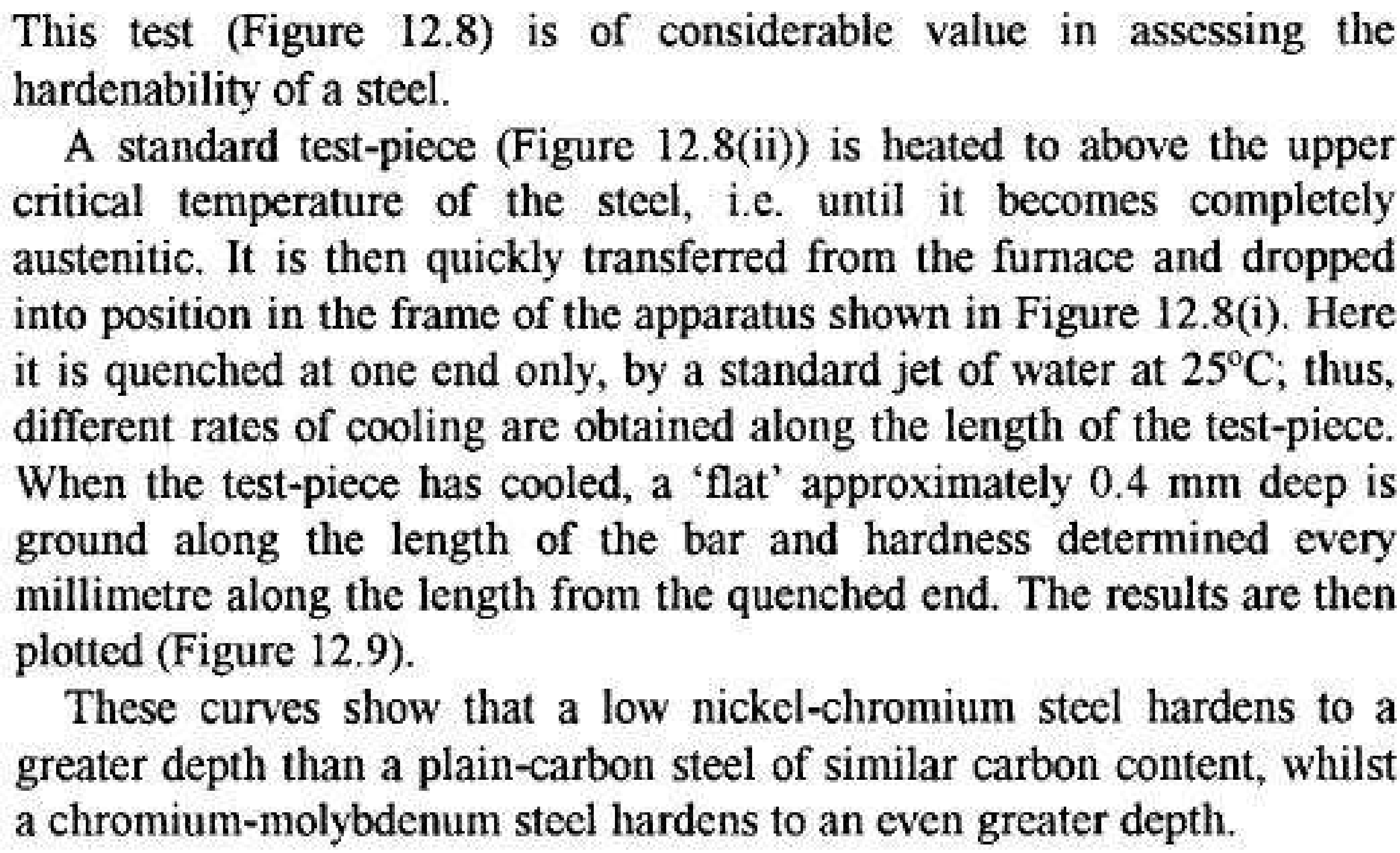


Figure 12.7 *Specimens of different diameter have been quenched in different media and the depth of hardening assessed in each case. A low-alloy steel containing 0.25 per cent C, 0.6 per cent Mn, 0.2 per cent Ni, and 0.2 per cent Mo was used.*

The Jominy test



This test (Figure 12.8) is of considerable value in assessing the hardenability of a steel.

A standard test-piece (Figure 12.8(ii)) is heated to above the upper critical temperature of the steel, i.e. until it becomes completely austenitic. It is then quickly transferred from the furnace and dropped into position in the frame of the apparatus shown in Figure 12.8(i). Here it is quenched at one end only, by a standard jet of water at 25°C; thus, different rates of cooling are obtained along the length of the test-piece. When the test-piece has cooled, a 'flat' approximately 0.4 mm deep is ground along the length of the bar and hardness determined every millimetre along the length from the quenched end. The results are then plotted (Figure 12.9).

These curves show that a low nickel-chromium steel hardens to a greater depth than a plain-carbon steel of similar carbon content, whilst a chromium-molybdenum steel hardens to an even greater depth.

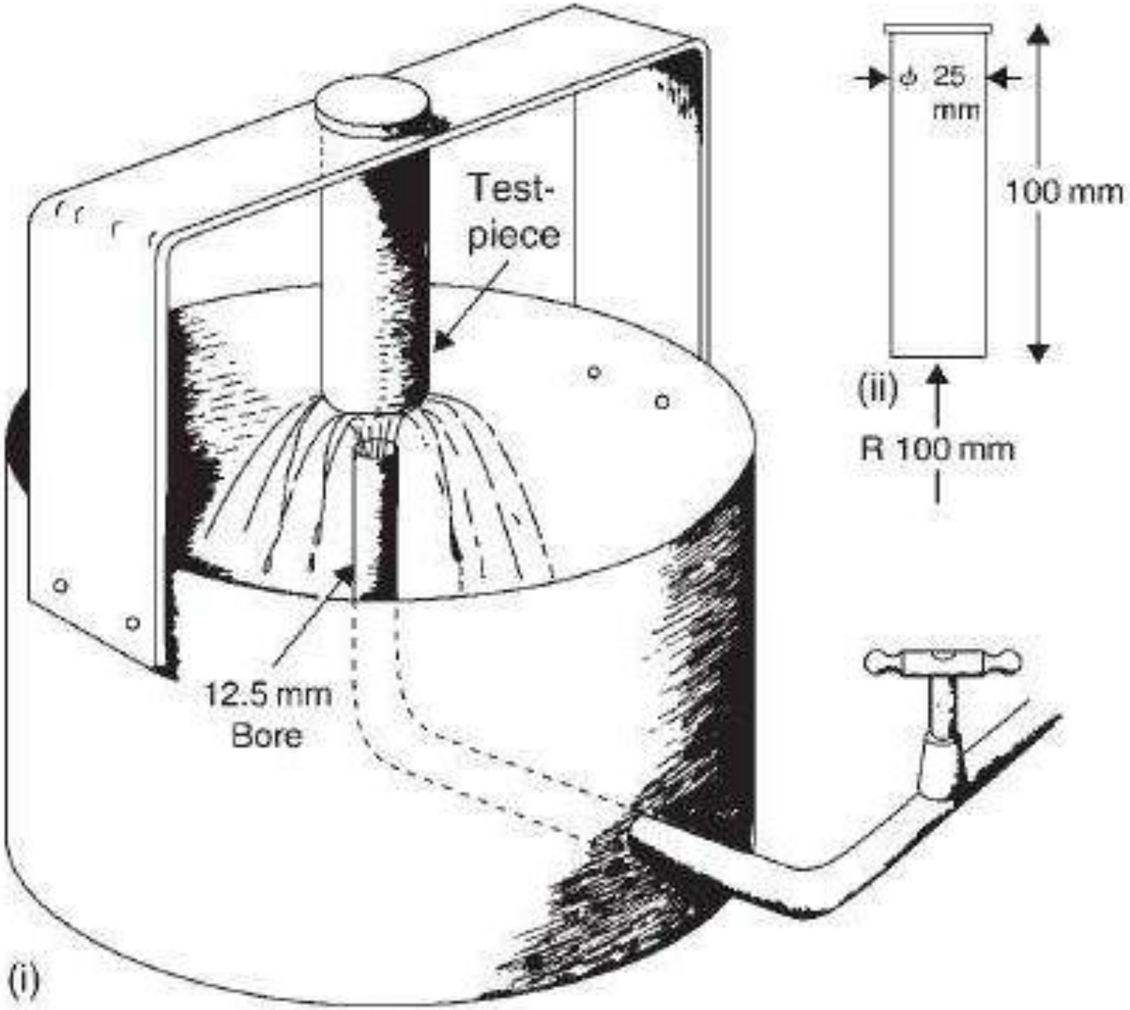


Figure 12.8 *The Jominy end-quench test. (i) The apparatus: the end of the water pipe is 12 mm below the bottom of the test-piece, but the 'free height' of the water jet is 63 mm. (ii) A typical test-piece.*

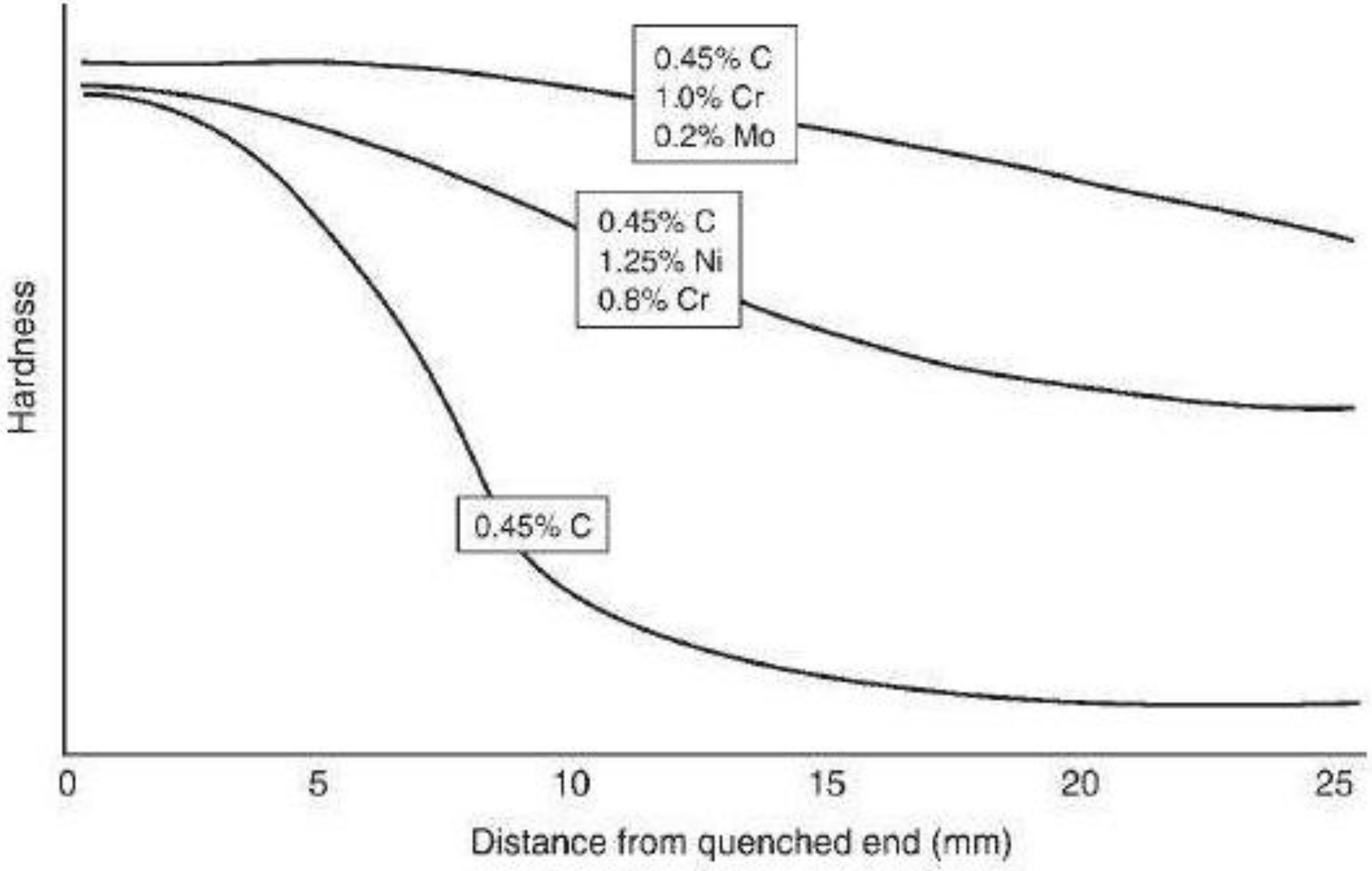
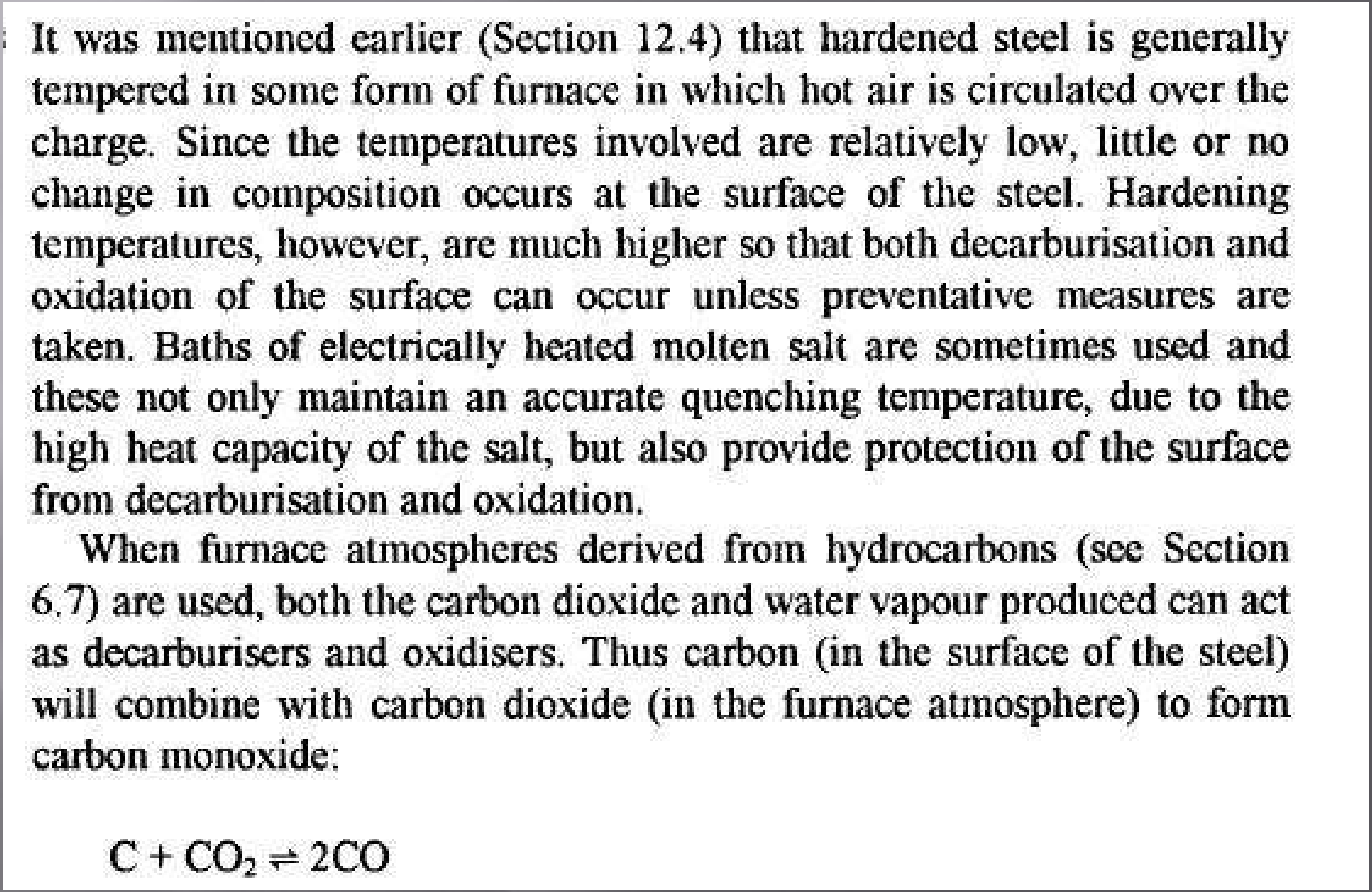


Figure 12.9 *Hardness as a function of depth for various steels of similar carbon content, as shown by the Jominy test.*

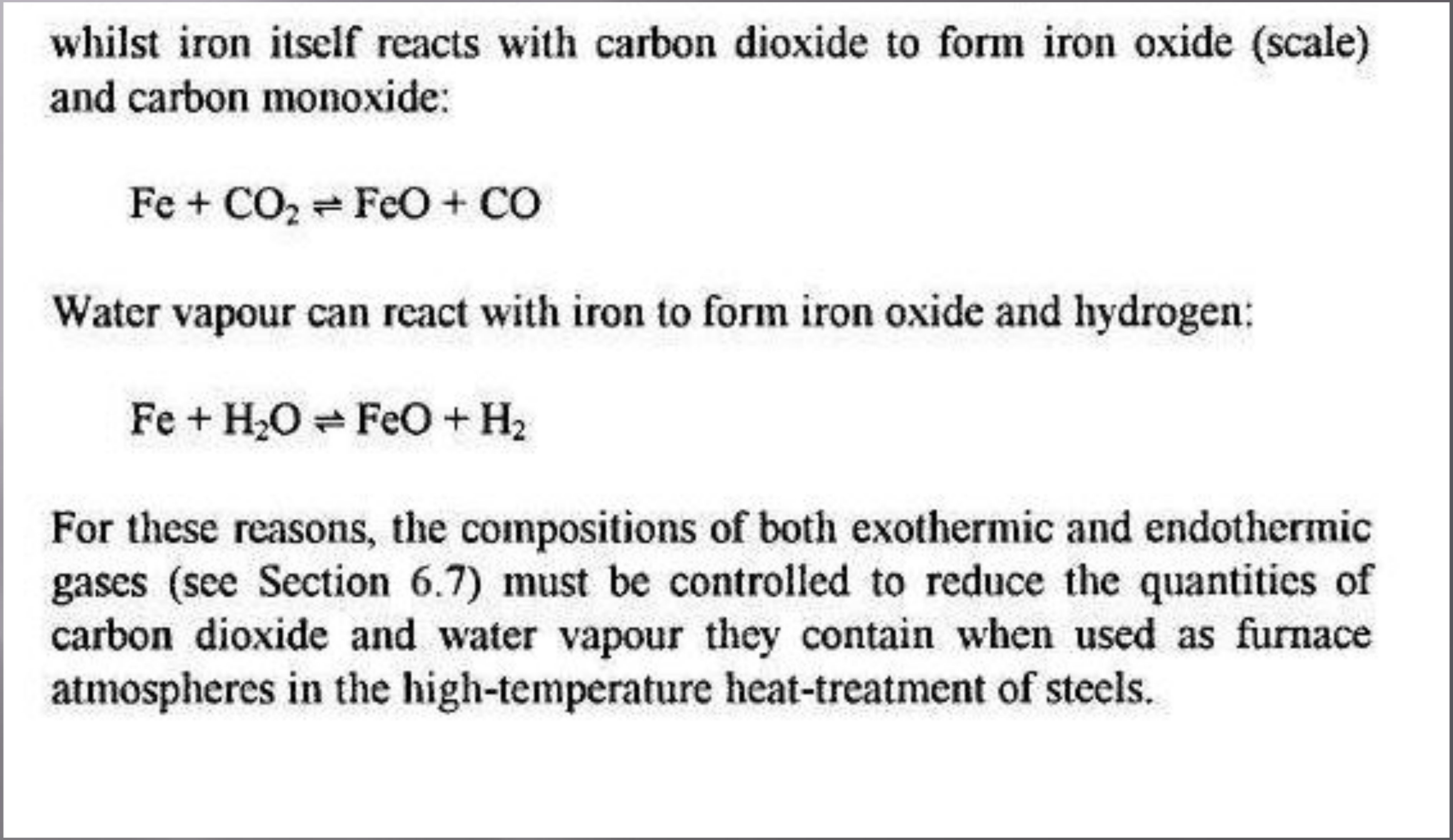
Heat treatment furnaces



It was mentioned earlier (Section 12.4) that hardened steel is generally tempered in some form of furnace in which hot air is circulated over the charge. Since the temperatures involved are relatively low, little or no change in composition occurs at the surface of the steel. Hardening temperatures, however, are much higher so that both decarburisation and oxidation of the surface can occur unless preventative measures are taken. Baths of electrically heated molten salt are sometimes used and these not only maintain an accurate quenching temperature, due to the high heat capacity of the salt, but also provide protection of the surface from decarburisation and oxidation.

When furnace atmospheres derived from hydrocarbons (see Section 6.7) are used, both the carbon dioxide and water vapour produced can act as decarburisers and oxidisers. Thus carbon (in the surface of the steel) will combine with carbon dioxide (in the furnace atmosphere) to form carbon monoxide:

$$C + CO_2 \rightleftharpoons 2CO$$



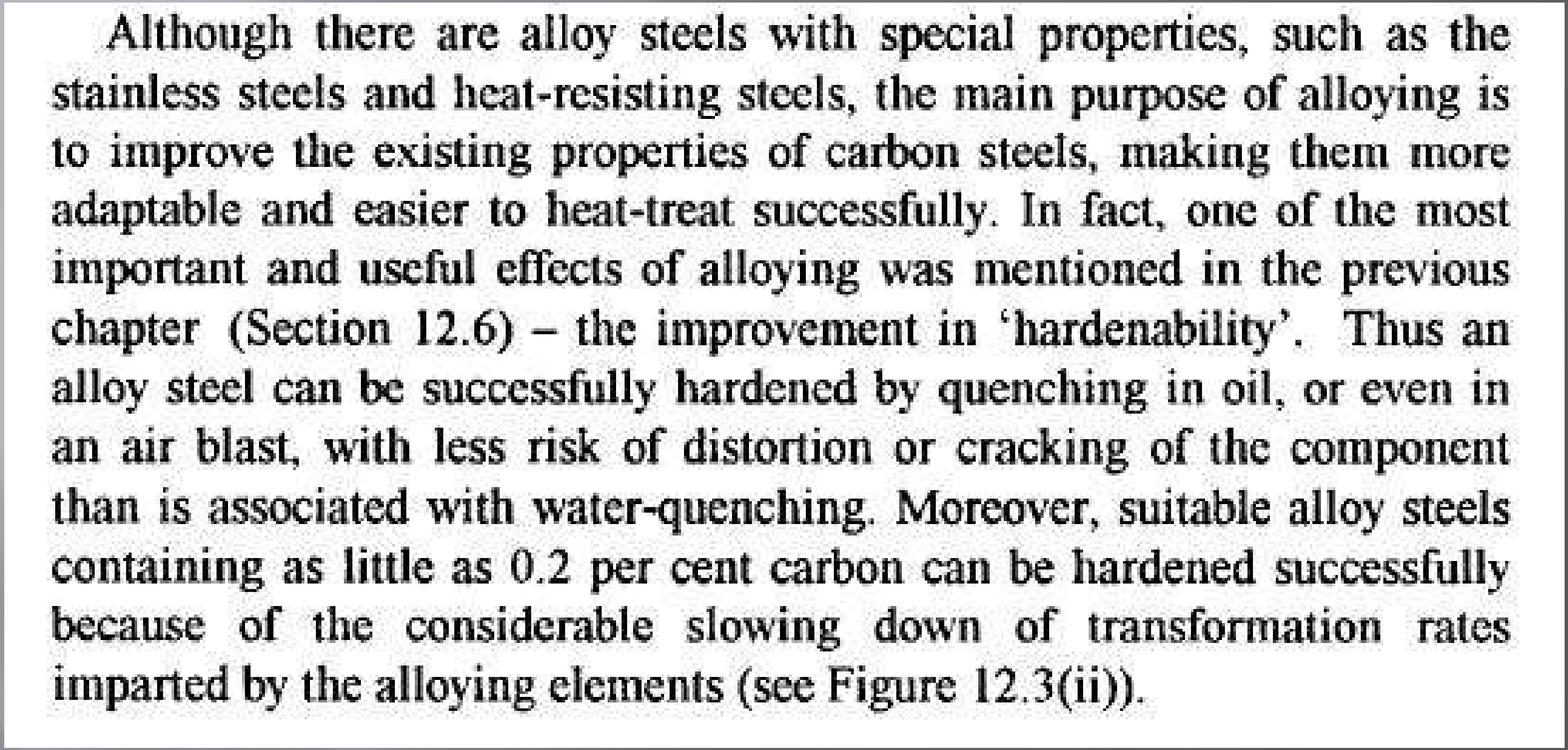
whilst iron itself reacts with carbon dioxide to form iron oxide (scale) and carbon monoxide:

$$Fe + CO_2 \rightleftharpoons FeO + CO$$

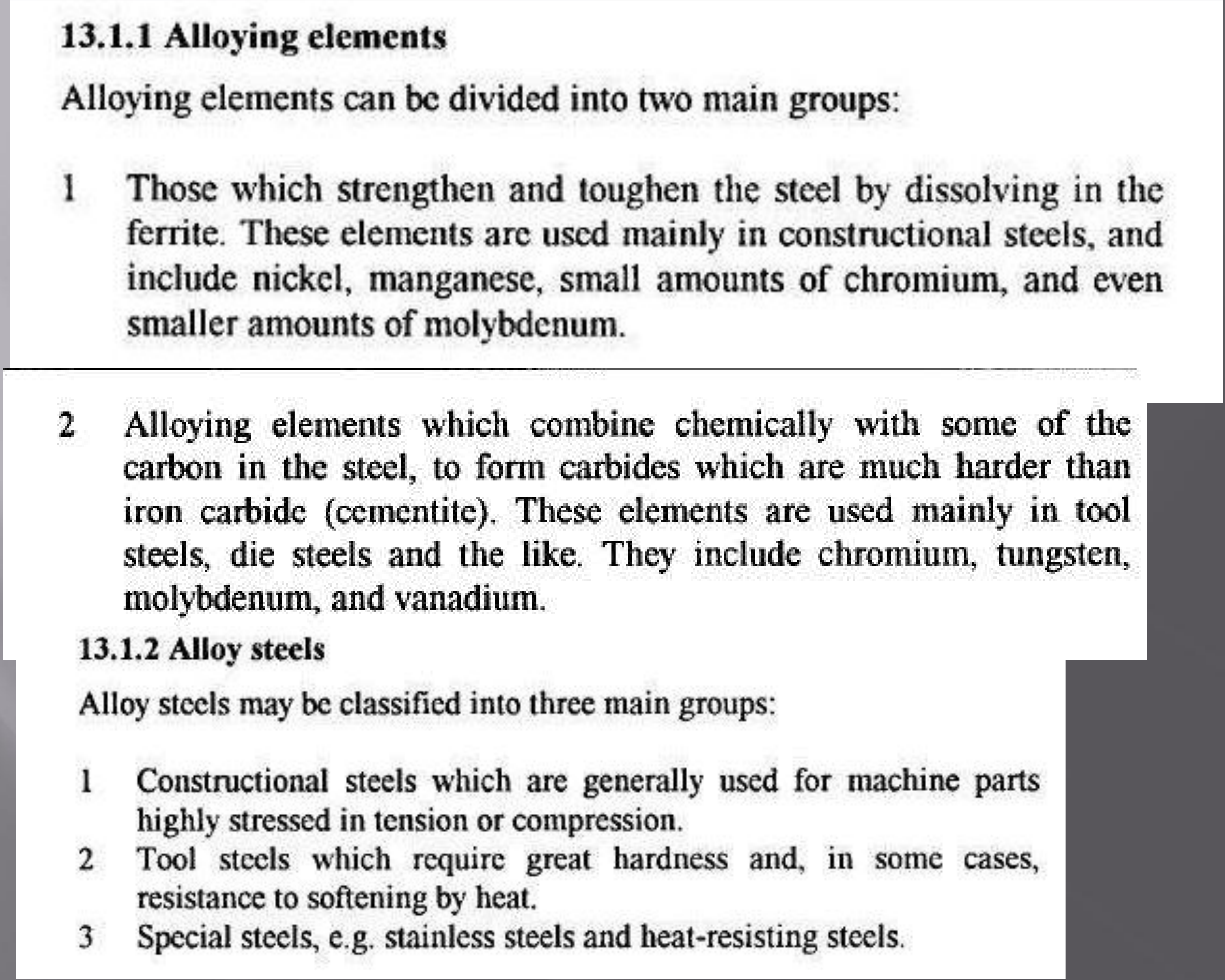
Water vapour can react with iron to form iron oxide and hydrogen:

$$Fe + H_2O \rightleftharpoons FeO + H_2$$

For these reasons, the compositions of both exothermic and endothermic gases (see Section 6.7) must be controlled to reduce the quantities of carbon dioxide and water vapour they contain when used as furnace atmospheres in the high-temperature heat-treatment of steels.



Although there are alloy steels with special properties, such as the stainless steels and heat-resisting steels, the main purpose of alloying is to improve the existing properties of carbon steels, making them more adaptable and easier to heat-treat successfully. In fact, one of the most important and useful effects of alloying was mentioned in the previous chapter (Section 12.6) – the improvement in 'hardenability'. Thus an alloy steel can be successfully hardened by quenching in oil, or even in an air blast, with less risk of distortion or cracking of the component than is associated with water-quenching. Moreover, suitable alloy steels containing as little as 0.2 per cent carbon can be hardened successfully because of the considerable slowing down of transformation rates imparted by the alloying elements (see Figure 12.3(ii)).



13.1.1 Alloying elements

Alloying elements can be divided into two main groups:

1 Those which strengthen and toughen the steel by dissolving in the ferrite. These elements are used mainly in constructional steels, and include nickel, manganese, small amounts of chromium, and even smaller amounts of molybdenum.

2 Alloying elements which combine chemically with some of the carbon in the steel, to form carbides which are much harder than iron carbide (cementite). These elements are used mainly in tool steels, die steels and the like. They include chromium, tungsten, molybdenum, and vanadium.

13.1.2 Alloy steels

Alloy steels may be classified into three main groups:

1 Constructional steels which are generally used for machine parts highly stressed in tension or compression.
2 Tool steels which require great hardness and, in some cases, resistance to softening by heat.
3 Special steels, e.g. stainless steels and heat-resisting steels.

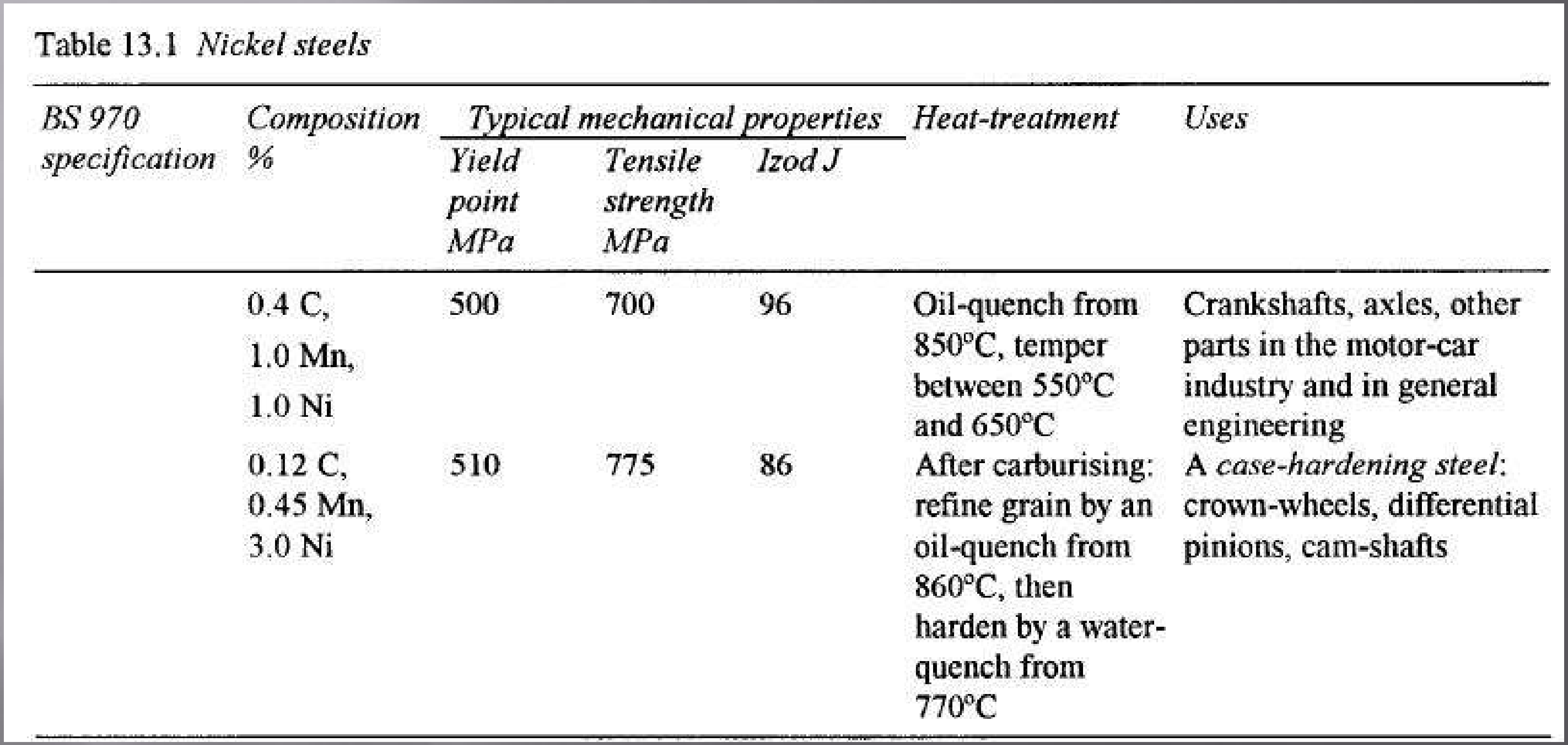
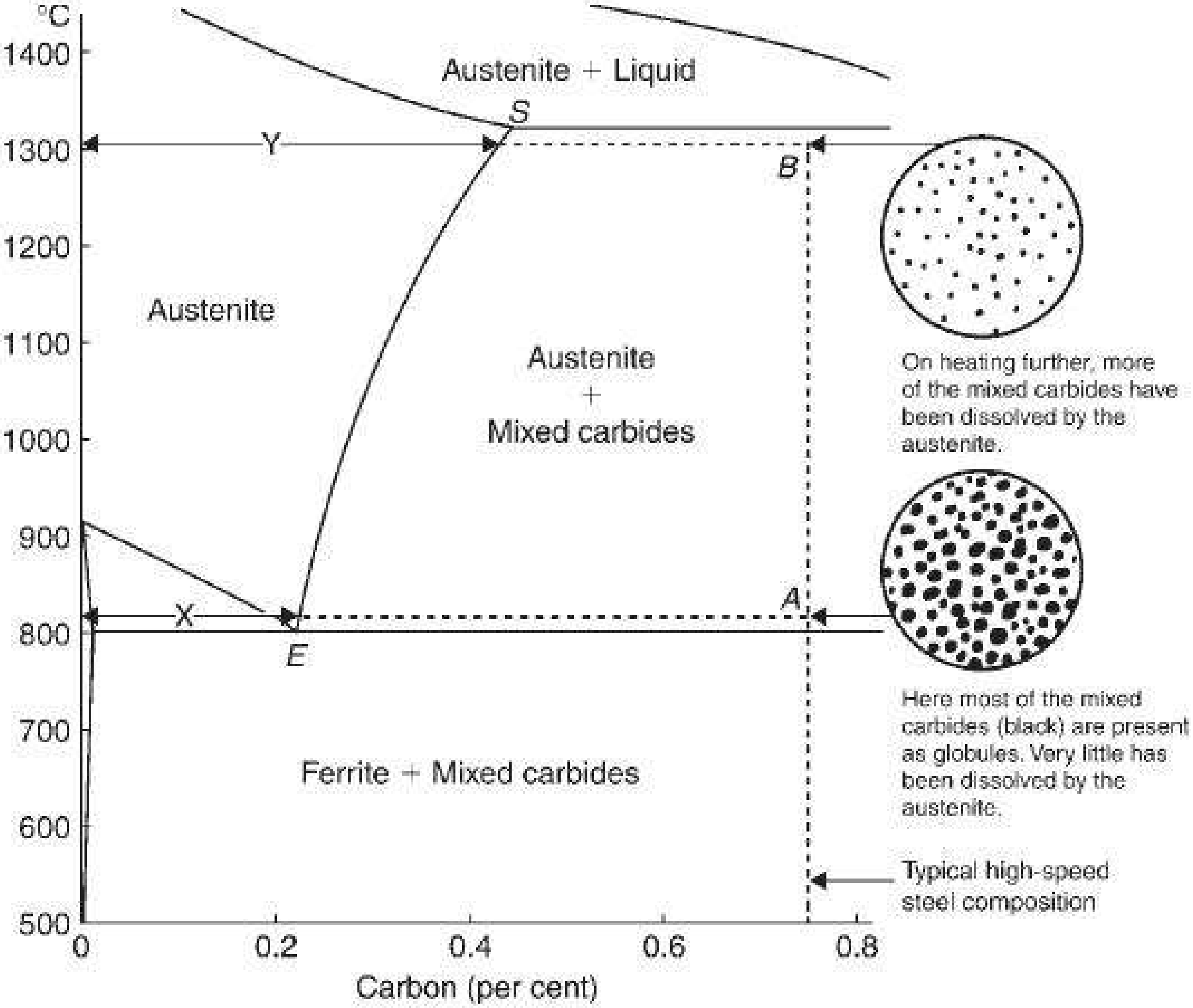


Table 13.1 *Nickel steels*

BS 970 specification	*Composition %*	*Typical mechanical properties*			*Heat-treatment*	*Uses*
		Yield point MPa	*Tensile strength MPa*	*Izod J*		
	0.4 C, 1.0 Mn, 1.0 Ni	500	700	96	Oil-quench from 850°C, temper between 550°C and 650°C	Crankshafts, axles, other parts in the motor-car industry and in general engineering
	0.12 C, 0.45 Mn, 3.0 Ni	510	775	86	After carburising: refine grain by an oil-quench from 860°C, then harden by a water-quench from 770°C	A *case-hardening steel*: crown-wheels, differential pinions, cam-shafts

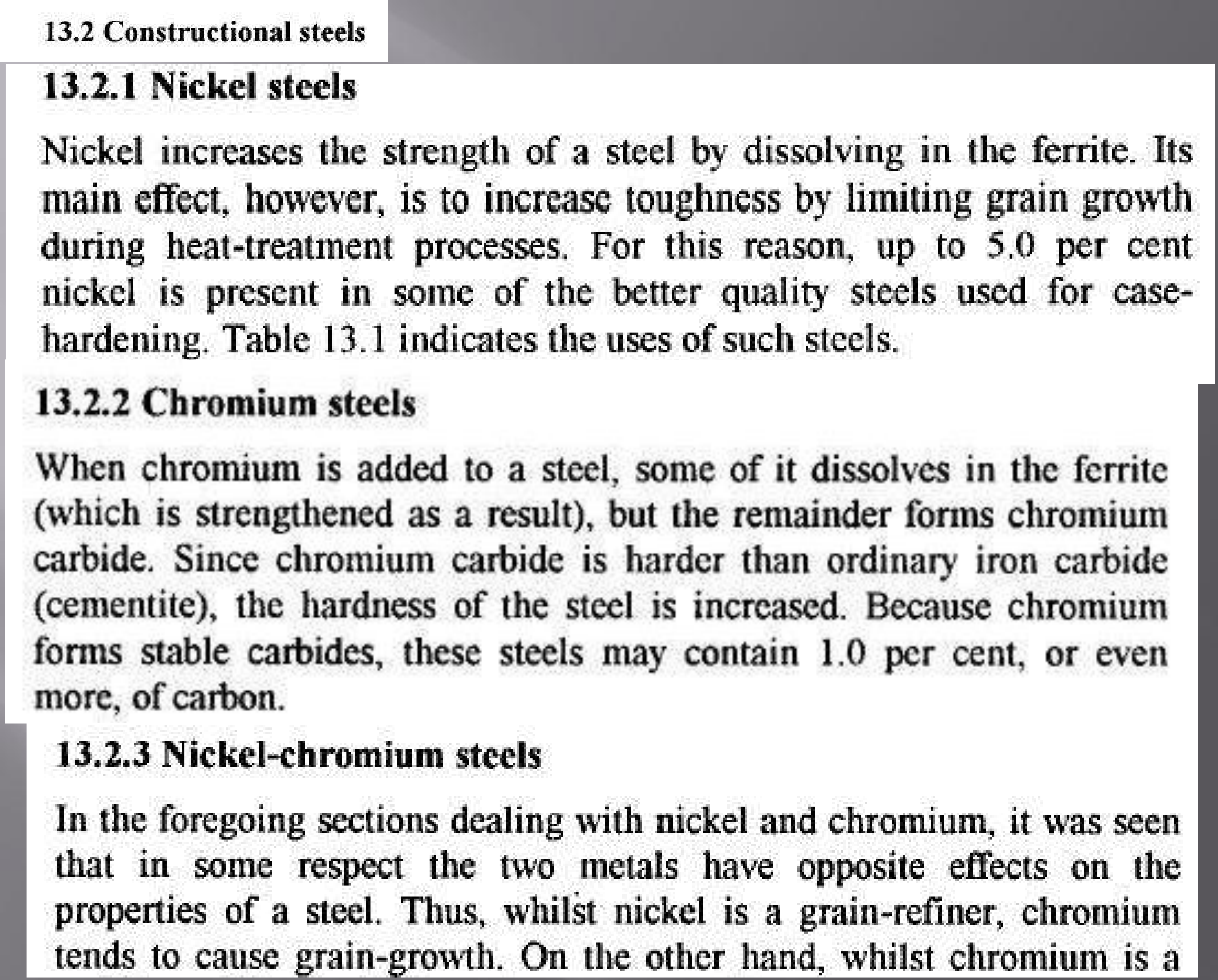


On heating further, more of the mixed carbides have been dissolved by the austenite.

Here most of the mixed carbides (black) are present as globules. Very little has been dissolved by the austenite.

Typical high-speed steel composition

Figure 13.1 *A modified equilibrium diagram for high-speed steel. If the*



13.2 Constructional steels

13.2.1 Nickel steels

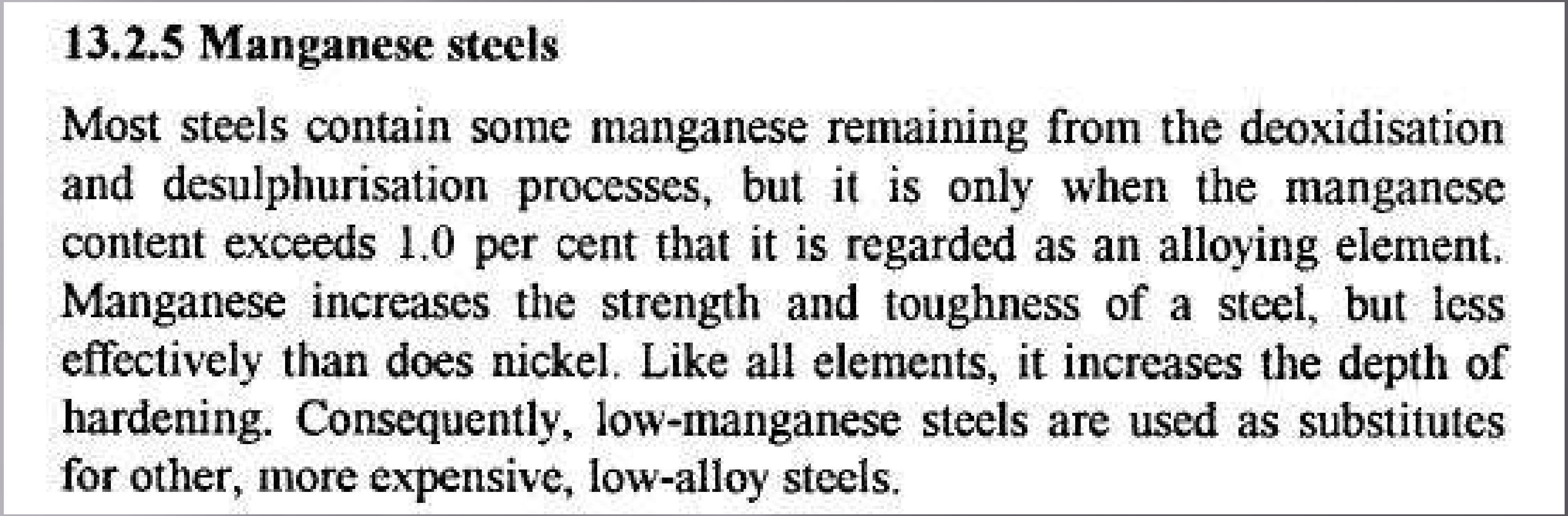
Nickel increases the strength of a steel by dissolving in the ferrite. Its main effect, however, is to increase toughness by limiting grain growth during heat-treatment processes. For this reason, up to 5.0 per cent nickel is present in some of the better quality steels used for case-hardening. Table 13.1 indicates the uses of such steels.

13.2.2 Chromium steels

When chromium is added to a steel, some of it dissolves in the ferrite (which is strengthened as a result), but the remainder forms chromium carbide. Since chromium carbide is harder than ordinary iron carbide (cementite), the hardness of the steel is increased. Because chromium forms stable carbides, these steels may contain 1.0 per cent, or even more, of carbon.

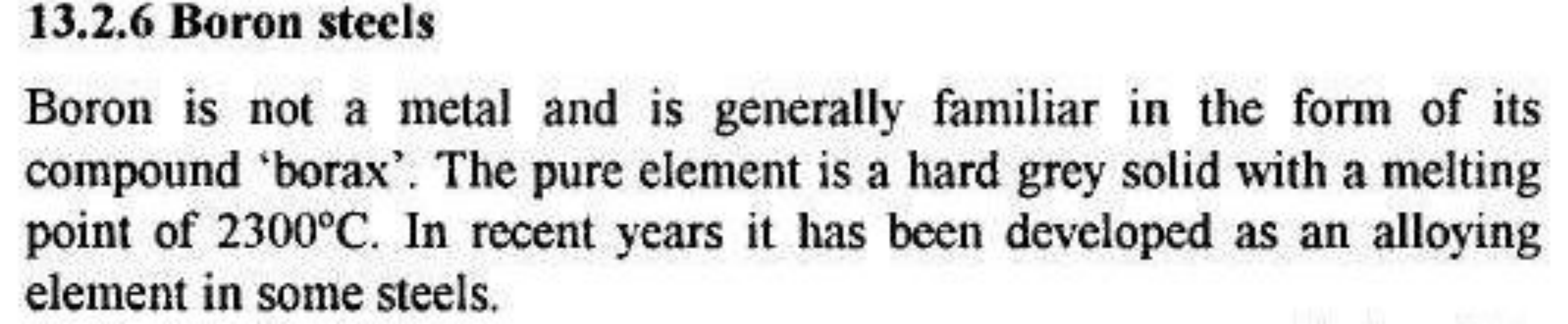
13.2.3 Nickel-chromium steels

In the foregoing sections dealing with nickel and chromium, it was seen that in some respect the two metals have opposite effects on the properties of a steel. Thus, whilst nickel is a grain-refiner, chromium tends to cause grain-growth. On the other hand, whilst chromium is a



13.2.5 Manganese steels

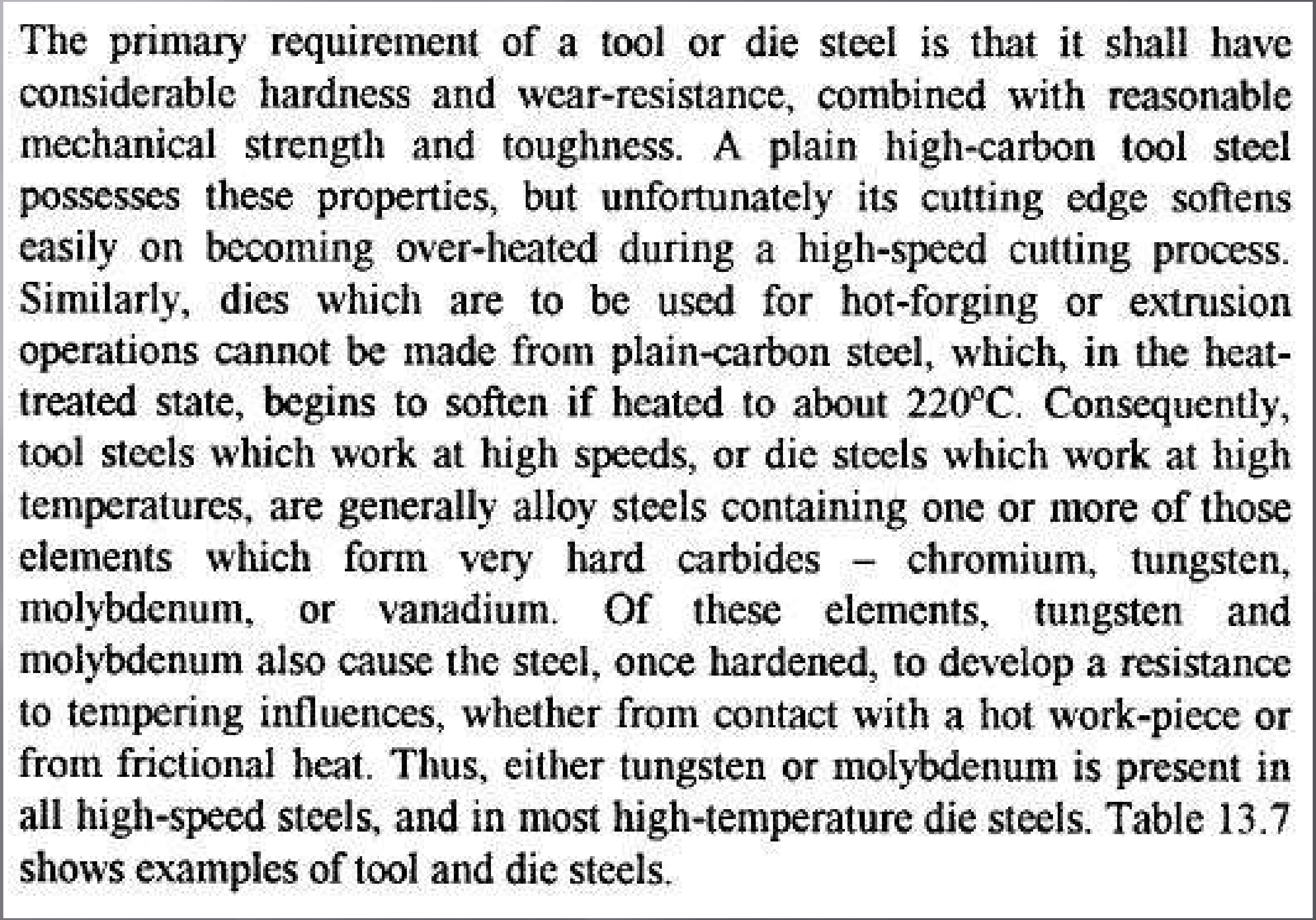
Most steels contain some manganese remaining from the deoxidisation and desulphurisation processes, but it is only when the manganese content exceeds 1.0 per cent that it is regarded as an alloying element. Manganese increases the strength and toughness of a steel, but less effectively than does nickel. Like all elements, it increases the depth of hardening. Consequently, low-manganese steels are used as substitutes for other, more expensive, low-alloy steels.



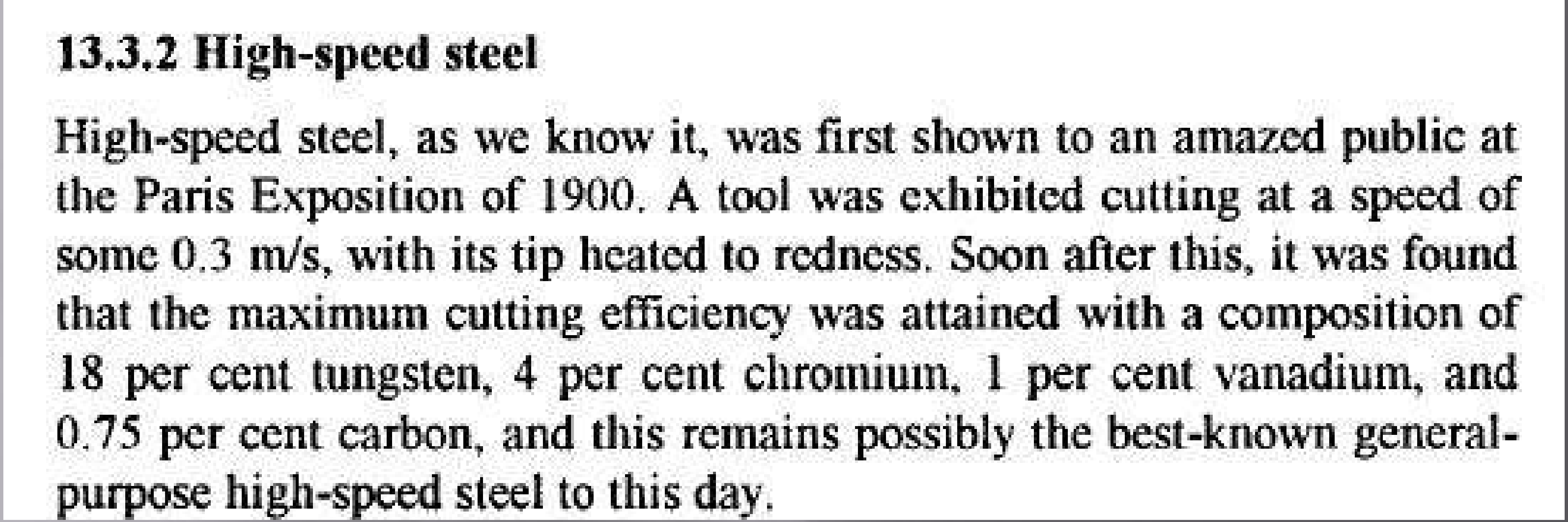
13.2.6 Boron steels

Boron is not a metal and is generally familiar in the form of its compound ‘borax’. The pure element is a hard grey solid with a melting point of 2300°C. In recent years it has been developed as an alloying element in some steels.

Tool and die steels

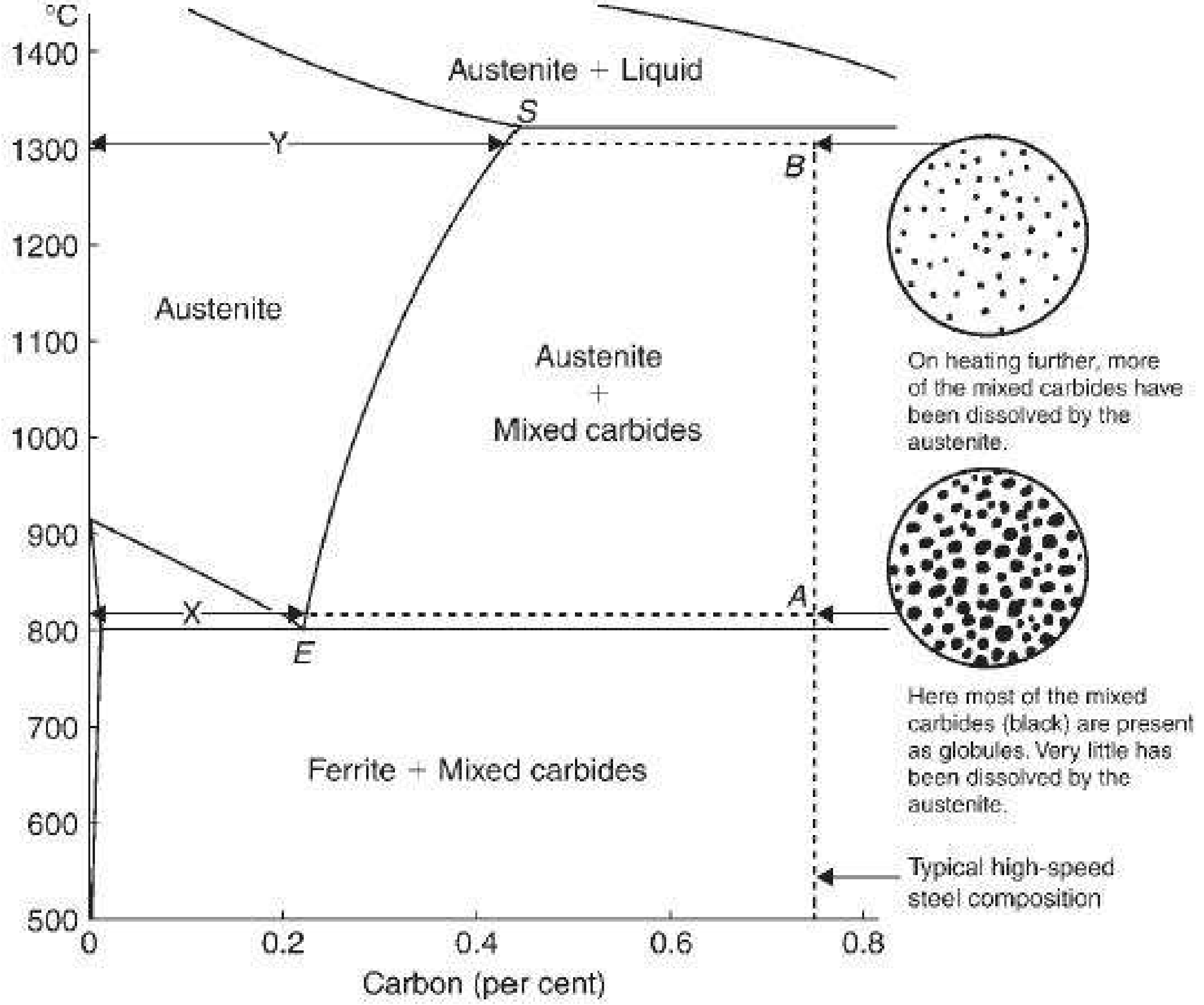


The primary requirement of a tool or die steel is that it shall have considerable hardness and wear-resistance, combined with reasonable mechanical strength and toughness. A plain high-carbon tool steel possesses these properties, but unfortunately its cutting edge softens easily on becoming over-heated during a high-speed cutting process. Similarly, dies which are to be used for hot-forging or extrusion operations cannot be made from plain-carbon steel, which, in the heat-treated state, begins to soften if heated to about 220°C. Consequently, tool steels which work at high speeds, or die steels which work at high temperatures, are generally alloy steels containing one or more of those elements which form very hard carbides – chromium, tungsten, molybdenum, or vanadium. Of these elements, tungsten and molybdenum also cause the steel, once hardened, to develop a resistance to tempering influences, whether from contact with a hot work-piece or from frictional heat. Thus, either tungsten or molybdenum is present in all high-speed steels, and in most high-temperature die steels. Table 13.7 shows examples of tool and die steels.



13.3.2 High-speed steel

High-speed steel, as we know it, was first shown to an amazed public at the Paris Exposition of 1900. A tool was exhibited cutting at a speed of some 0.3 m/s, with its tip heated to redness. Soon after this, it was found that the maximum cutting efficiency was attained with a composition of 18 per cent tungsten, 4 per cent chromium, 1 per cent vanadium, and 0.75 per cent carbon, and this remains possibly the best-known general-purpose high-speed steel to this day.



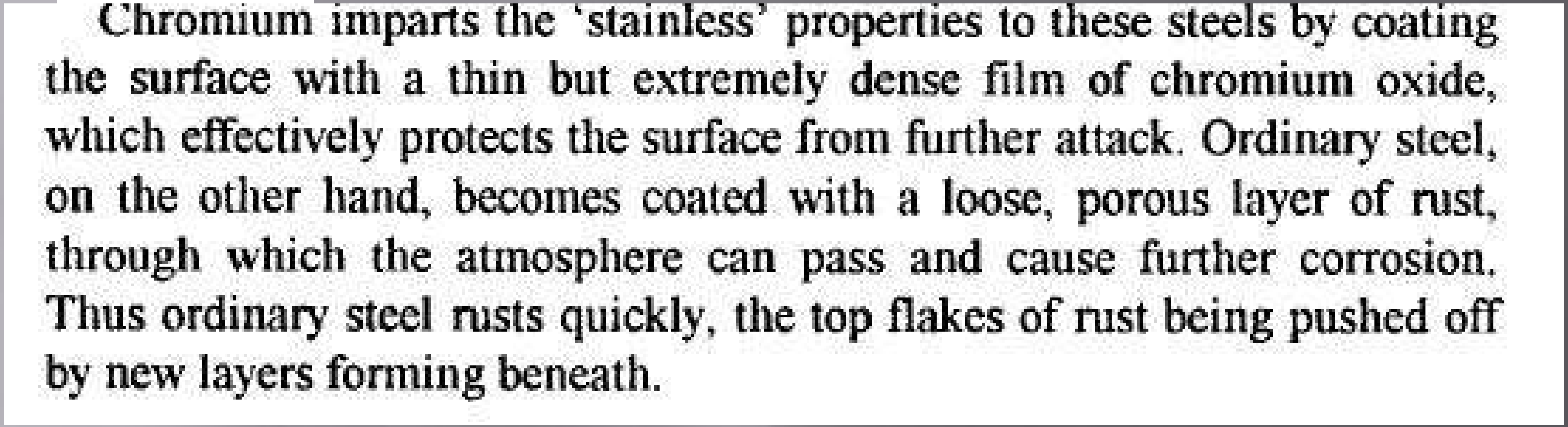
On heating further, more of the mixed carbides have been dissolved by the austenite.

Here most of the mixed carbides (black) are present as globules. Very little has been dissolved by the austenite.

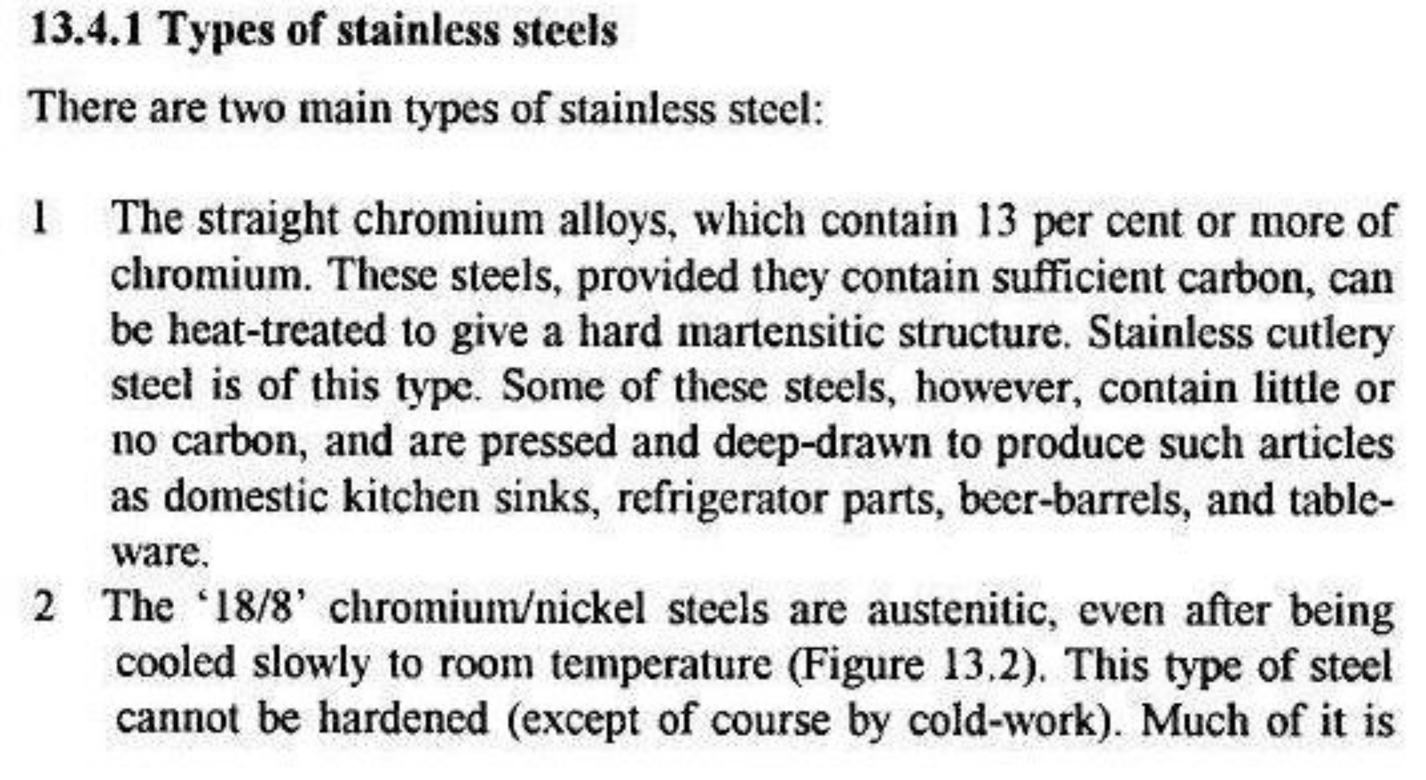
Typical high-speed steel composition

Figure 13.1 *A modified equilibrium diagram for high-speed steel. If the 'typical high-speed steel composition' is heated to A, only an amount of mixed carbides equivalent to X is dissolved by the austenite. Hence, on quenching, the steel would be soft and would not resist temperature*

Stainless steels



Chromium imparts the 'stainless' properties to these steels by coating the surface with a thin but extremely dense film of chromium oxide, which effectively protects the surface from further attack. Ordinary steel, on the other hand, becomes coated with a loose, porous layer of rust, through which the atmosphere can pass and cause further corrosion. Thus ordinary steel rusts quickly, the top flakes of rust being pushed off by new layers forming beneath.



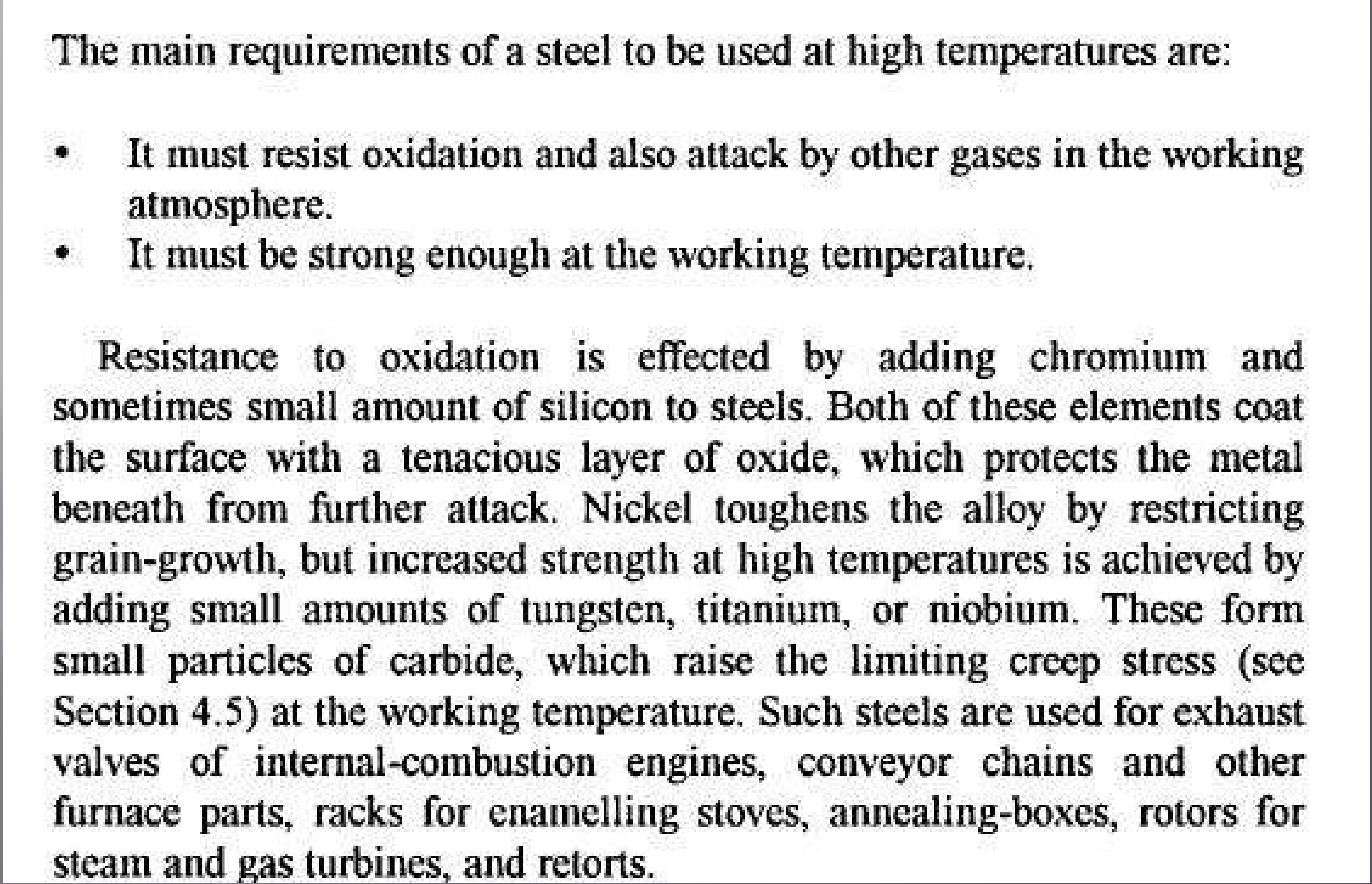
13.4.1 Types of stainless steels

There are two main types of stainless steel:

1 The straight chromium alloys, which contain 13 per cent or more of chromium. These steels, provided they contain sufficient carbon, can be heat-treated to give a hard martensitic structure. Stainless cutlery steel is of this type. Some of these steels, however, contain little or no carbon, and are pressed and deep-drawn to produce such articles as domestic kitchen sinks, refrigerator parts, beer-barrels, and tableware.

2 The '18/8' chromium/nickel steels are austenitic, even after being cooled slowly to room temperature (Figure 13.2). This type of steel cannot be hardened (except of course by cold-work). Much of it is

Heat-resisting steels



The main requirements of a steel to be used at high temperatures are:

- It must resist oxidation and also attack by other gases in the working atmosphere.
- It must be strong enough at the working temperature.

Resistance to oxidation is effected by adding chromium and sometimes small amount of silicon to steels. Both of these elements coat the surface with a tenacious layer of oxide, which protects the metal beneath from further attack. Nickel toughens the alloy by restricting grain-growth, but increased strength at high temperatures is achieved by adding small amounts of tungsten, titanium, or niobium. These form small particles of carbide, which raise the limiting creep stress (see Section 4.5) at the working temperature. Such steels are used for exhaust valves of internal-combustion engines, conveyor chains and other furnace parts, racks for enamelling stoves, annealing-boxes, rotors for steam and gas turbines, and retorts.

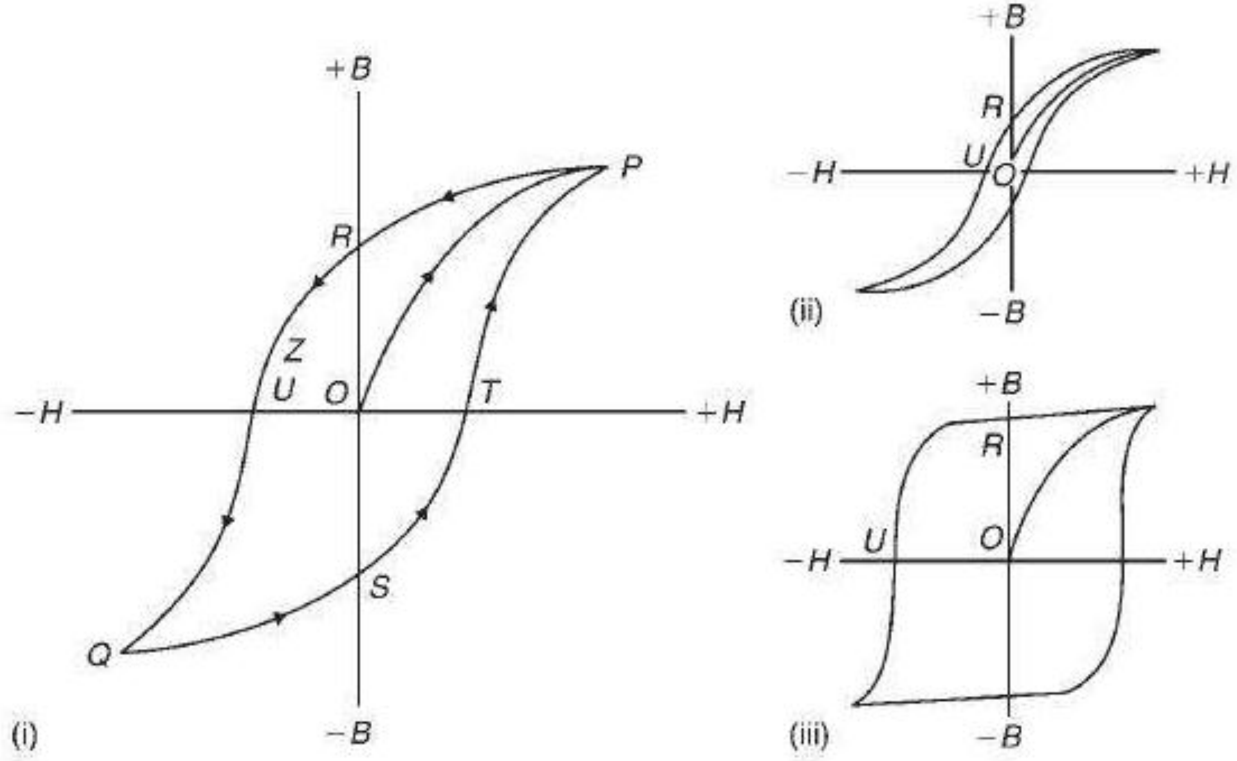


Figure 13.6 *Magnetic hysteresis: (i) the derivation of a hysteresis 'loop'; (ii) typical hysteresis loop for a magnetically 'soft' alloy, (iii) typical hysteresis loop for a magnetically 'hard' (permanent magnet) alloy.*

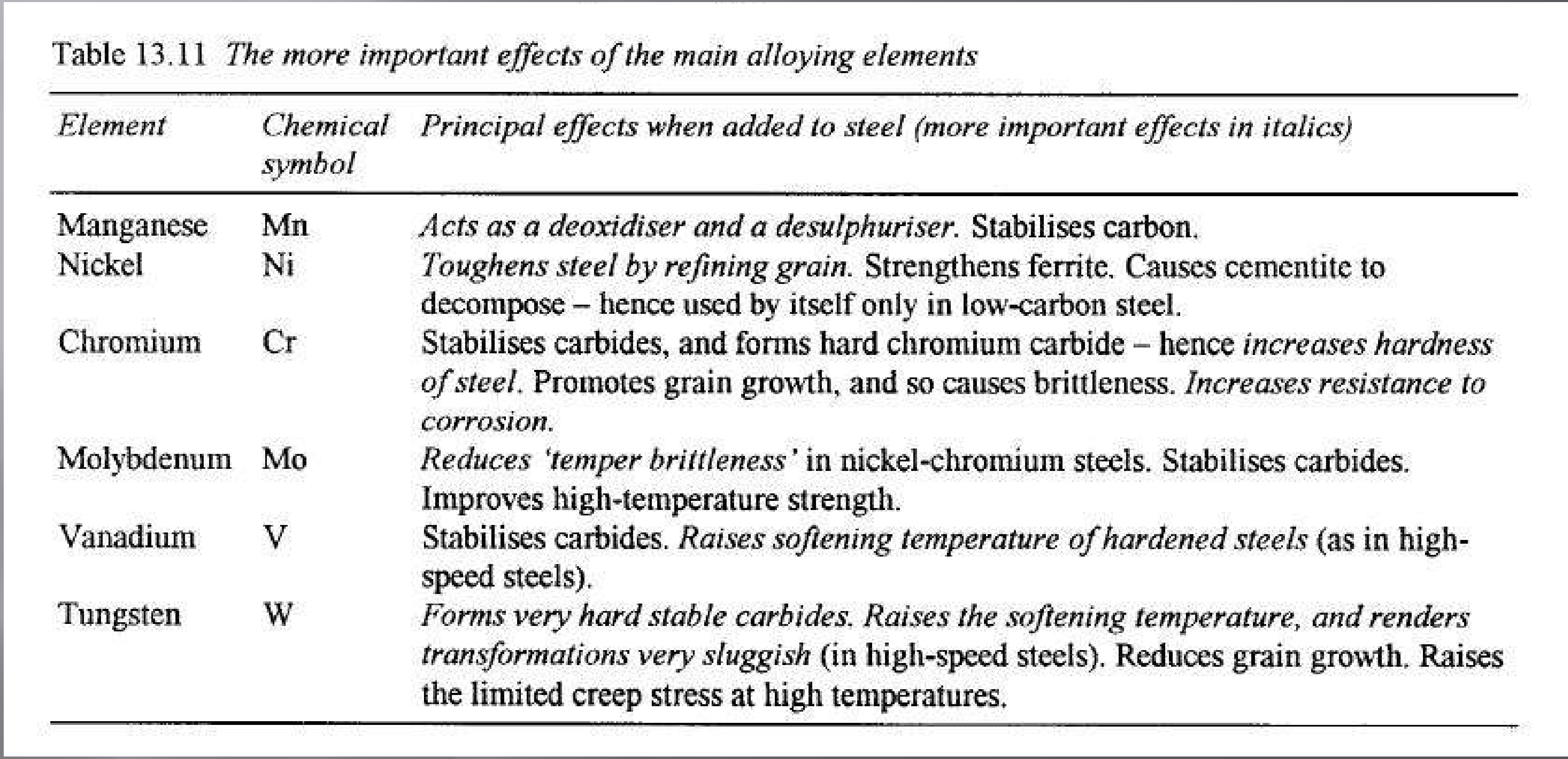
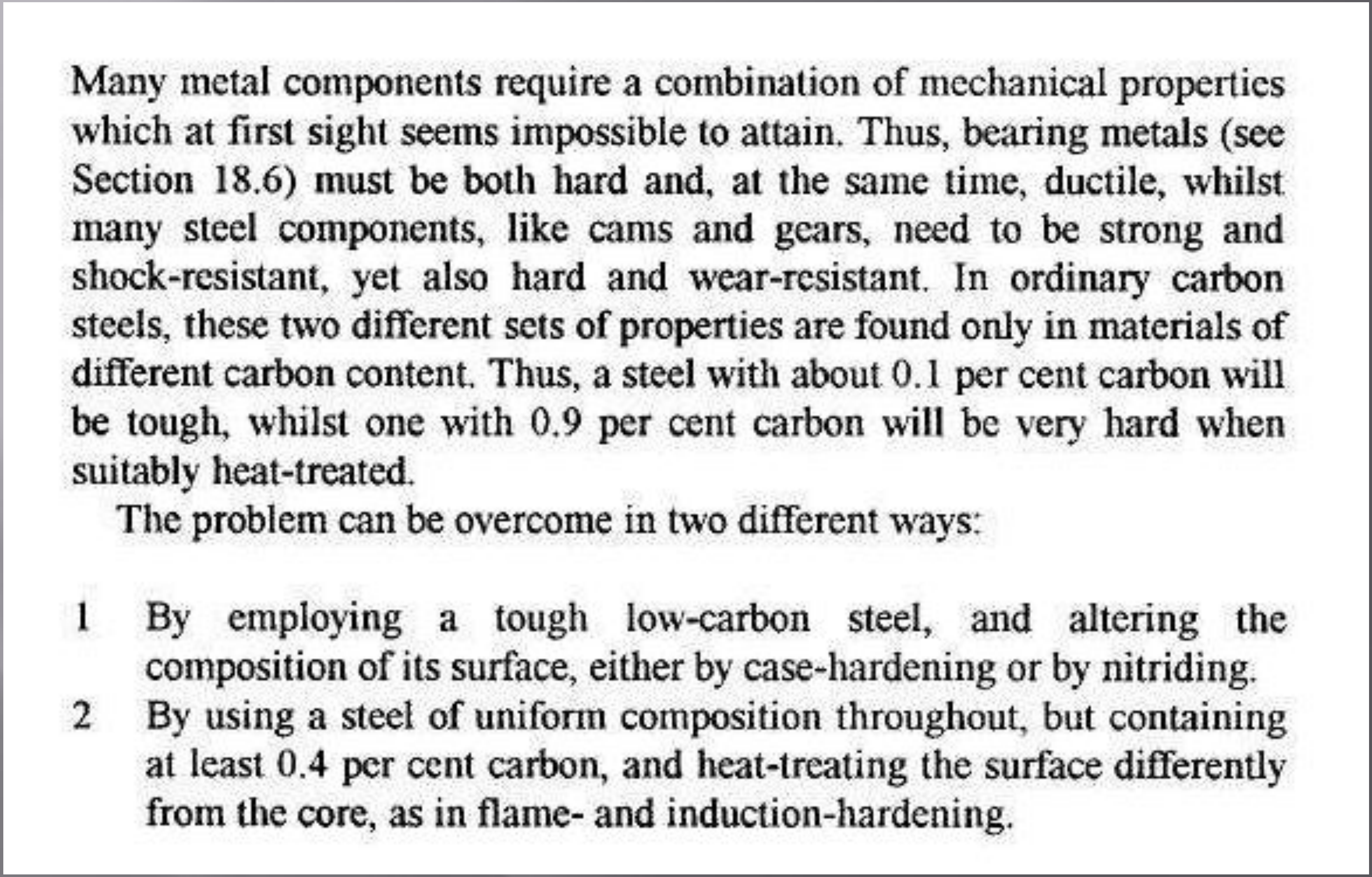


Table 13.11 *The more important effects of the main alloying elements*

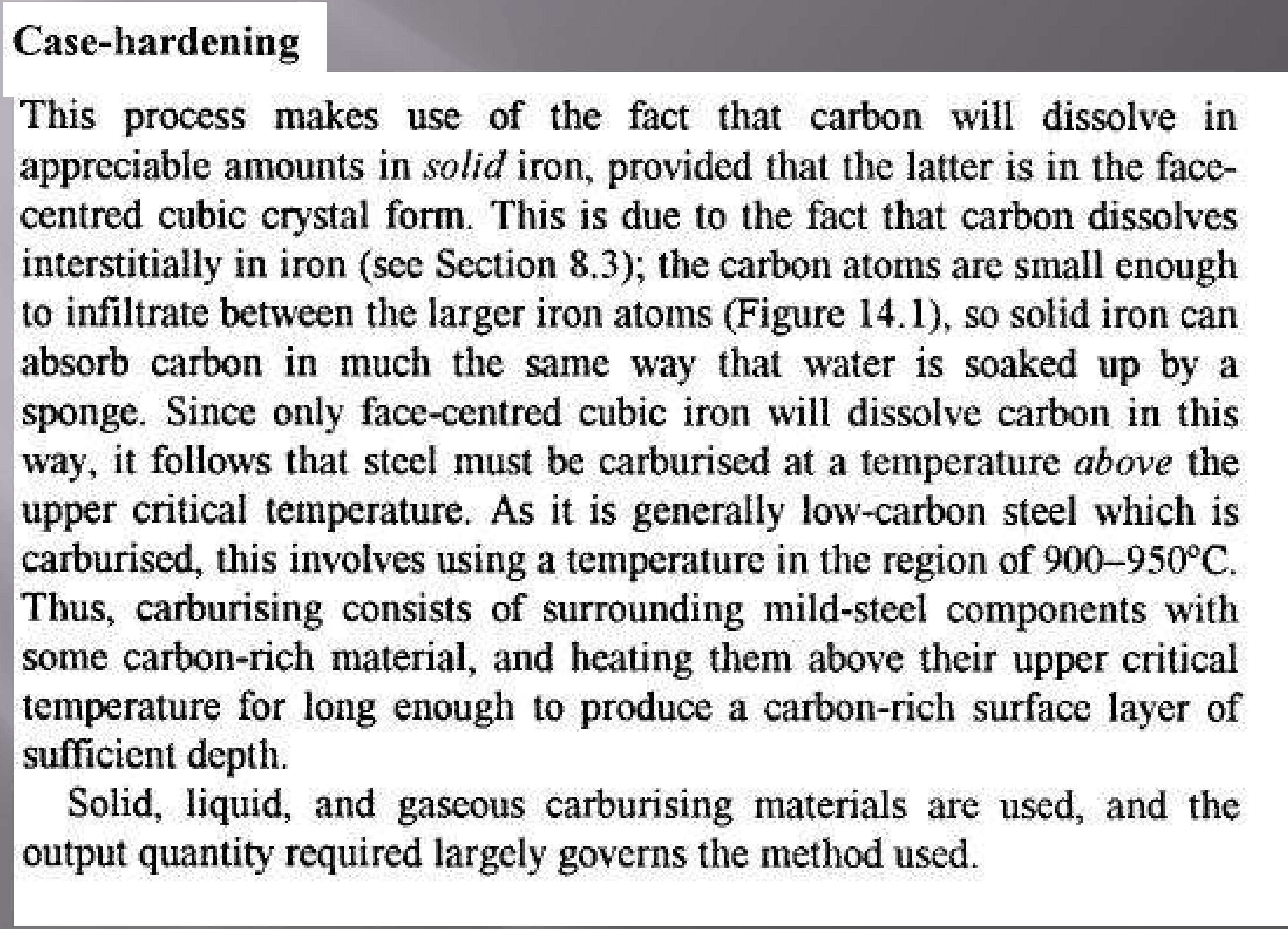
Element	*Chemical symbol*	*Principal effects when added to steel (more important effects in italics)*
Manganese	Mn	*Acts as a deoxidiser and a desulphuriser.* Stabilises carbon.
Nickel	Ni	*Toughens steel by refining grain.* Strengthens ferrite. Causes cementite to decompose – hence used by itself only in low-carbon steel.
Chromium	Cr	Stabilises carbides, and forms hard chromium carbide – hence *increases hardness of steel*. Promotes grain growth, and so causes brittleness. *Increases resistance to corrosion.*
Molybdenum	Mo	*Reduces 'temper brittleness'* in nickel-chromium steels. Stabilises carbides. Improves high-temperature strength.
Vanadium	V	Stabilises carbides. *Raises softening temperature of hardened steels* (as in high-speed steels).
Tungsten	W	*Forms very hard stable carbides. Raises the softening temperature, and renders transformations very sluggish* (in high-speed steels). Reduces grain growth. Raises the limited creep stress at high temperatures.



Many metal components require a combination of mechanical properties which at first sight seems impossible to attain. Thus, bearing metals (see Section 18.6) must be both hard and, at the same time, ductile, whilst many steel components, like cams and gears, need to be strong and shock-resistant, yet also hard and wear-resistant. In ordinary carbon steels, these two different sets of properties are found only in materials of different carbon content. Thus, a steel with about 0.1 per cent carbon will be tough, whilst one with 0.9 per cent carbon will be very hard when suitably heat-treated.

The problem can be overcome in two different ways:

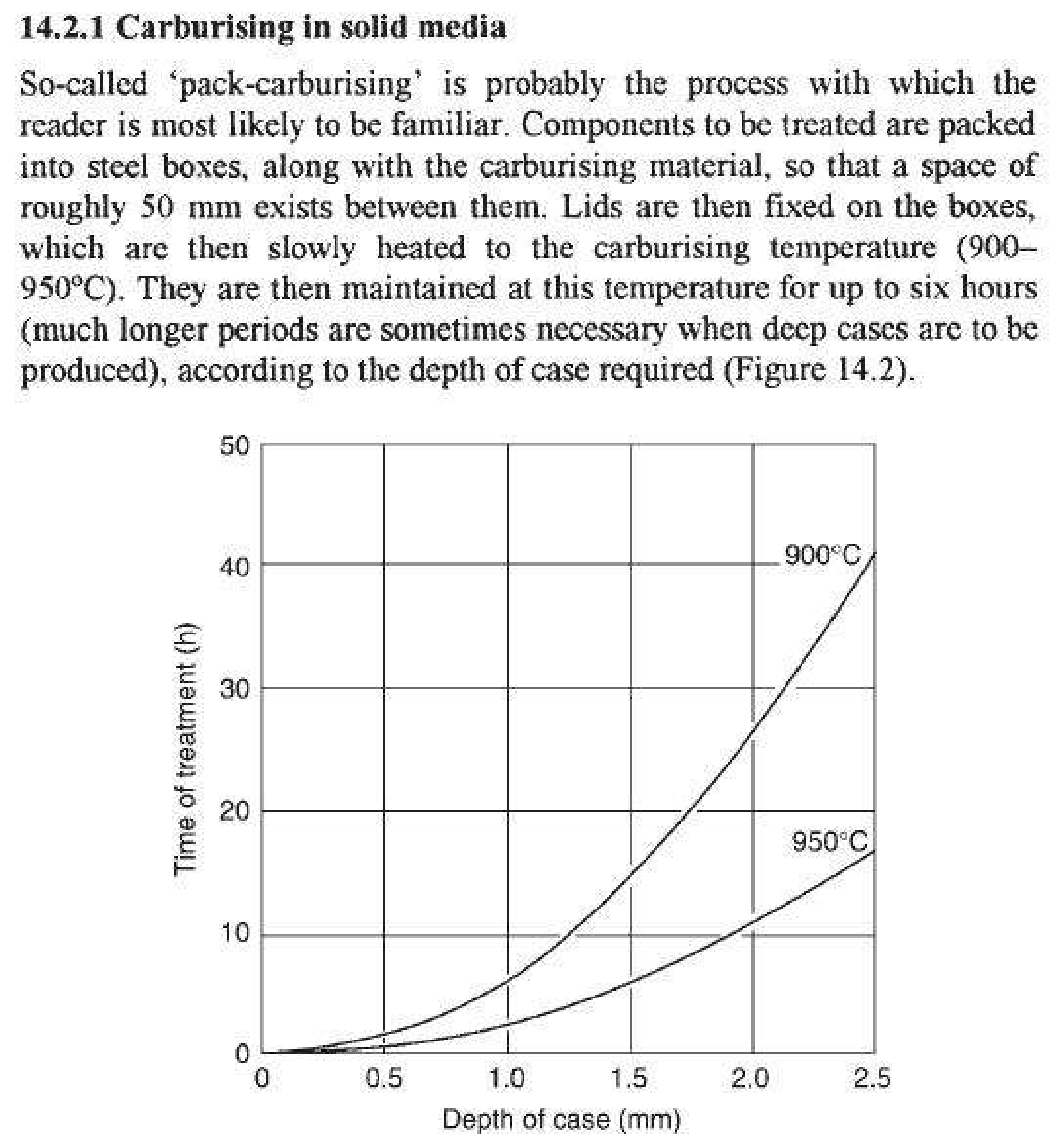
1 By employing a tough low-carbon steel, and altering the composition of its surface, either by case-hardening or by nitriding.
2 By using a steel of uniform composition throughout, but containing at least 0.4 per cent carbon, and heat-treating the surface differently from the core, as in flame- and induction-hardening.



Case-hardening

This process makes use of the fact that carbon will dissolve in appreciable amounts in *solid* iron, provided that the latter is in the face-centred cubic crystal form. This is due to the fact that carbon dissolves interstitially in iron (see Section 8.3); the carbon atoms are small enough to infiltrate between the larger iron atoms (Figure 14.1), so solid iron can absorb carbon in much the same way that water is soaked up by a sponge. Since only face-centred cubic iron will dissolve carbon in this way, it follows that steel must be carburised at a temperature *above* the upper critical temperature. As it is generally low-carbon steel which is carburised, this involves using a temperature in the region of 900–950°C. Thus, carburising consists of surrounding mild-steel components with some carbon-rich material, and heating them above their upper critical temperature for long enough to produce a carbon-rich surface layer of sufficient depth.

Solid, liquid, and gaseous carburising materials are used, and the output quantity required largely governs the method used.



14.2.1 Carburising in solid media

So-called ‘pack-carburising’ is probably the process with which the reader is most likely to be familiar. Components to be treated are packed into steel boxes, along with the carburising material, so that a space of roughly 50 mm exists between them. Lids are then fixed on the boxes, which are then slowly heated to the carburising temperature (900–950°C). They are then maintained at this temperature for up to six hours (much longer periods are sometimes necessary when deep cases are to be produced), according to the depth of case required (Figure 14.2).

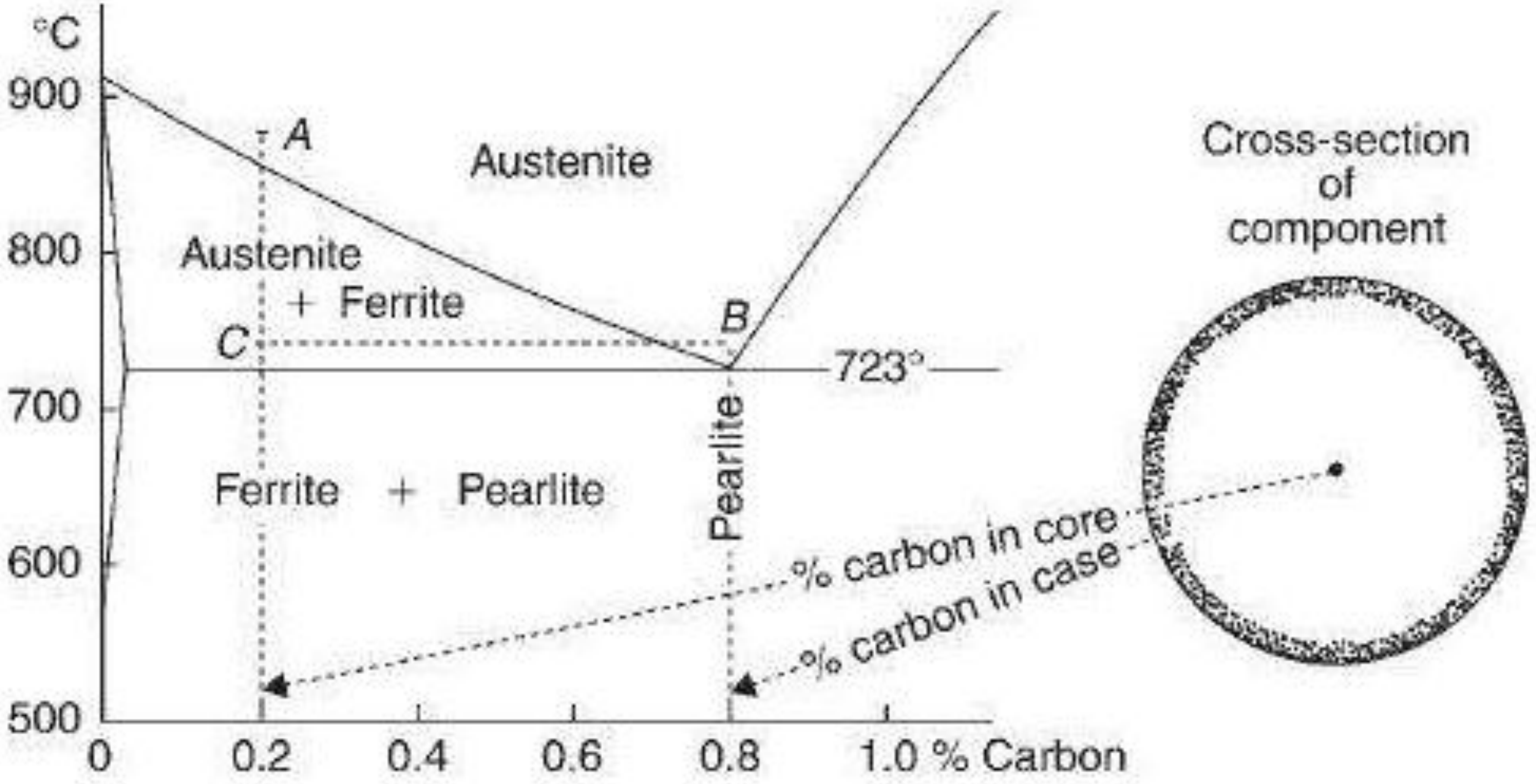
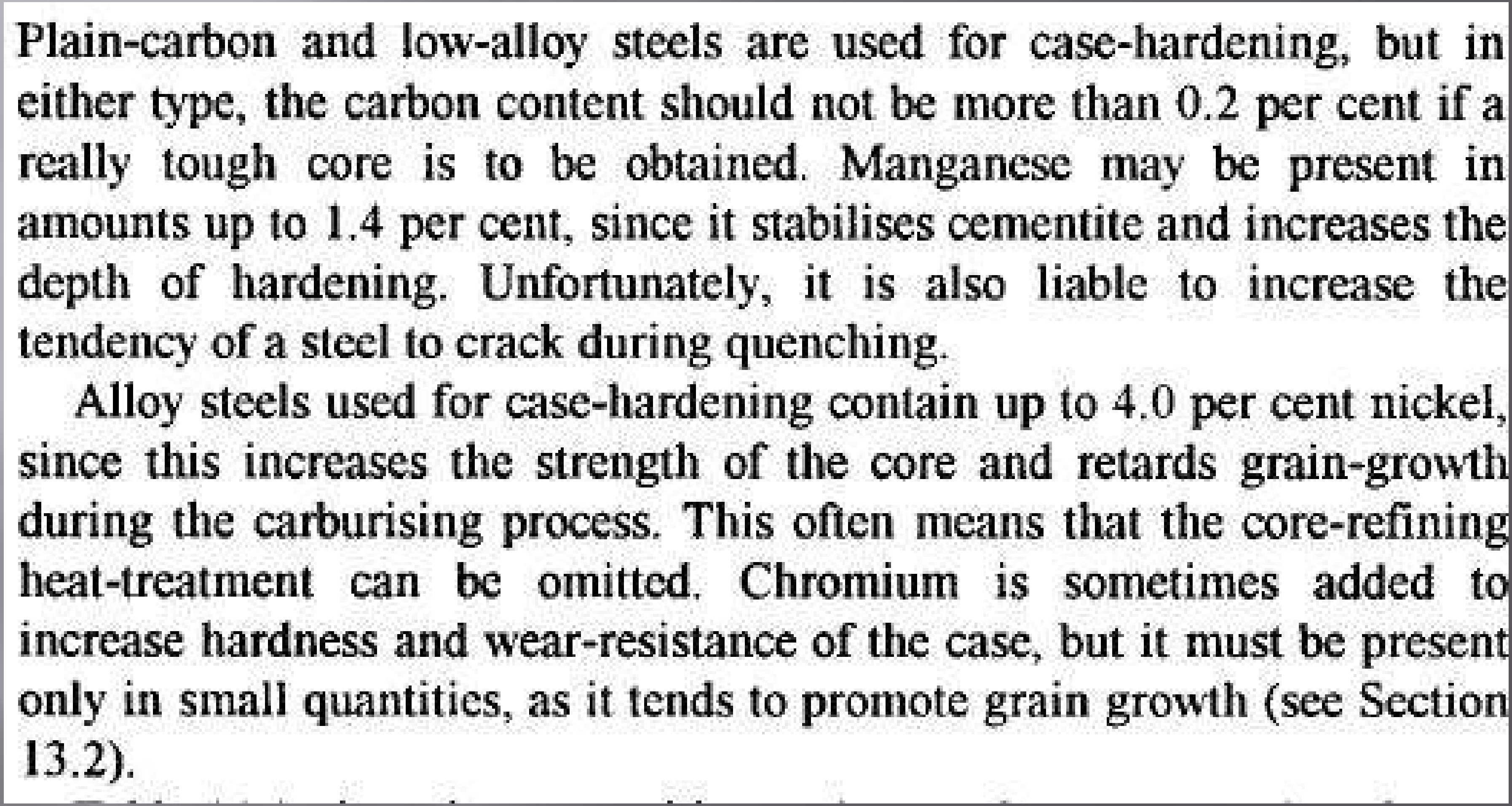


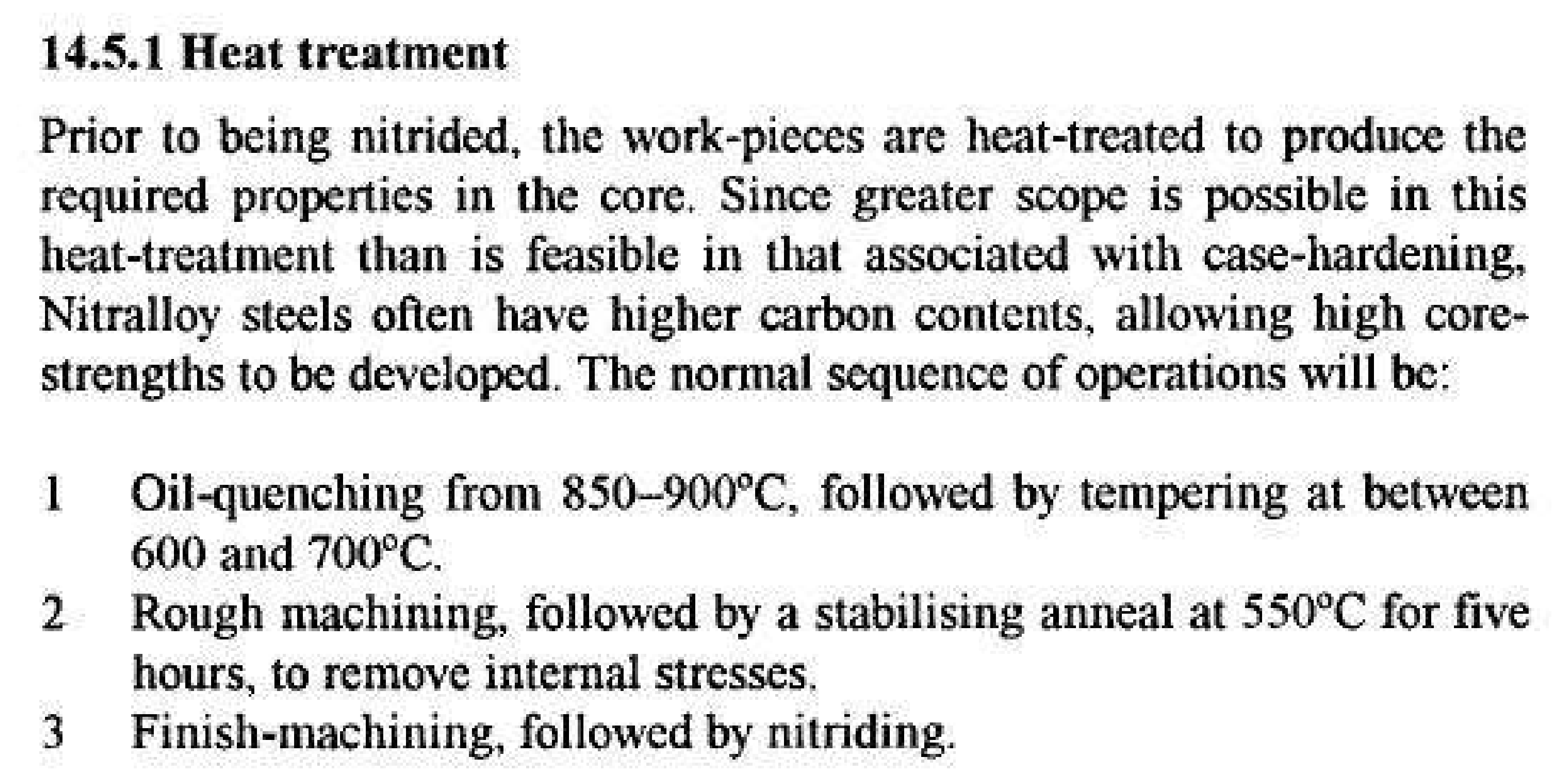
Figure 14.4 *Heat treatment of a carburised component in relation to the equilibrium diagram.*

Case-hardening steels



Plain-carbon and low-alloy steels are used for case-hardening, but in either type, the carbon content should not be more than 0.2 per cent if a really tough core is to be obtained. Manganese may be present in amounts up to 1.4 per cent, since it stabilises cementite and increases the depth of hardening. Unfortunately, it is also liable to increase the tendency of a steel to crack during quenching.

Alloy steels used for case-hardening contain up to 4.0 per cent nickel, since this increases the strength of the core and retards grain-growth during the carburising process. This often means that the core-refining heat-treatment can be omitted. Chromium is sometimes added to increase hardness and wear-resistance of the case, but it must be present only in small quantities, as it tends to promote grain growth (see Section 13.2).

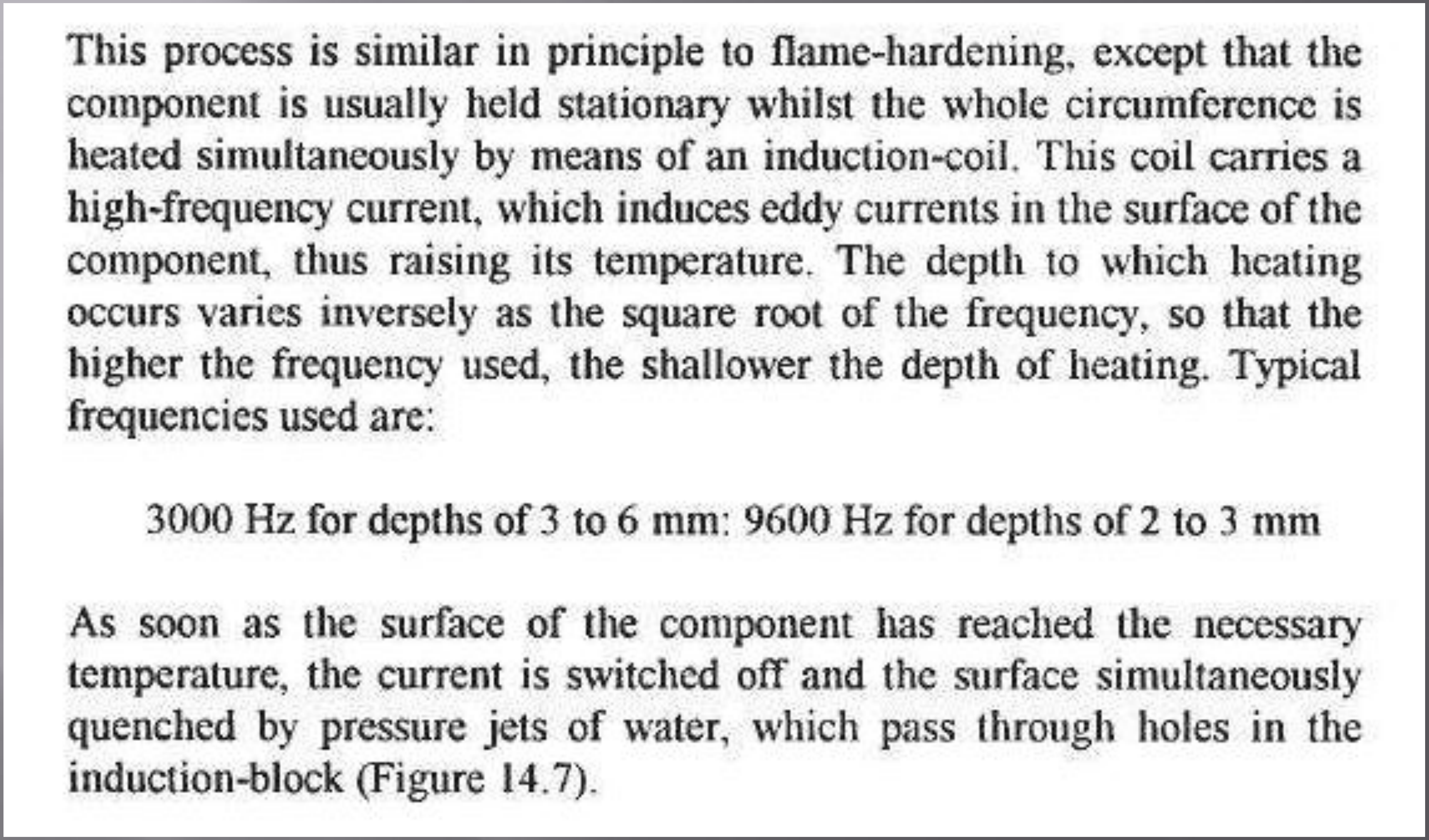


14.5.1 Heat treatment

Prior to being nitrided, the work-pieces are heat-treated to produce the required properties in the core. Since greater scope is possible in this heat-treatment than is feasible in that associated with case-hardening, Nitralloy steels often have higher carbon contents, allowing high core-strengths to be developed. The normal sequence of operations will be:

1. Oil-quenching from 850–900°C, followed by tempering at between 600 and 700°C.
2. Rough machining, followed by a stabilising anneal at 550°C for five hours, to remove internal stresses.
3. Finish-machining, followed by nitriding.

Induction-hardening



This process is similar in principle to flame-hardening, except that the component is usually held stationary whilst the whole circumference is heated simultaneously by means of an induction-coil. This coil carries a high-frequency current, which induces eddy currents in the surface of the component, thus raising its temperature. The depth to which heating occurs varies inversely as the square root of the frequency, so that the higher the frequency used, the shallower the depth of heating. Typical frequencies used are:

3000 Hz for depths of 3 to 6 mm: 9600 Hz for depths of 2 to 3 mm

As soon as the surface of the component has reached the necessary temperature, the current is switched off and the surface simultaneously quenched by pressure jets of water, which pass through holes in the induction-block (Figure 14.7).

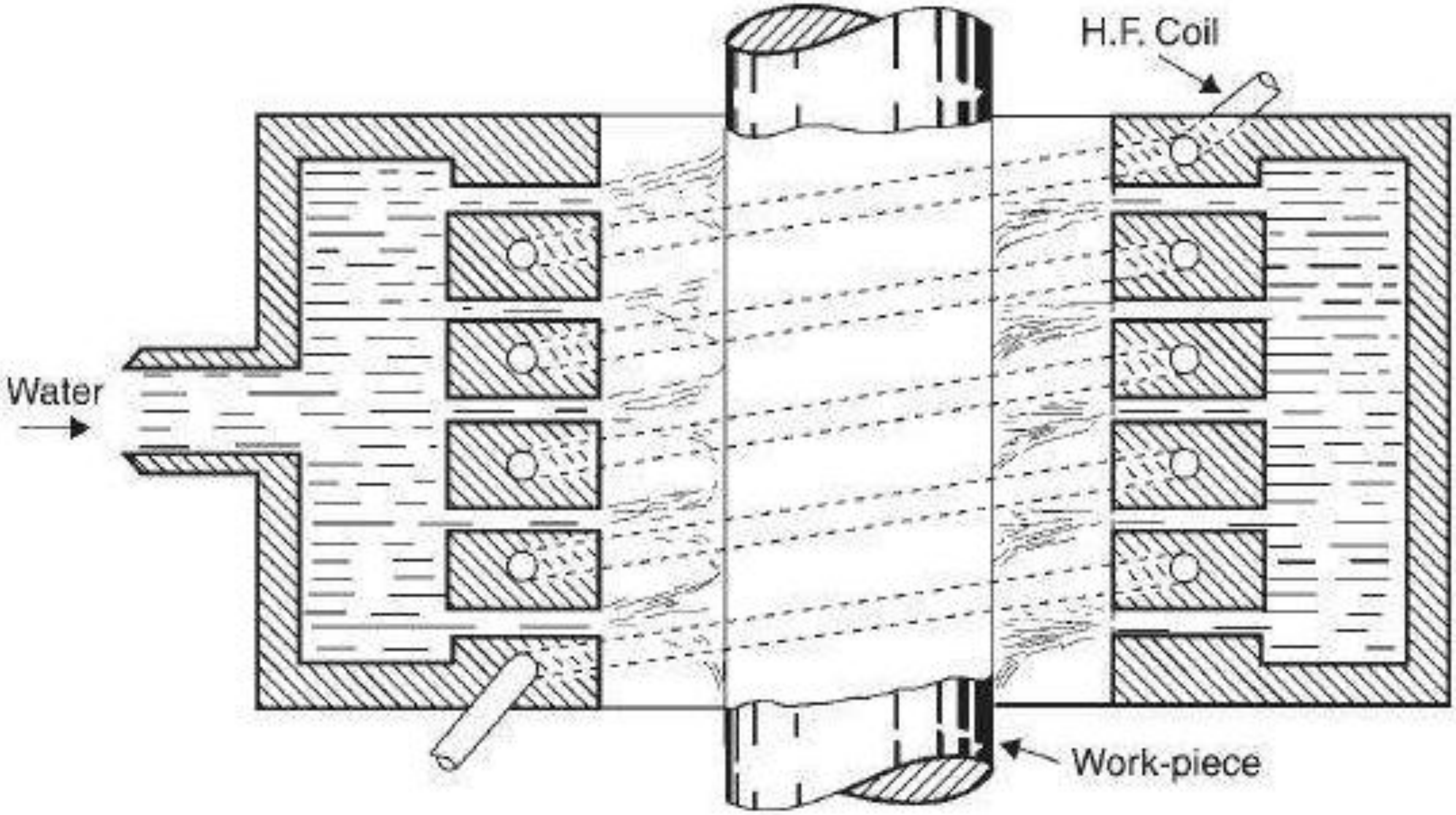


Figure 14.7 *The principles of induction-hardening.*

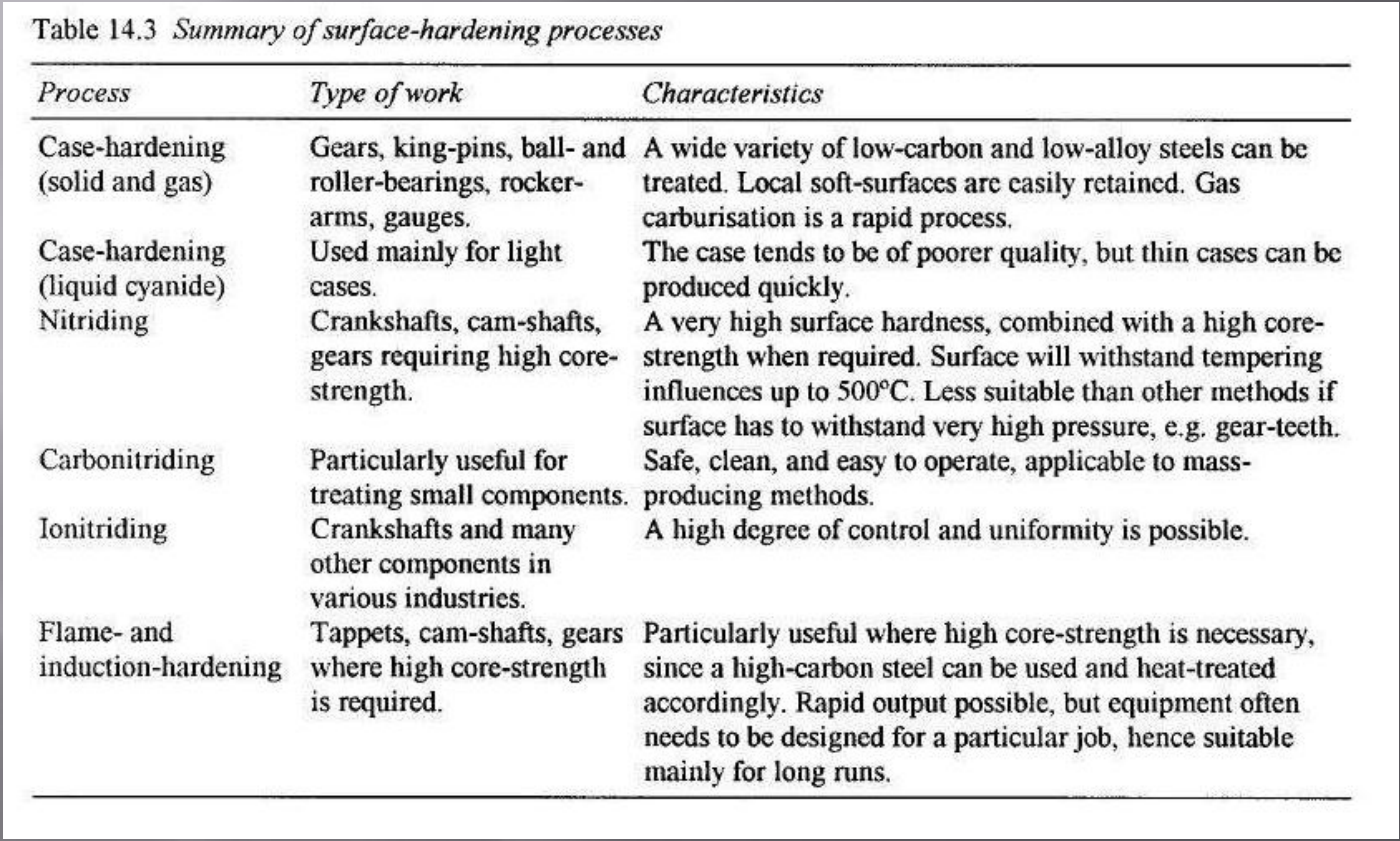
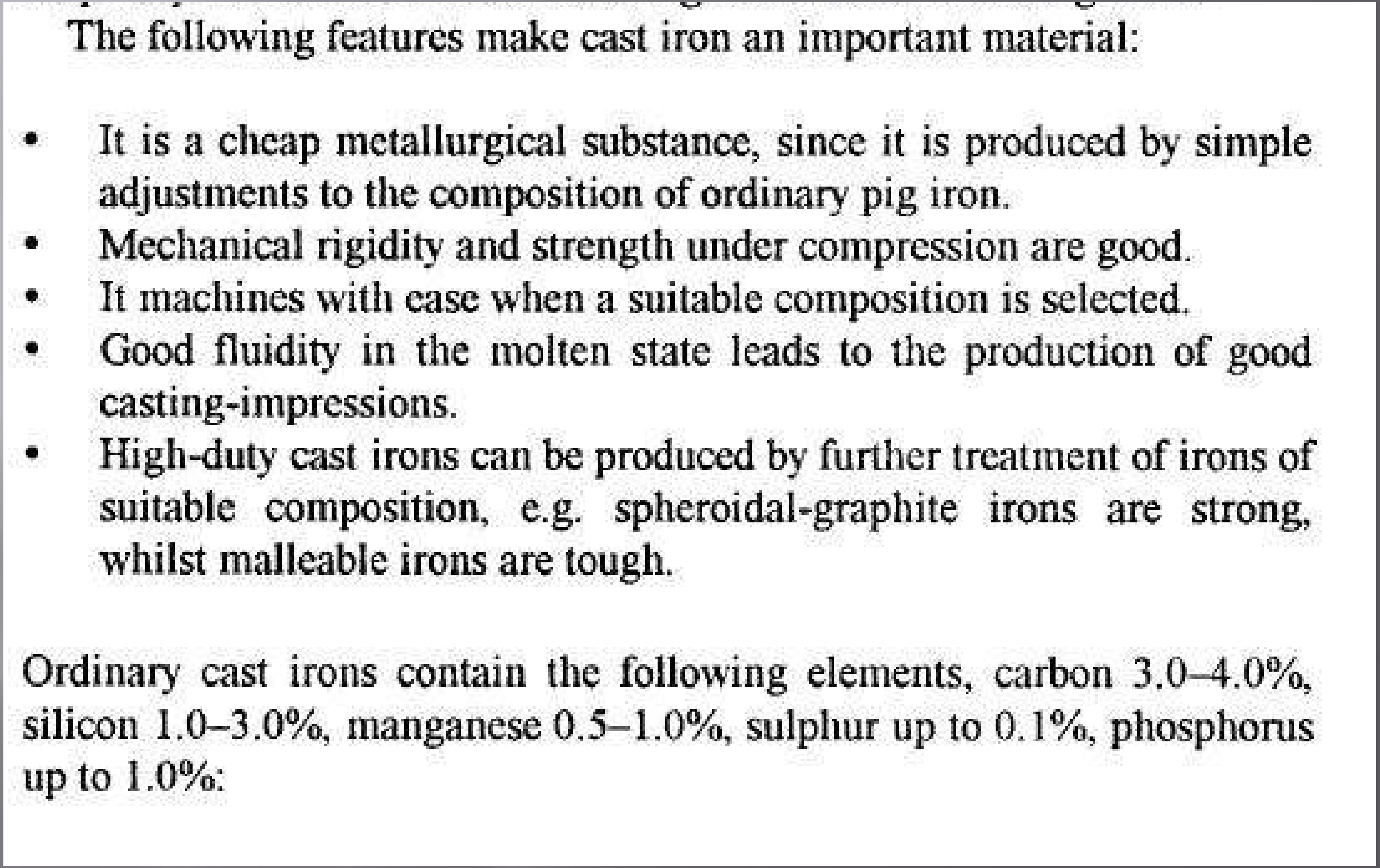


Table 14.3 *Summary of surface-hardening processes*

Process	*Type of work*	*Characteristics*
Case-hardening (solid and gas)	Gears, king-pins, ball- and roller-bearings, rocker-arms, gauges.	A wide variety of low-carbon and low-alloy steels can be treated. Local soft-surfaces are easily retained. Gas carburisation is a rapid process.
Case-hardening (liquid cyanide)	Used mainly for light cases.	The case tends to be of poorer quality, but thin cases can be produced quickly.
Nitriding	Crankshafts, cam-shafts, gears requiring high core-strength.	A very high surface hardness, combined with a high core-strength when required. Surface will withstand tempering influences up to 500°C. Less suitable than other methods if surface has to withstand very high pressure, e.g. gear-teeth.
Carbonitriding	Particularly useful for treating small components.	Safe, clean, and easy to operate, applicable to mass-producing methods.
Ionitriding	Crankshafts and many other components in various industries.	A high degree of control and uniformity is possible.
Flame- and induction-hardening	Tappets, cam-shafts, gears where high core-strength is required.	Particularly useful where high core-strength is necessary, since a high-carbon steel can be used and heat-treated accordingly. Rapid output possible, but equipment often needs to be designed for a particular job, hence suitable mainly for long runs.

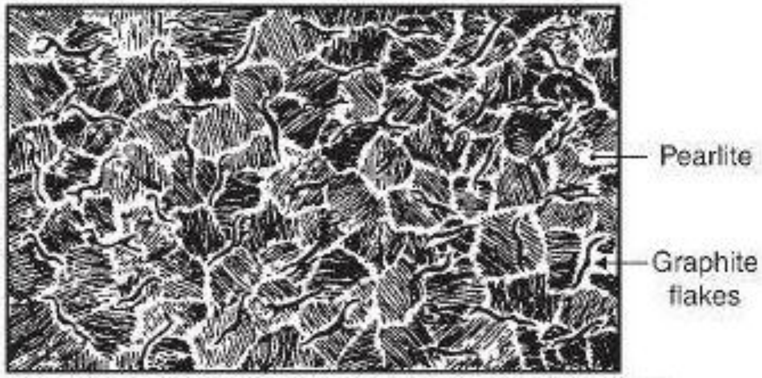


The following features make cast iron an important material:

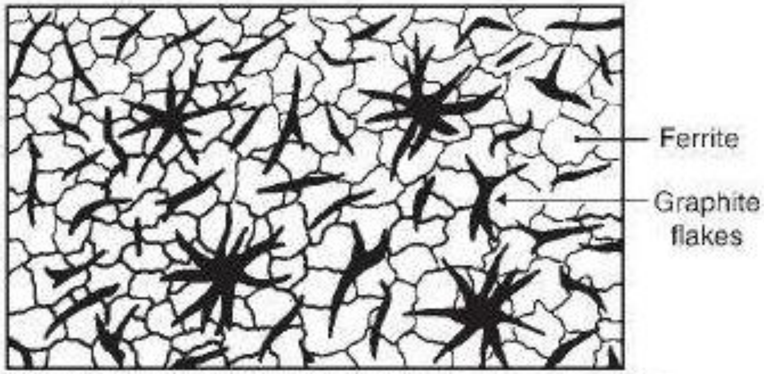
- It is a cheap metallurgical substance, since it is produced by simple adjustments to the composition of ordinary pig iron.
- Mechanical rigidity and strength under compression are good.
- It machines with ease when a suitable composition is selected.
- Good fluidity in the molten state leads to the production of good casting-impressions.
- High-duty cast irons can be produced by further treatment of irons of suitable composition, e.g. spheroidal-graphite irons are strong, whilst malleable irons are tough.

Ordinary cast irons contain the following elements, carbon 3.0–4.0%, silicon 1.0–3.0%, manganese 0.5–1.0%, sulphur up to 0.1%, phosphorus up to 1.0%:

(i) **White cast iron** (low silicon) – primary cementite network in a matrix of pearlite.



(ii) **Fine grey iron** (medium silicon) – small graphite flakes in a matrix of pearlite.



(iii) **Coarse grey iron** (high silicon) – large graphite flakes in a matrix of ferrite.

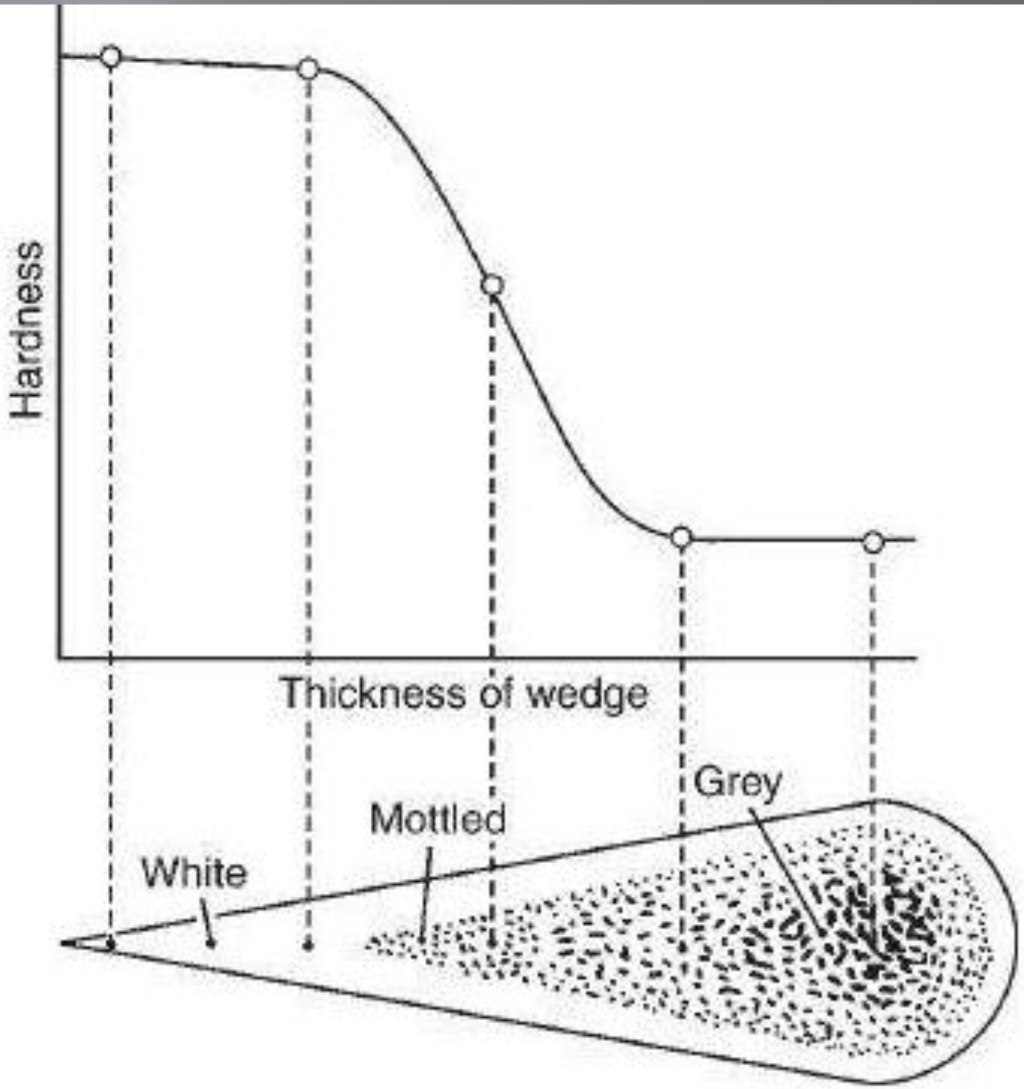
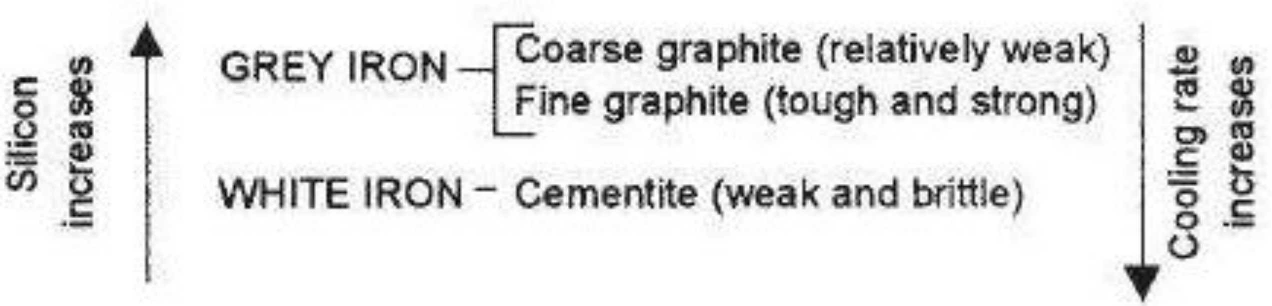


Figure 15.3 *The effect of sectional thickness on the depth of chilling of a grey iron.*

- The silicon content of the iron.
- The rate at which the iron solidifies and cools, which in turn depends upon the cross-sectional thickness of the casting.

Thus the foundryman must strike a balance between the silicon content of the iron and the rate at which it cools.



Silicon increases

GREY IRON – Coarse graphite (relatively weak)
Fine graphite (tough and strong)

WHITE IRON – Cementite (weak and brittle)

Cooling rate increases

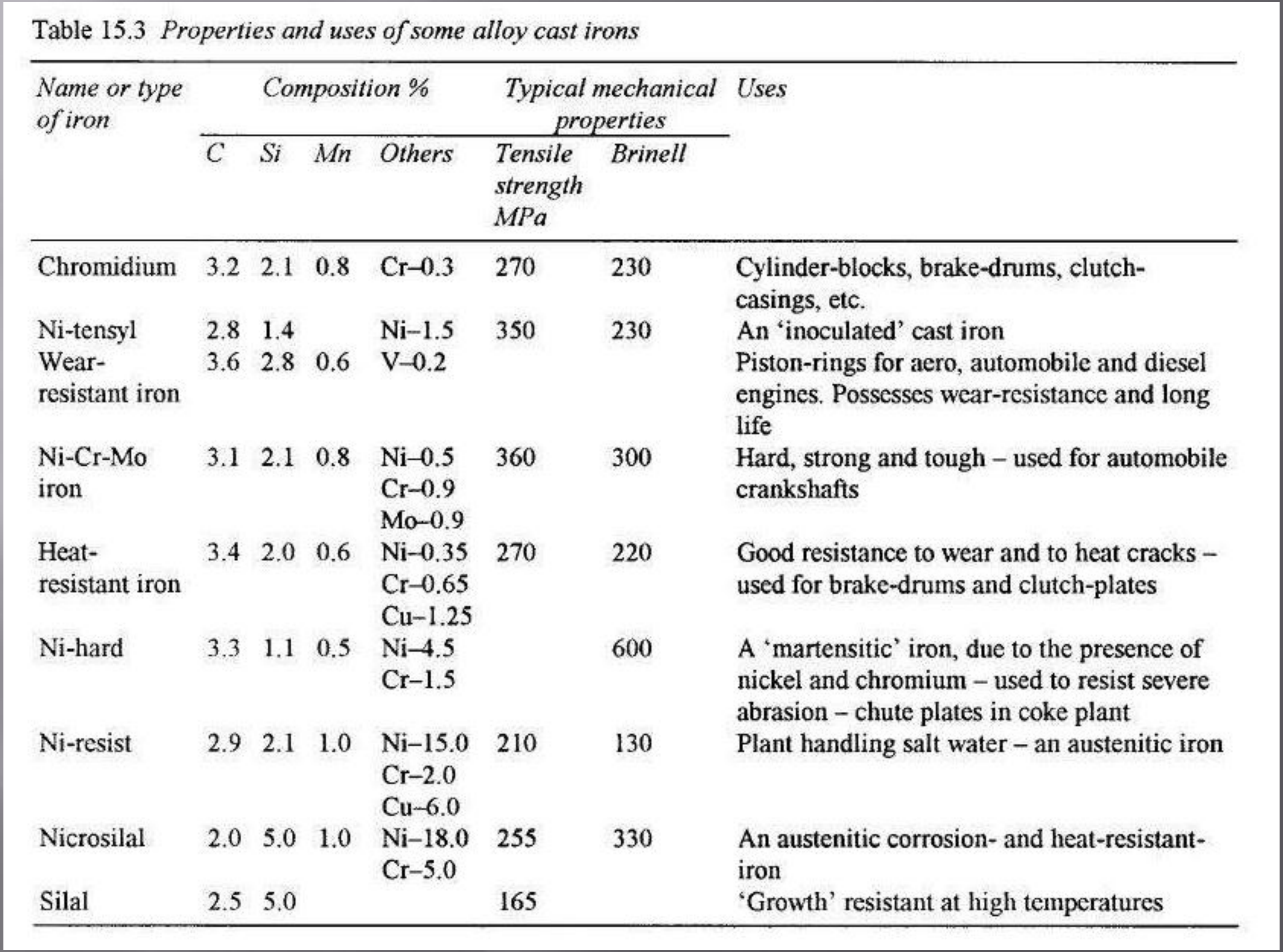
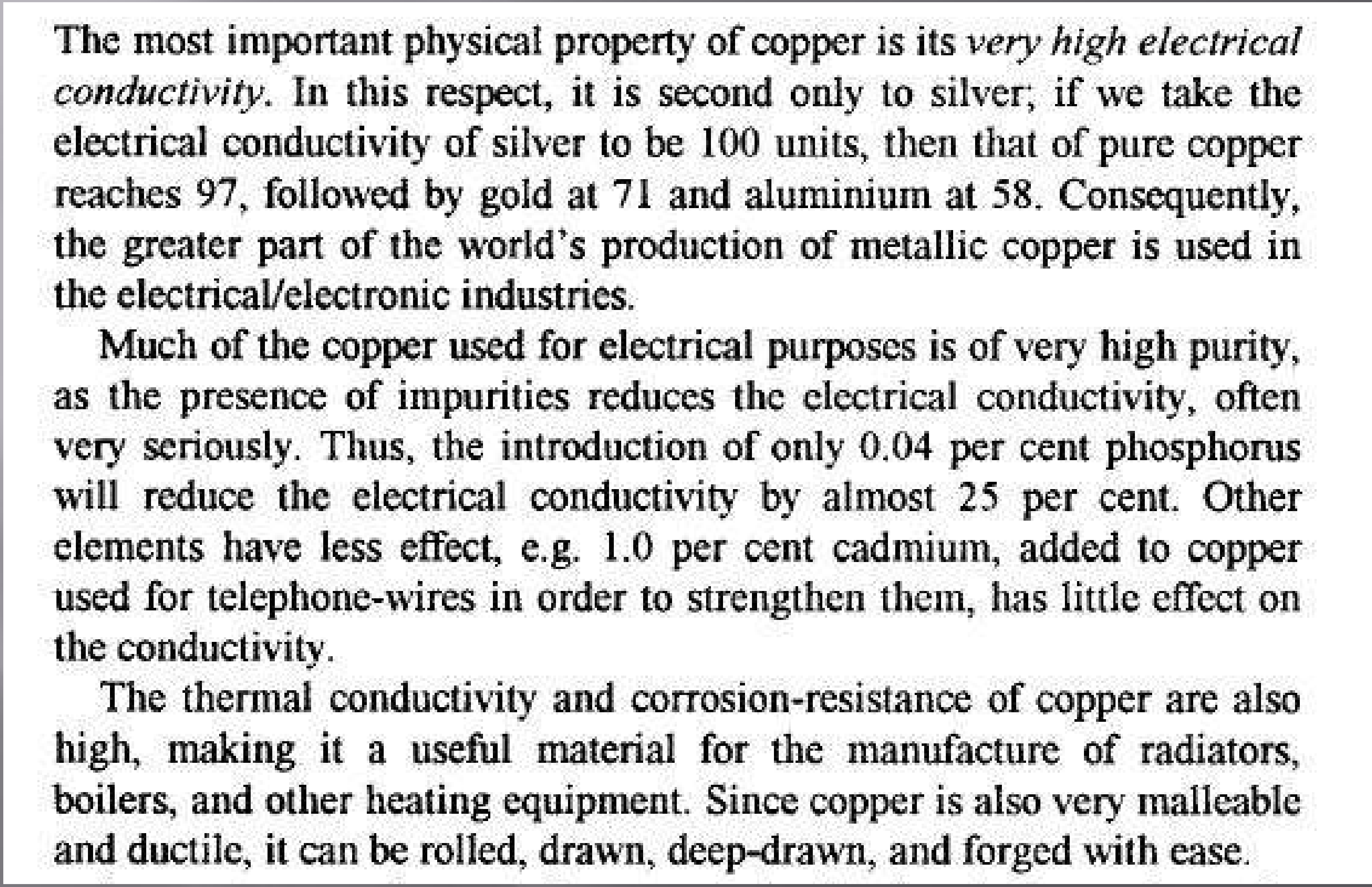


Table 15.3 *Properties and uses of some alloy cast irons*

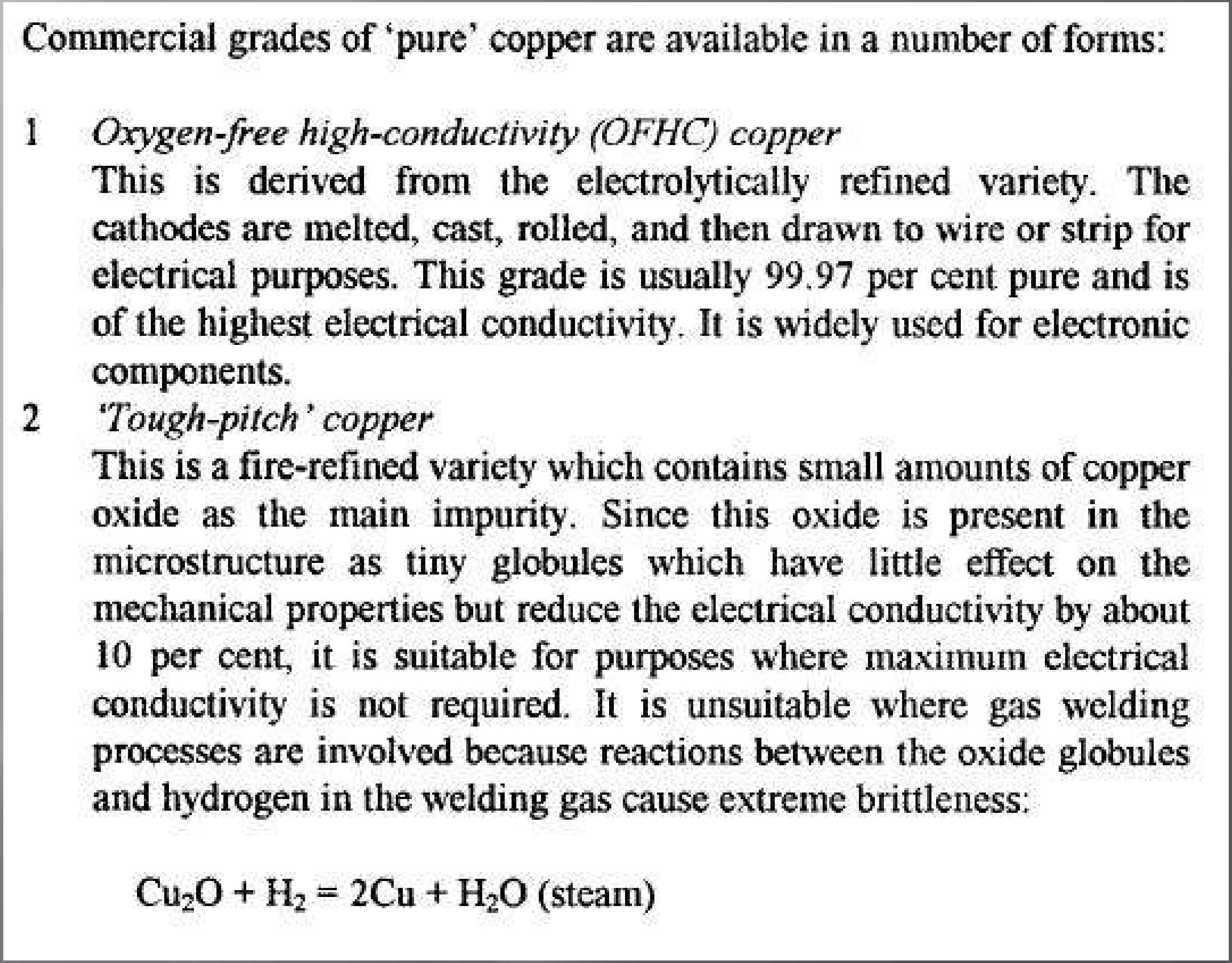
Name or type of iron	*Composition %*				*Typical mechanical properties*		*Uses*
	C	*Si*	*Mn*	*Others*	*Tensile strength MPa*	*Brinell*	
Chromidium	3.2	2.1	0.8	Cr–0.3	270	230	Cylinder-blocks, brake-drums, clutch-casings, etc.
Ni-tensyl	2.8	1.4		Ni–1.5	350	230	An 'inoculated' cast iron
Wear-resistant iron	3.6	2.8	0.6	V–0.2			Piston-rings for aero, automobile and diesel engines. Possesses wear-resistance and long life
Ni-Cr-Mo iron	3.1	2.1	0.8	Ni–0.5 Cr–0.9 Mo–0.9	360	300	Hard, strong and tough – used for automobile crankshafts
Heat-resistant iron	3.4	2.0	0.6	Ni–0.35 Cr–0.65 Cu–1.25	270	220	Good resistance to wear and to heat cracks – used for brake-drums and clutch-plates
Ni-hard	3.3	1.1	0.5	Ni–4.5 Cr–1.5		600	A 'martensitic' iron, due to the presence of nickel and chromium – used to resist severe abrasion – chute plates in coke plant
Ni-resist	2.9	2.1	1.0	Ni–15.0 Cr–2.0 Cu–6.0	210	130	Plant handling salt water – an austenitic iron
Nicrosilal	2.0	5.0	1.0	Ni–18.0 Cr–5.0	255	330	An austenitic corrosion- and heat-resistant-iron
Silal	2.5	5.0			165		'Growth' resistant at high temperatures



The most important physical property of copper is its *very high electrical conductivity*. In this respect, it is second only to silver; if we take the electrical conductivity of silver to be 100 units, then that of pure copper reaches 97, followed by gold at 71 and aluminium at 58. Consequently, the greater part of the world's production of metallic copper is used in the electrical/electronic industries.

Much of the copper used for electrical purposes is of very high purity, as the presence of impurities reduces the electrical conductivity, often very seriously. Thus, the introduction of only 0.04 per cent phosphorus will reduce the electrical conductivity by almost 25 per cent. Other elements have less effect, e.g. 1.0 per cent cadmium, added to copper used for telephone-wires in order to strengthen them, has little effect on the conductivity.

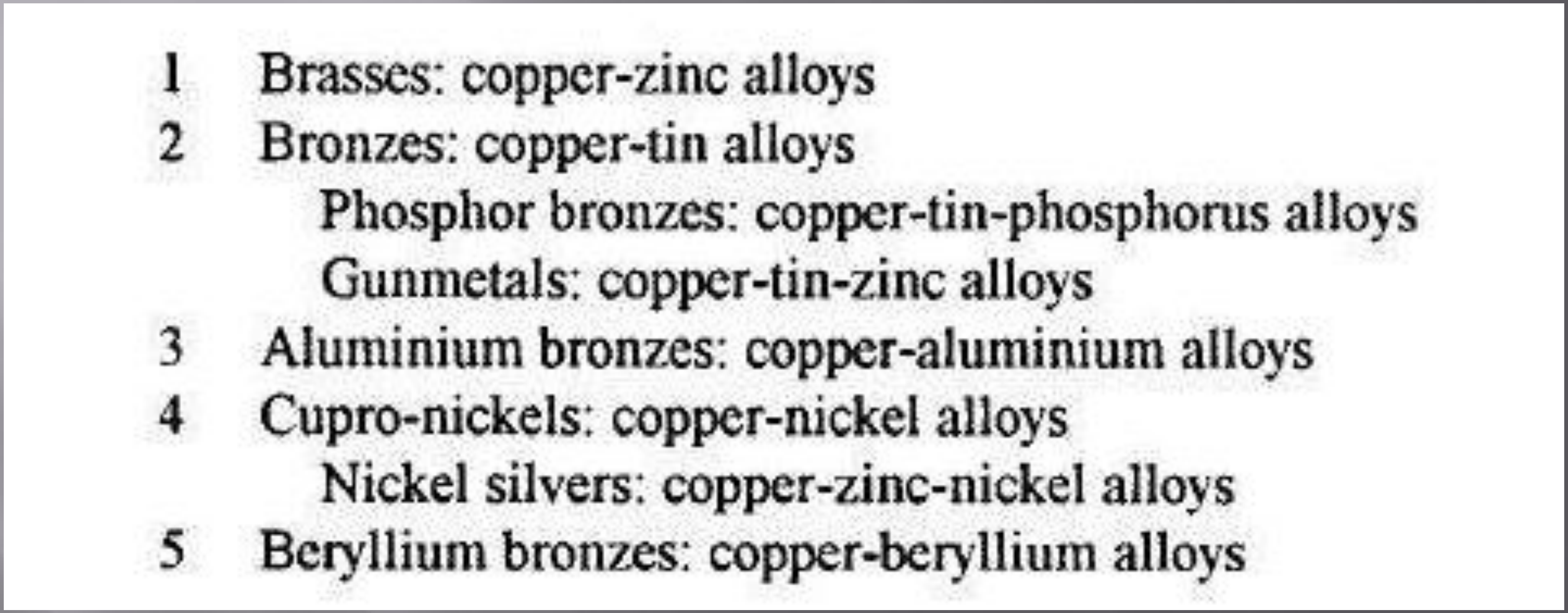
The thermal conductivity and corrosion-resistance of copper are also high, making it a useful material for the manufacture of radiators, boilers, and other heating equipment. Since copper is also very malleable and ductile, it can be rolled, drawn, deep-drawn, and forged with ease.



Commercial grades of 'pure' copper are available in a number of forms:

1. *Oxygen-free high-conductivity (OFHC) copper*
   This is derived from the electrolytically refined variety. The cathodes are melted, cast, rolled, and then drawn to wire or strip for electrical purposes. This grade is usually 99.97 per cent pure and is of the highest electrical conductivity. It is widely used for electronic components.
2. *'Tough-pitch' copper*
   This is a fire-refined variety which contains small amounts of copper oxide as the main impurity. Since this oxide is present in the microstructure as tiny globules which have little effect on the mechanical properties but reduce the electrical conductivity by about 10 per cent, it is suitable for purposes where maximum electrical conductivity is not required. It is unsuitable where gas welding processes are involved because reactions between the oxide globules and hydrogen in the welding gas cause extreme brittleness:

$$Cu_2O + H_2 = 2Cu + H_2O \text{ (steam)}$$



1. Brasses: copper-zinc alloys
2. Bronzes: copper-tin alloys
   - Phosphor bronzes: copper-tin-phosphorus alloys
   - Gunmetals: copper-tin-zinc alloys
3. Aluminium bronzes: copper-aluminium alloys
4. Cupro-nickels: copper-nickel alloys
   - Nickel silvers: copper-zinc-nickel alloys
5. Beryllium bronzes: copper-beryllium alloys

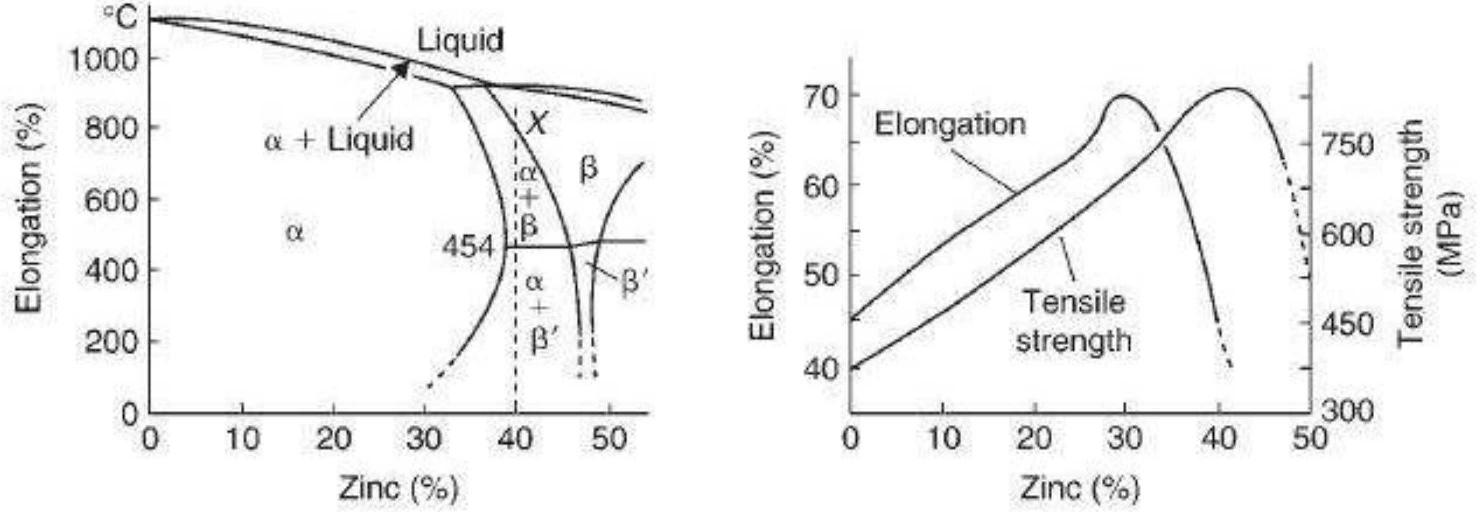


Figure 16.1 *The section of the copper-zinc equilibrium diagram which covers brasses of engineering importance.*

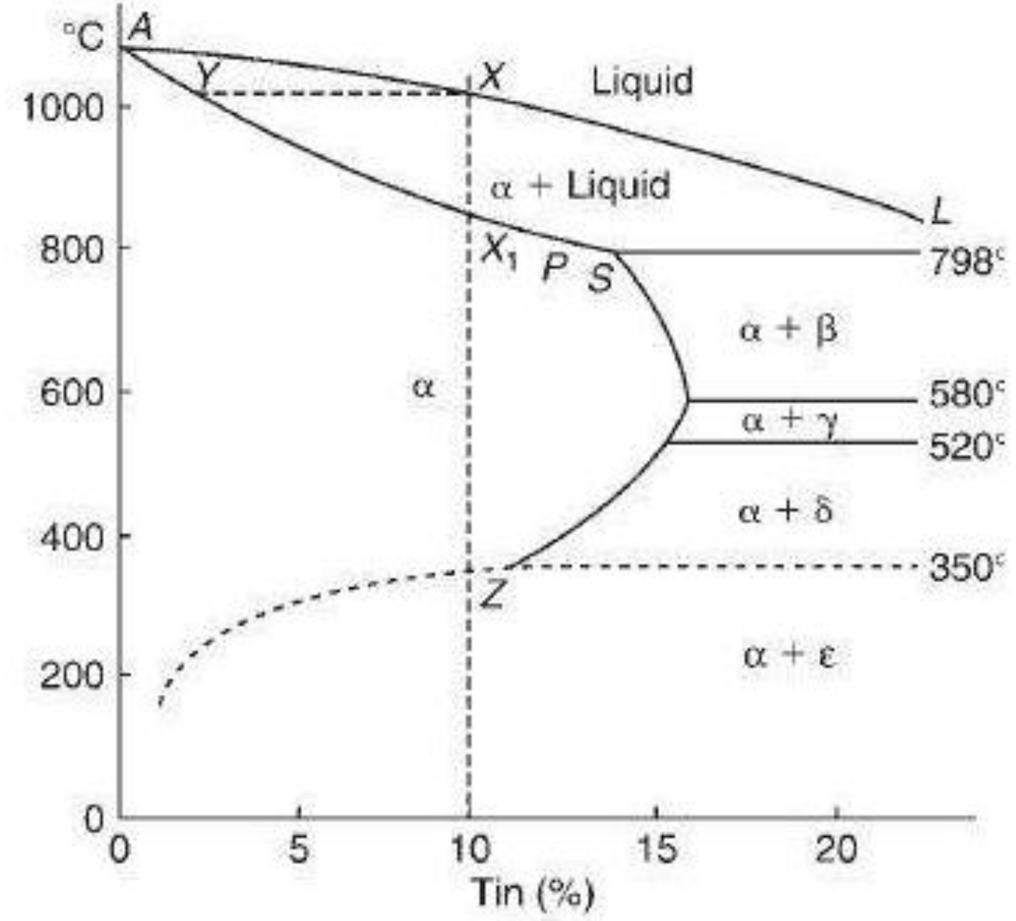
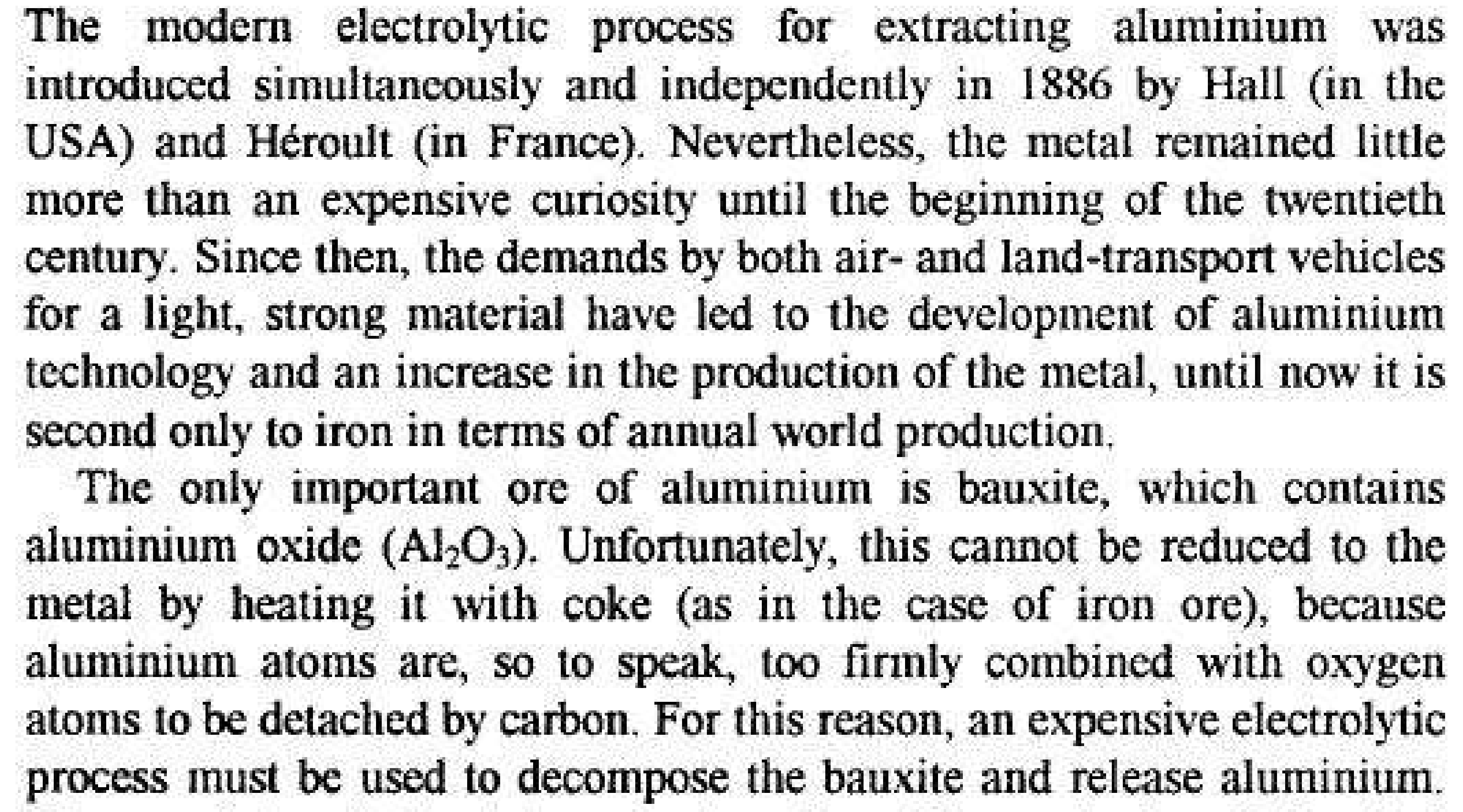
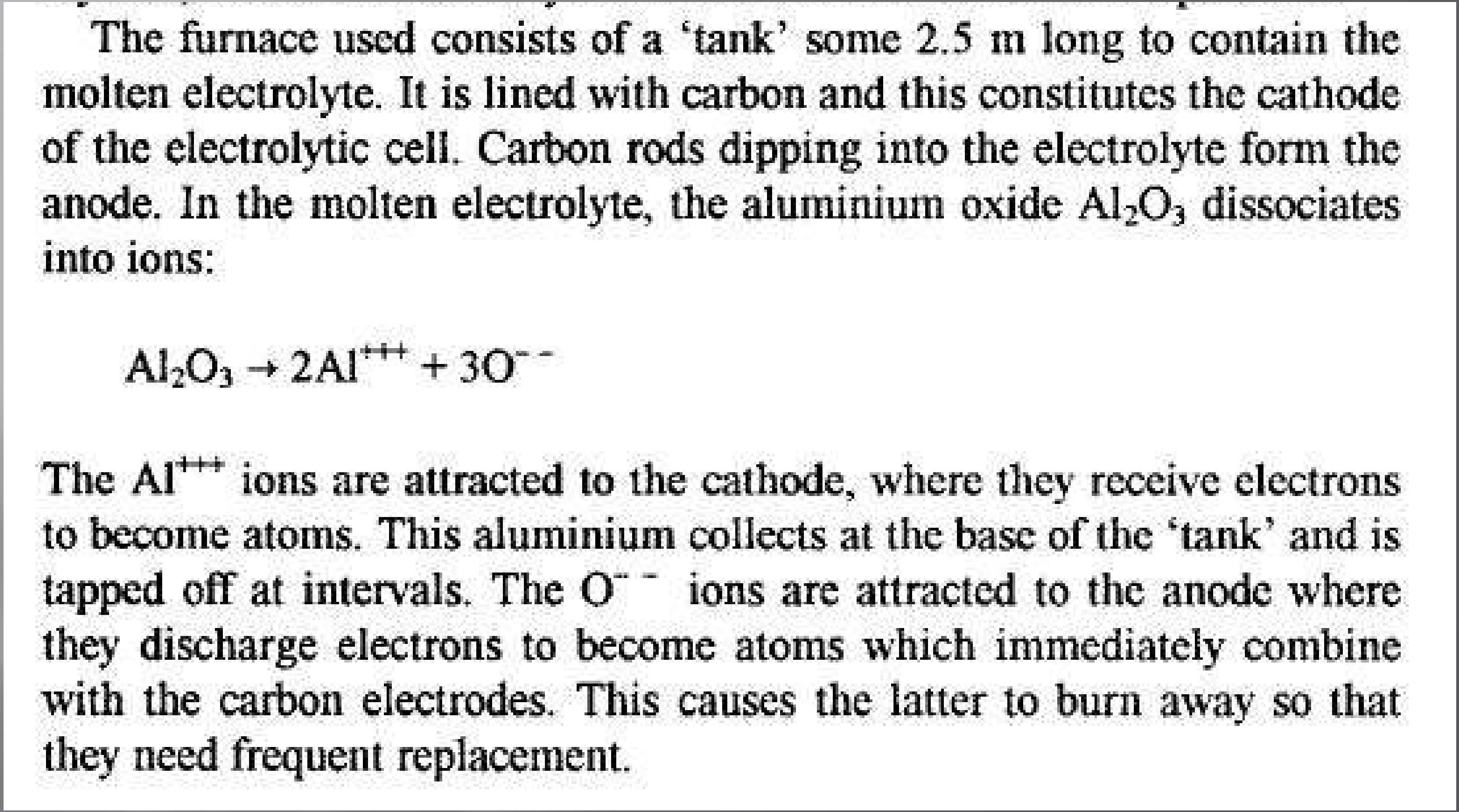


Figure 16.3 *Part of the copper-tin equilibrium diagram. The phase* δ *is an intermetallic compound* $Cu_{31}Sn_8$ *whilst* ε *is the intermetallic compound* Cu_3Sn*, but this latter will never be present in a bronze casting which solidifies and cools under normal industrial conditions.*



The modern electrolytic process for extracting aluminium was introduced simultaneously and independently in 1886 by Hall (in the USA) and Héroult (in France). Nevertheless, the metal remained little more than an expensive curiosity until the beginning of the twentieth century. Since then, the demands by both air- and land-transport vehicles for a light, strong material have led to the development of aluminium technology and an increase in the production of the metal, until now it is second only to iron in terms of annual world production.

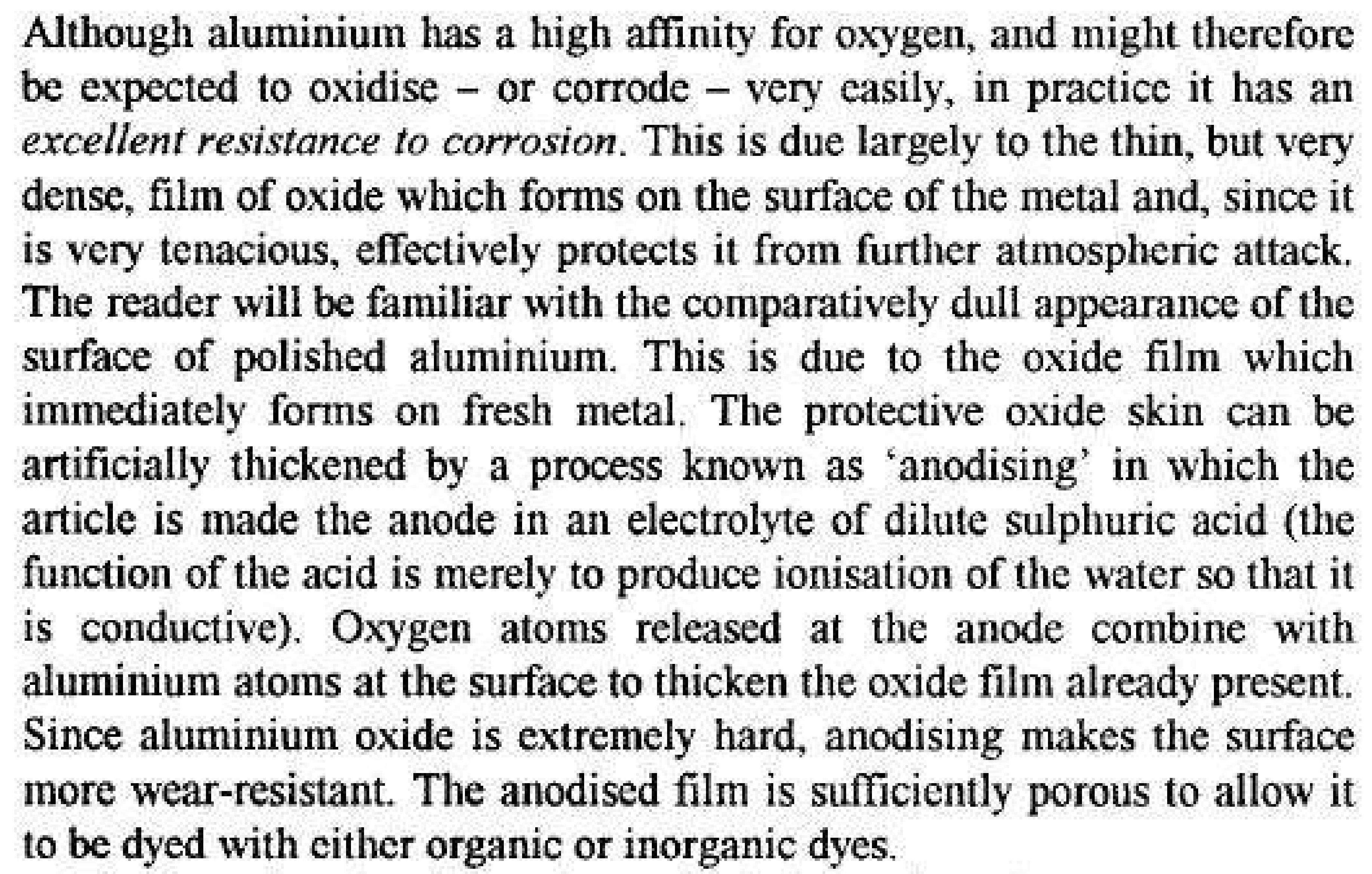
The only important ore of aluminium is bauxite, which contains aluminium oxide (Al_2O_3). Unfortunately, this cannot be reduced to the metal by heating it with coke (as in the case of iron ore), because aluminium atoms are, so to speak, too firmly combined with oxygen atoms to be detached by carbon. For this reason, an expensive electrolytic process must be used to decompose the bauxite and release aluminium.



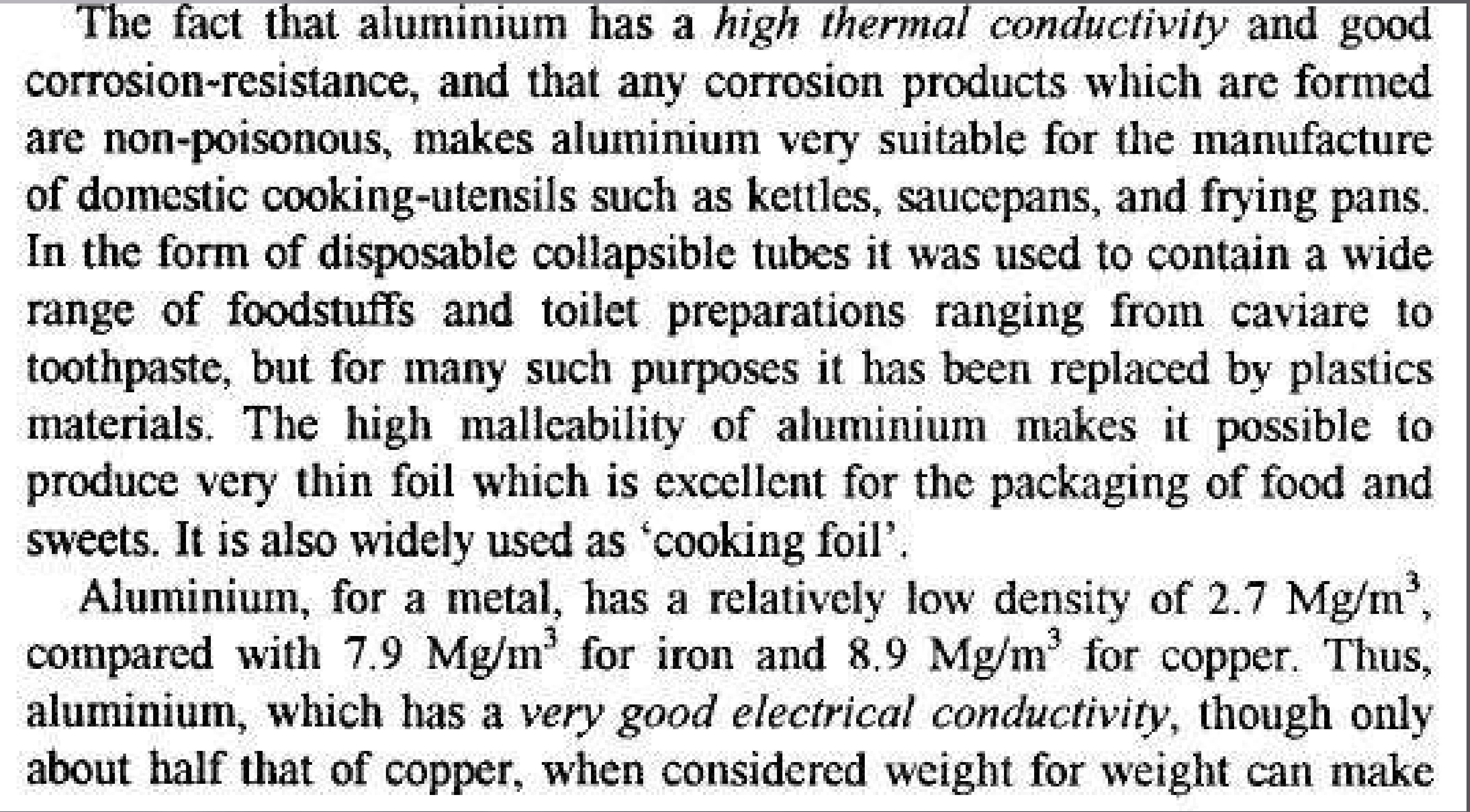
The furnace used consists of a 'tank' some 2.5 m long to contain the molten electrolyte. It is lined with carbon and this constitutes the cathode of the electrolytic cell. Carbon rods dipping into the electrolyte form the anode. In the molten electrolyte, the aluminium oxide Al_2O_3 dissociates into ions:

$$Al_2O_3 \rightarrow 2Al^{+++} + 3O^{--}$$

The Al^{+++} ions are attracted to the cathode, where they receive electrons to become atoms. This aluminium collects at the base of the 'tank' and is tapped off at intervals. The O^{--} ions are attracted to the anode where they discharge electrons to become atoms which immediately combine with the carbon electrodes. This causes the latter to burn away so that they need frequent replacement.

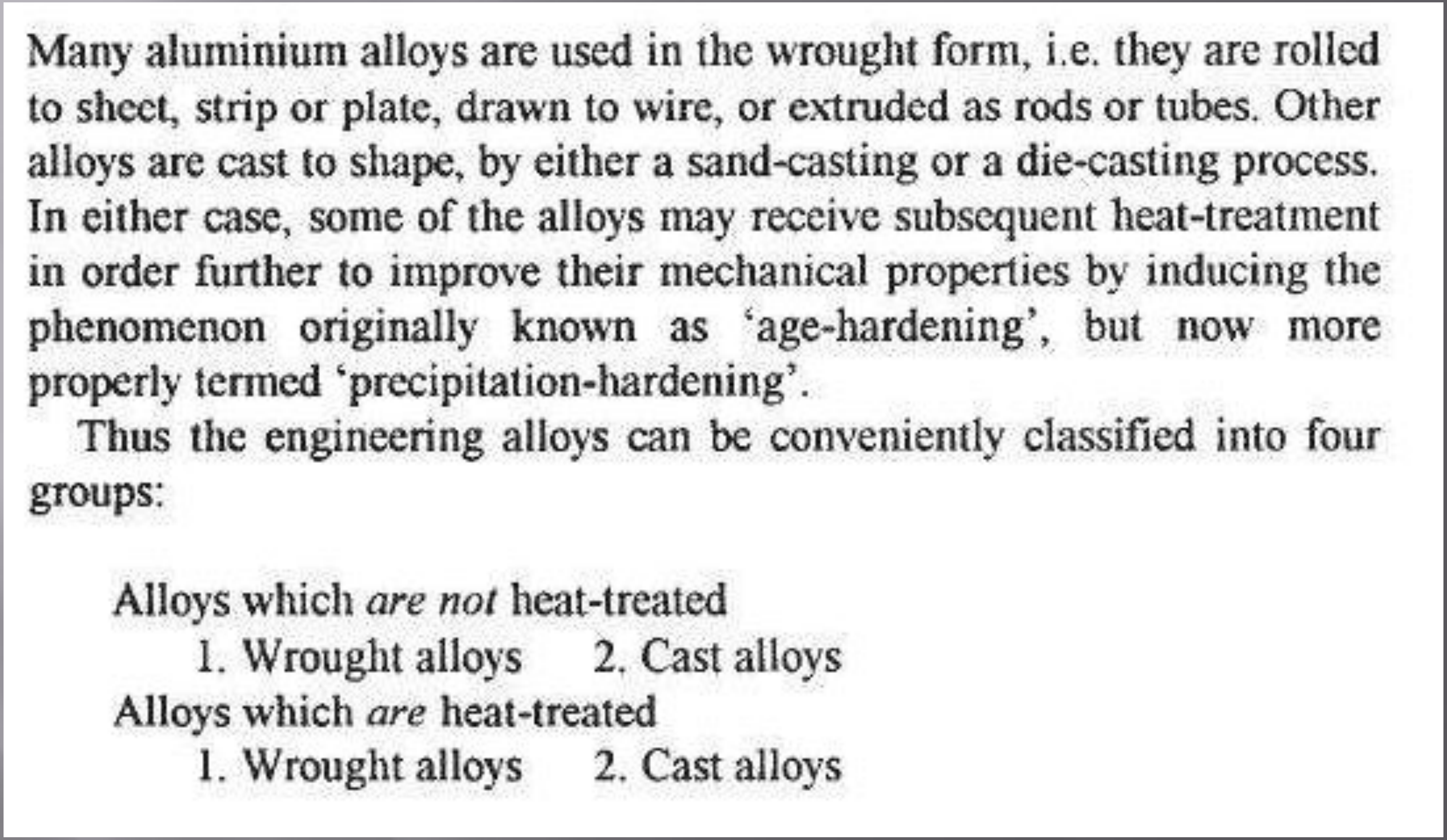


Although aluminium has a high affinity for oxygen, and might therefore be expected to oxidise – or corrode – very easily, in practice it has an *excellent resistance to corrosion*. This is due largely to the thin, but very dense, film of oxide which forms on the surface of the metal and, since it is very tenacious, effectively protects it from further atmospheric attack. The reader will be familiar with the comparatively dull appearance of the surface of polished aluminium. This is due to the oxide film which immediately forms on fresh metal. The protective oxide skin can be artificially thickened by a process known as 'anodising' in which the article is made the anode in an electrolyte of dilute sulphuric acid (the function of the acid is merely to produce ionisation of the water so that it is conductive). Oxygen atoms released at the anode combine with aluminium atoms at the surface to thicken the oxide film already present. Since aluminium oxide is extremely hard, anodising makes the surface more wear-resistant. The anodised film is sufficiently porous to allow it to be dyed with either organic or inorganic dyes.



The fact that aluminium has a *high thermal conductivity* and good corrosion-resistance, and that any corrosion products which are formed are non-poisonous, makes aluminium very suitable for the manufacture of domestic cooking-utensils such as kettles, saucepans, and frying pans. In the form of disposable collapsible tubes it was used to contain a wide range of foodstuffs and toilet preparations ranging from caviare to toothpaste, but for many such purposes it has been replaced by plastics materials. The high malleability of aluminium makes it possible to produce very thin foil which is excellent for the packaging of food and sweets. It is also widely used as 'cooking foil'.

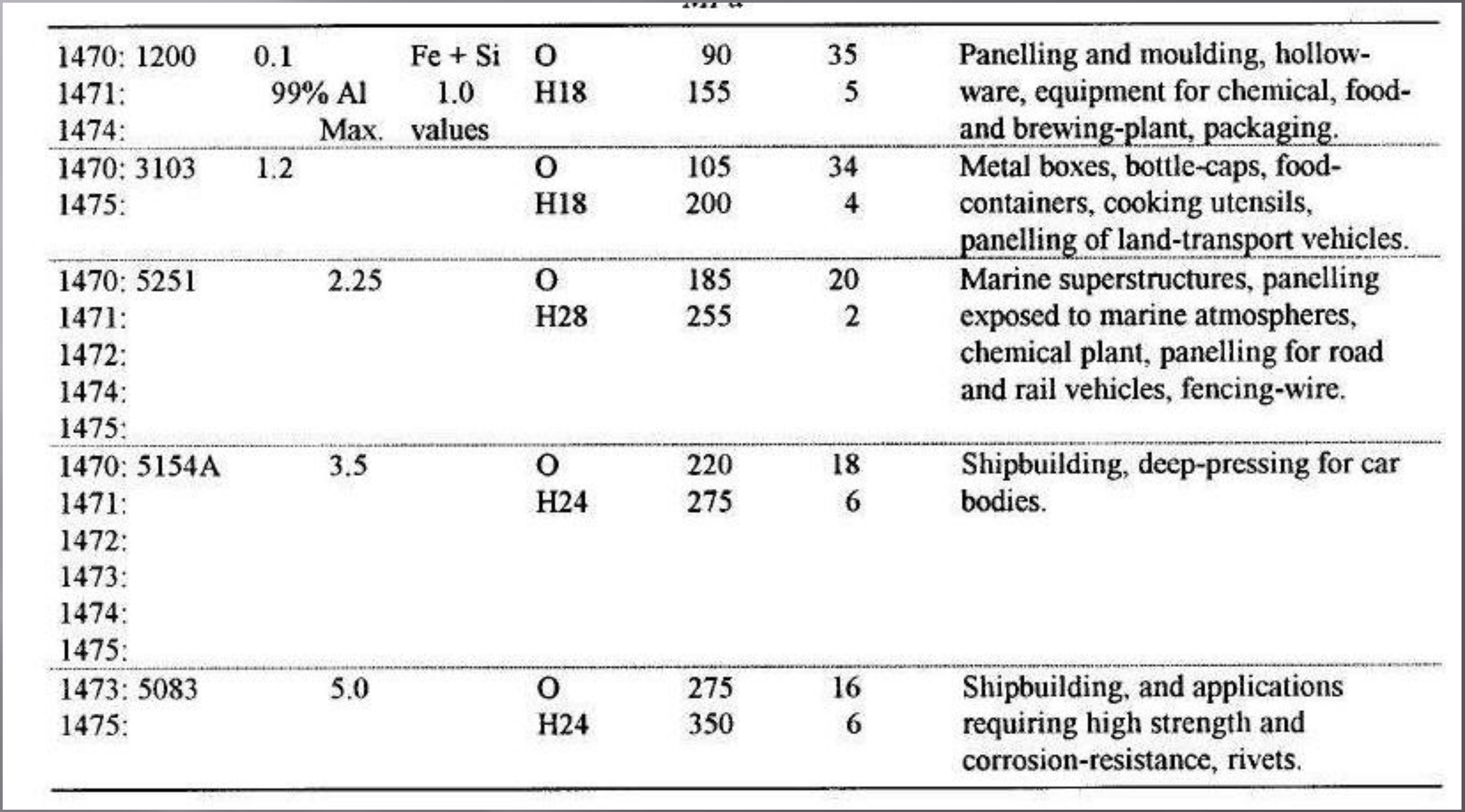
Aluminium, for a metal, has a relatively low density of 2.7 Mg/m^3, compared with 7.9 Mg/m^3 for iron and 8.9 Mg/m^3 for copper. Thus, aluminium, which has a *very good electrical conductivity*, though only about half that of copper, when considered weight for weight can make



Many aluminium alloys are used in the wrought form, i.e. they are rolled to sheet, strip or plate, drawn to wire, or extruded as rods or tubes. Other alloys are cast to shape, by either a sand-casting or a die-casting process. In either case, some of the alloys may receive subsequent heat-treatment in order further to improve their mechanical properties by inducing the phenomenon originally known as 'age-hardening', but now more properly termed 'precipitation-hardening'.

Thus the engineering alloys can be conveniently classified into four groups:

Alloys which *are not* heat-treated
    1. Wrought alloys   2. Cast alloys
Alloys which *are* heat-treated
    1. Wrought alloys   2. Cast alloys



1470: 1200 1471: 1474:	0.1	99% Al Max.	Fe + Si 1.0 values	O H18	90 155	35 5	Panelling and moulding, hollow-ware, equipment for chemical, food- and brewing-plant, packaging.
1470: 3103 1475:	1.2			O H18	105 200	34 4	Metal boxes, bottle-caps, food-containers, cooking utensils, panelling of land-transport vehicles.
1470: 5251 1471: 1472: 1474: 1475:		2.25		O H28	185 255	20 2	Marine superstructures, panelling exposed to marine atmospheres, chemical plant, panelling for road and rail vehicles, fencing-wire.
1470: 5154A 1471: 1472: 1473: 1474: 1475:		3.5		O H24	220 275	18 6	Shipbuilding, deep-pressing for car bodies.
1473: 5083 1475:		5.0		O H24	275 350	16 6	Shipbuilding, and applications requiring high strength and corrosion-resistance, rivets.

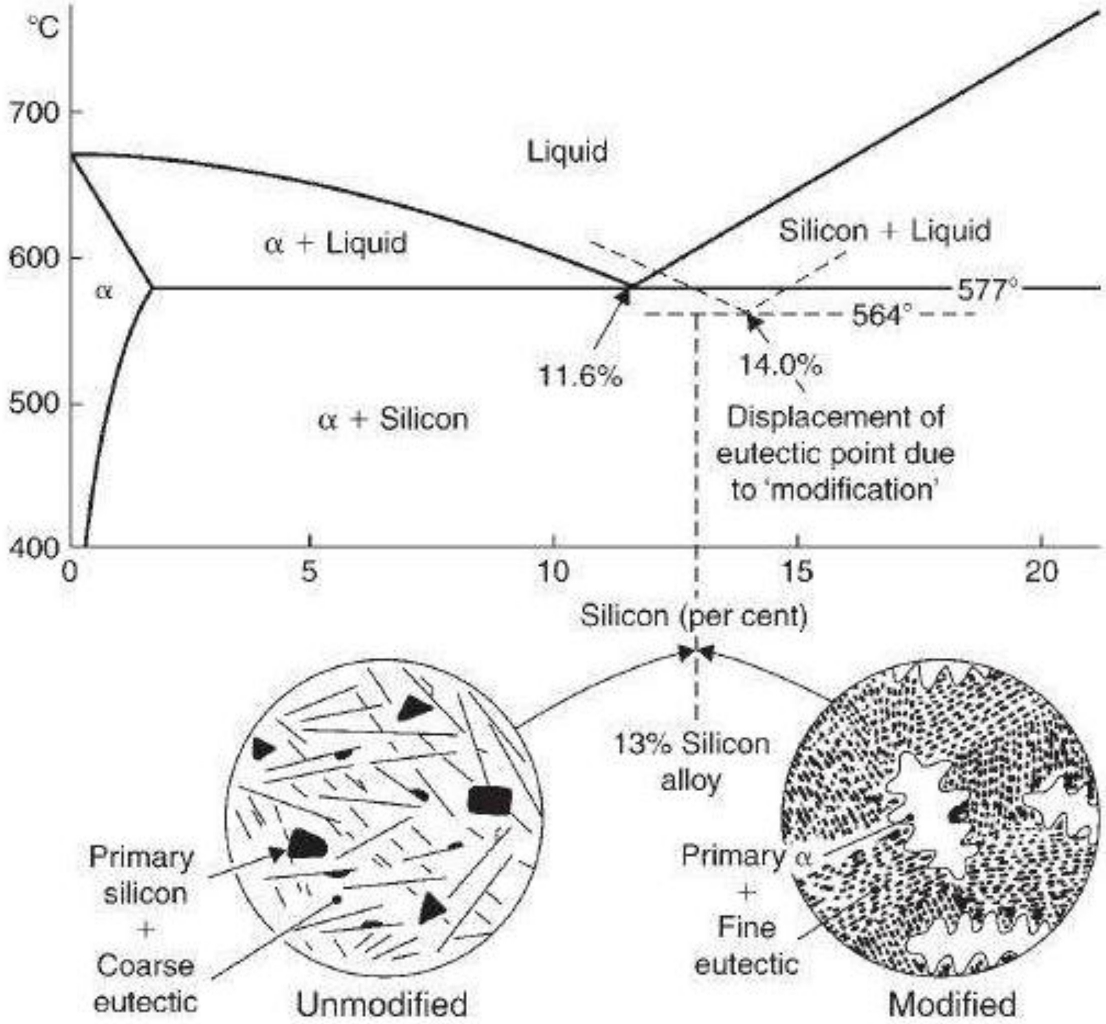
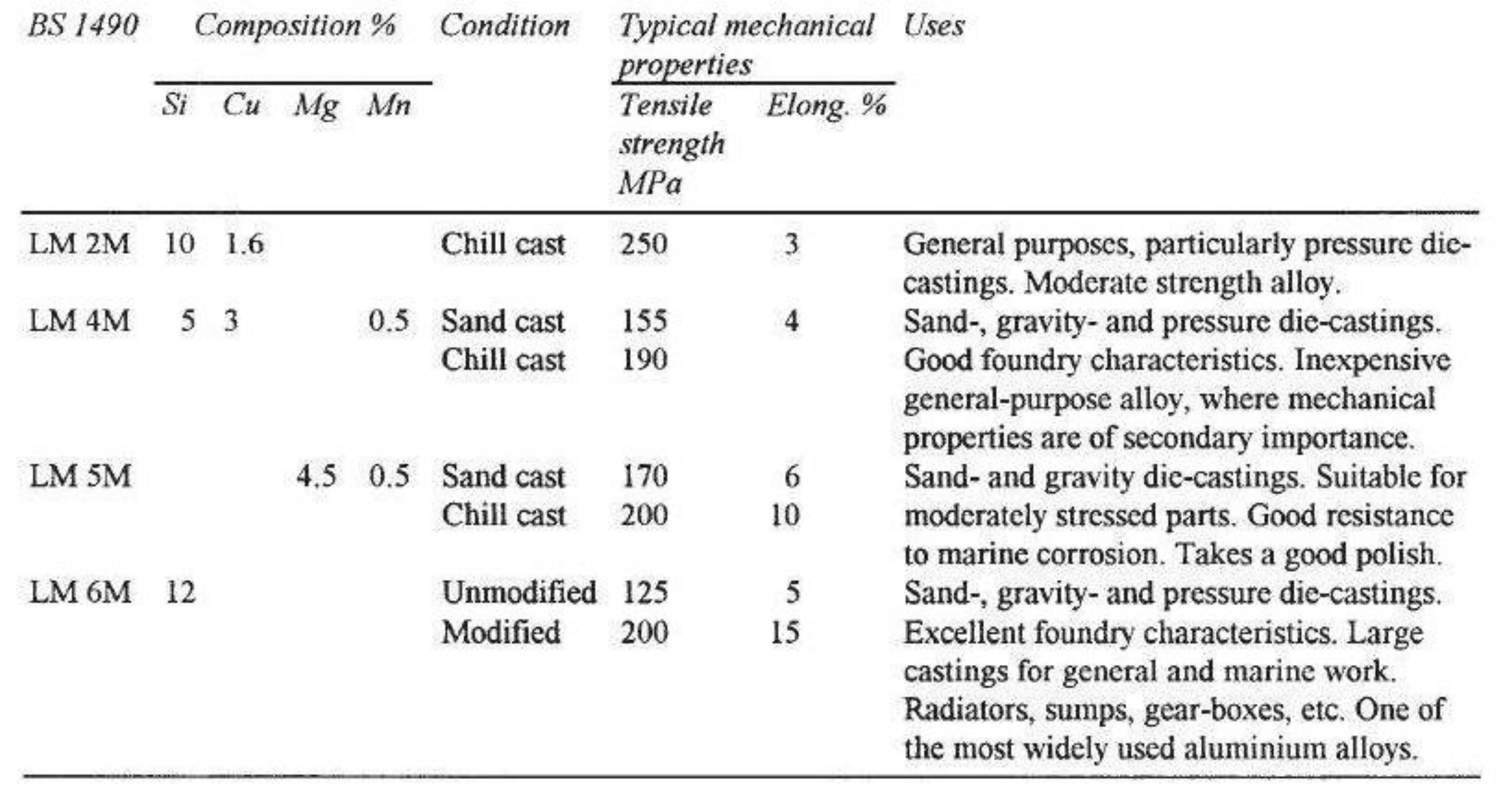


Figure 17.2 *The aluminium-silicon thermal equilibrium diagram. The effects of 'modification' on both the position of the eutectic point and the structure are also shown. See also Figure 17.3.*



BS 1490	*Composition %*				*Condition*	*Typical mechanical properties*		*Uses*
	Si	*Cu*	*Mg*	*Mn*		*Tensile strength MPa*	*Elong. %*	
LM 2M	10	1.6			Chill cast	250	3	General purposes, particularly pressure die-castings. Moderate strength alloy.
LM 4M	5	3		0.5	Sand cast	155	4	Sand-, gravity- and pressure die-castings. Good foundry characteristics. Inexpensive general-purpose alloy, where mechanical properties are of secondary importance.
					Chill cast	190		
LM 5M			4.5	0.5	Sand cast	170	6	Sand- and gravity die-castings. Suitable for moderately stressed parts. Good resistance to marine corrosion. Takes a good polish.
					Chill cast	200	10	
LM 6M	12				Unmodified	125	5	Sand-, gravity- and pressure die-castings. Excellent foundry characteristics. Large castings for general and marine work. Radiators, sumps, gear-boxes, etc. One of the most widely used aluminium alloys.
					Modified	200	15	

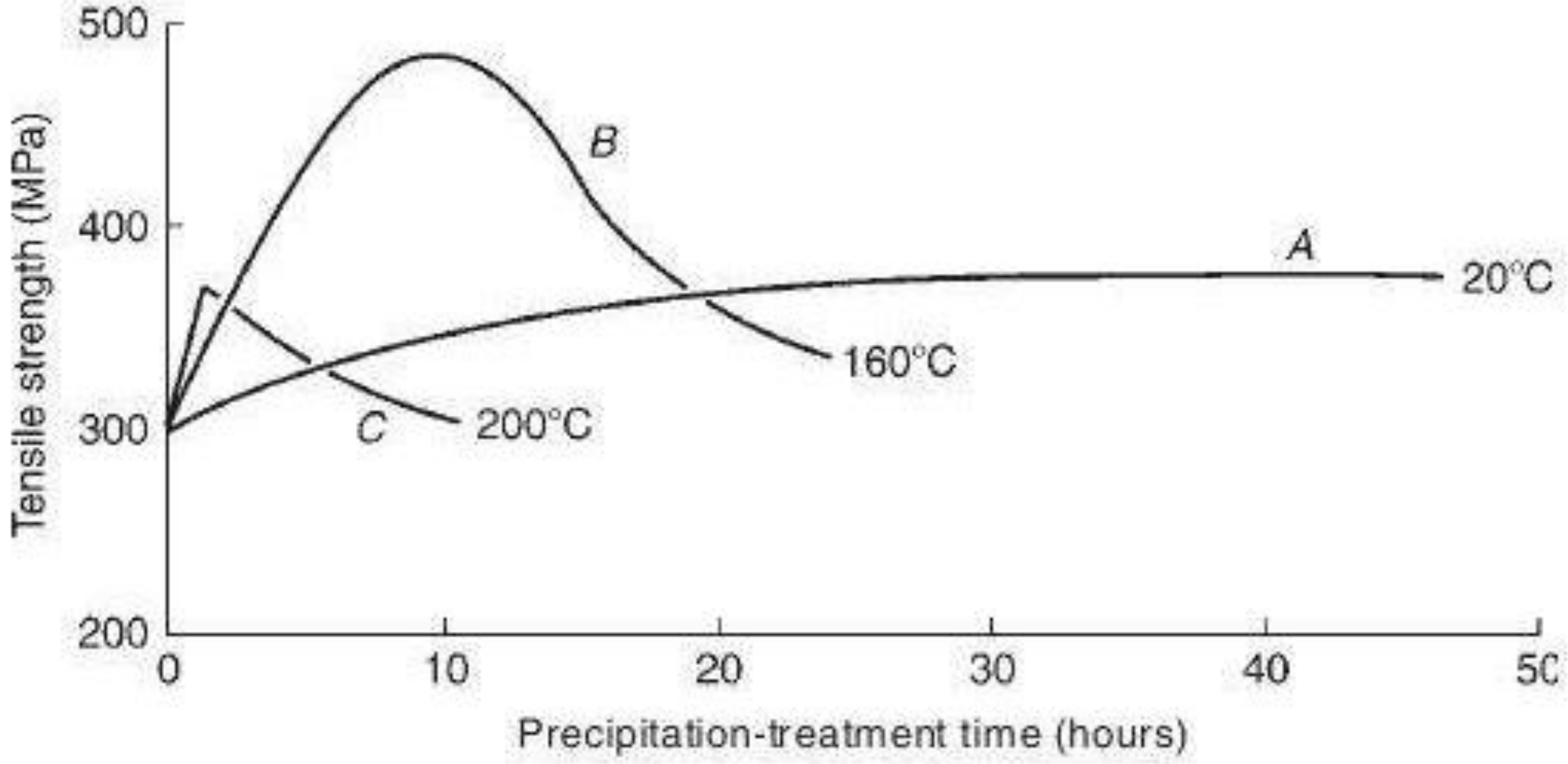
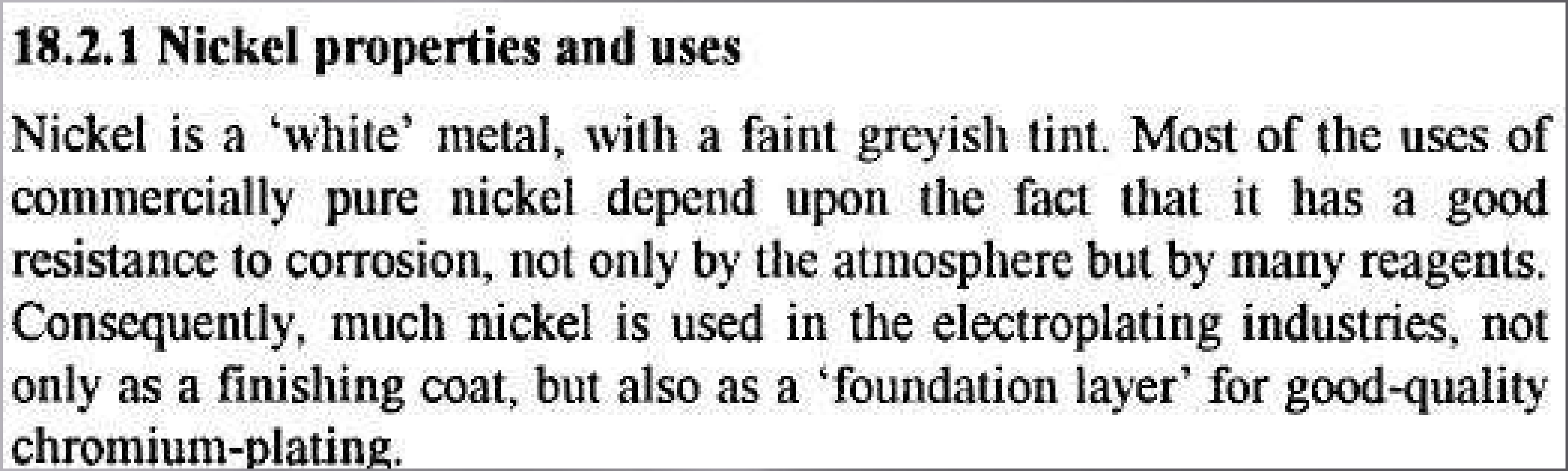
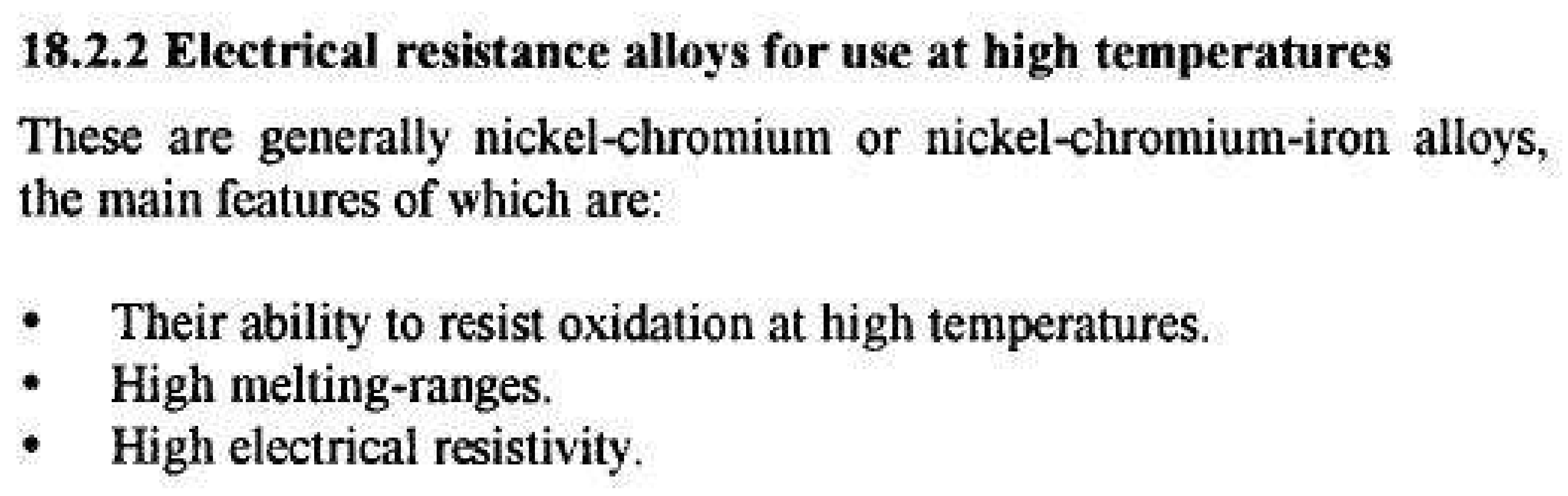


Figure 17.5 *The effects of time and temperature of precipitation-treatment on the strength of duralumin.*



18.2.1 Nickel properties and uses

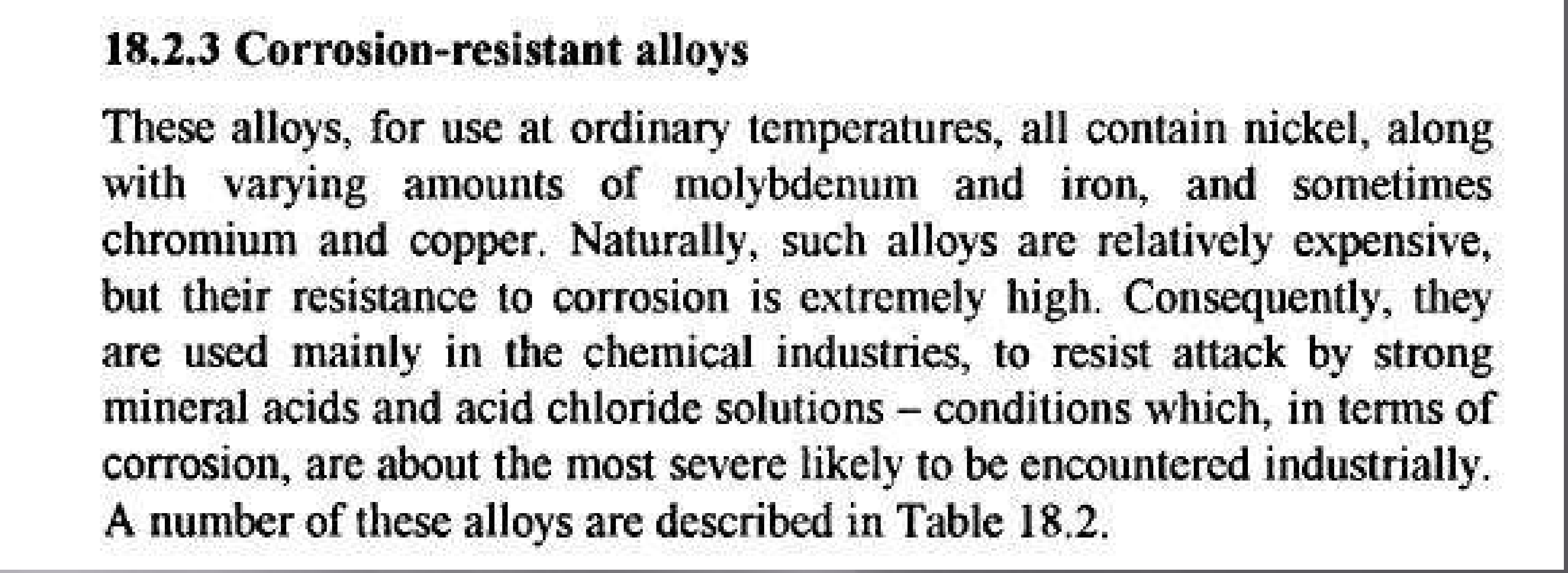
Nickel is a 'white' metal, with a faint greyish tint. Most of the uses of commercially pure nickel depend upon the fact that it has a good resistance to corrosion, not only by the atmosphere but by many reagents. Consequently, much nickel is used in the electroplating industries, not only as a finishing coat, but also as a 'foundation layer' for good-quality chromium-plating.



18.2.2 Electrical resistance alloys for use at high temperatures

These are generally nickel-chromium or nickel-chromium-iron alloys, the main features of which are:

- Their ability to resist oxidation at high temperatures.
- High melting-ranges.
- High electrical resistivity.



18.2.3 Corrosion-resistant alloys

These alloys, for use at ordinary temperatures, all contain nickel, along with varying amounts of molybdenum and iron, and sometimes chromium and copper. Naturally, such alloys are relatively expensive, but their resistance to corrosion is extremely high. Consequently, they are used mainly in the chemical industries, to resist attack by strong mineral acids and acid chloride solutions – conditions which, in terms of corrosion, are about the most severe likely to be encountered industrially. A number of these alloys are described in Table 18.2.

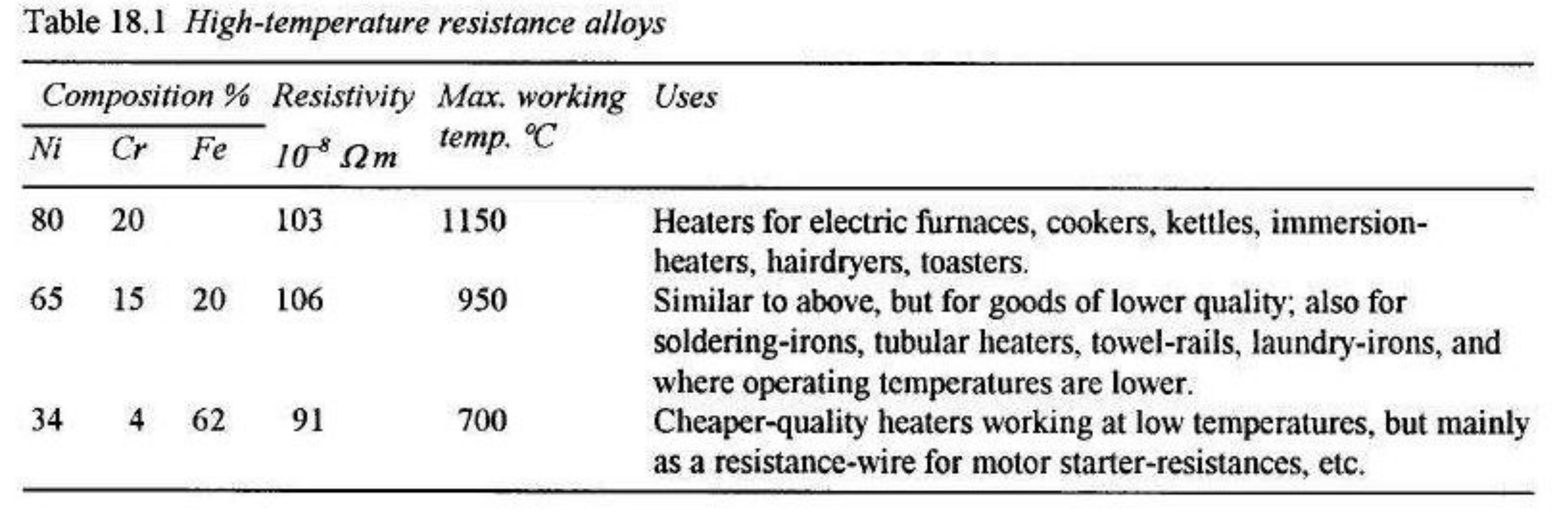


Table 18.1 *High-temperature resistance alloys*

Composition %			*Resistivity*	*Max. working temp. °C*	*Uses*
Ni	*Cr*	*Fe*	$10^{-8}\ \Omega m$		
80	20		103	1150	Heaters for electric furnaces, cookers, kettles, immersion-heaters, hairdryers, toasters.
65	15	20	106	950	Similar to above, but for goods of lower quality; also for soldering-irons, tubular heaters, towel-rails, laundry-irons, and where operating temperatures are lower.
34	4	62	91	700	Cheaper-quality heaters working at low temperatures, but mainly as a resistance-wire for motor starter-resistances, etc.

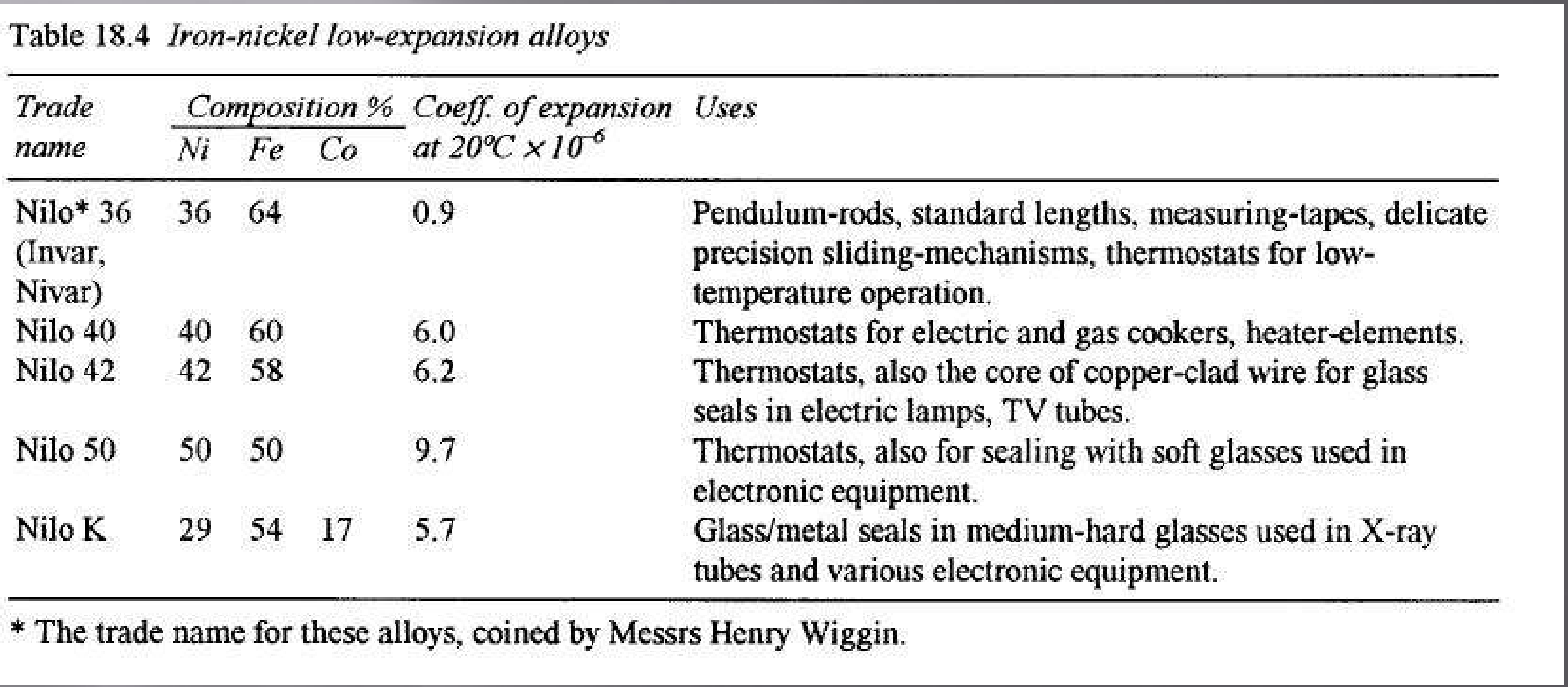
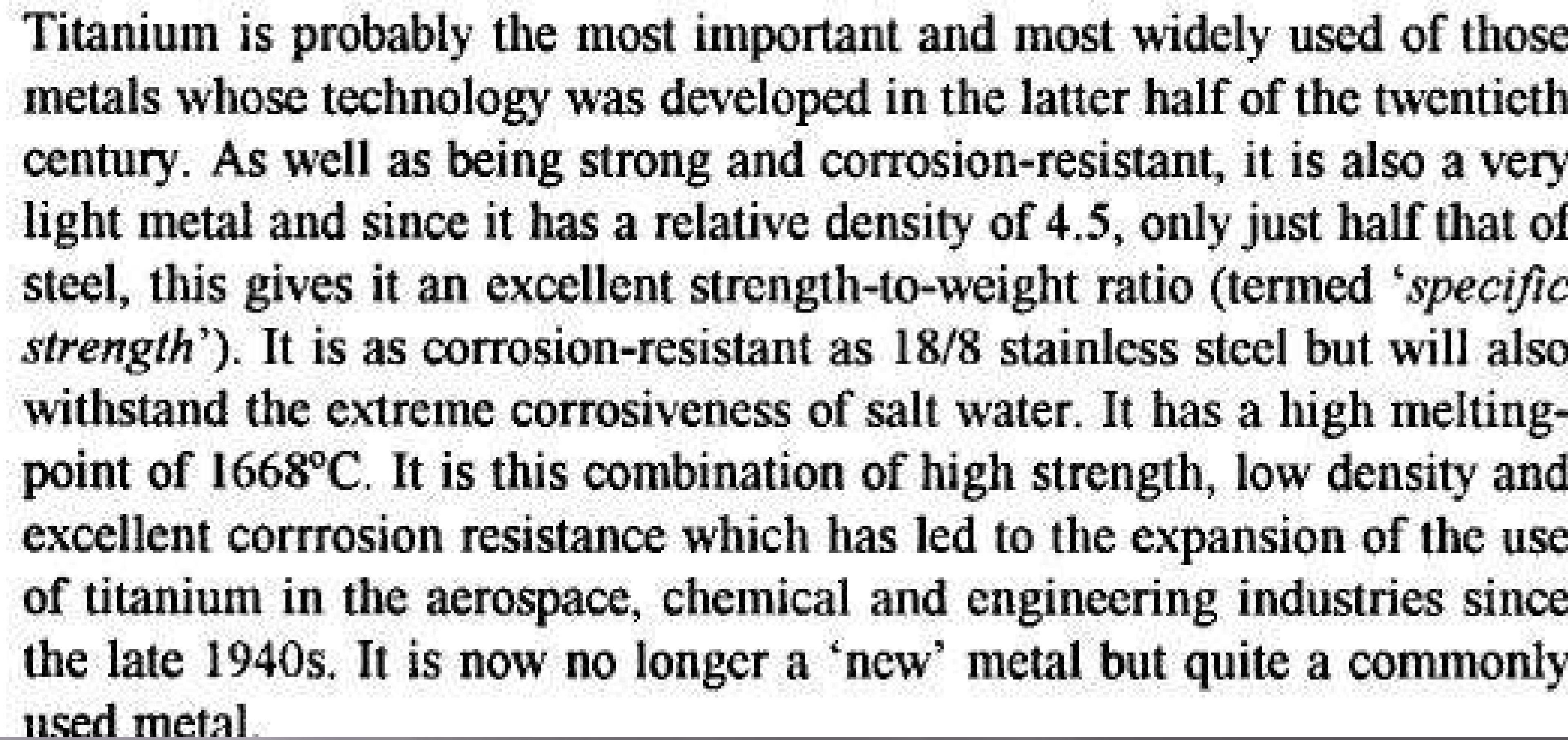


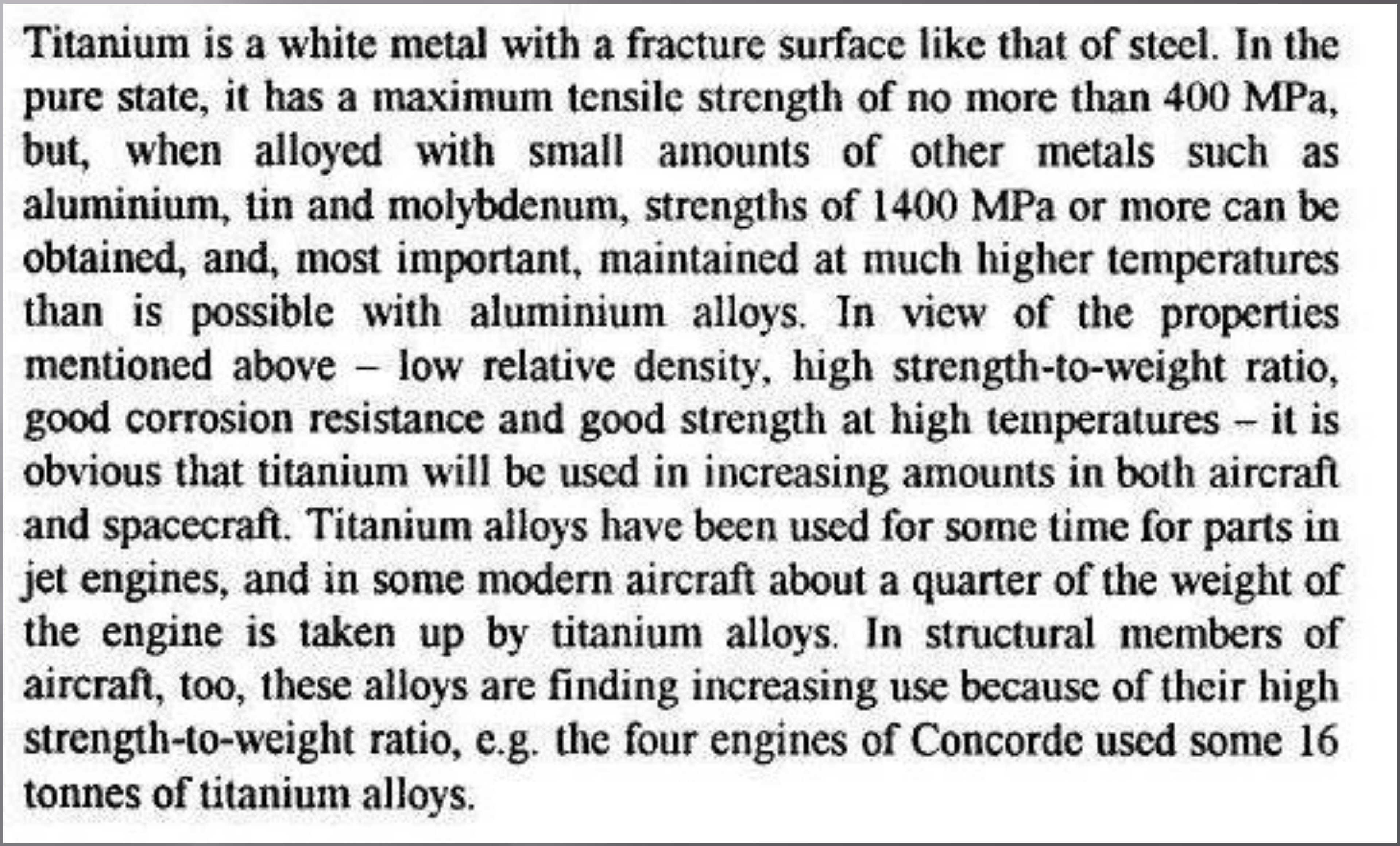
Table 18.4 *Iron-nickel low-expansion alloys*

Trade name	*Composition %*			*Coeff. of expansion at 20°C × 10^{-6}*	*Uses*
	Ni	*Fe*	*Co*		
Nilo* 36 (Invar, Nivar)	36	64		0.9	Pendulum-rods, standard lengths, measuring-tapes, delicate precision sliding-mechanisms, thermostats for low-temperature operation.
Nilo 40	40	60		6.0	Thermostats for electric and gas cookers, heater-elements.
Nilo 42	42	58		6.2	Thermostats, also the core of copper-clad wire for glass seals in electric lamps, TV tubes.
Nilo 50	50	50		9.7	Thermostats, also for sealing with soft glasses used in electronic equipment.
Nilo K	29	54	17	5.7	Glass/metal seals in medium-hard glasses used in X-ray tubes and various electronic equipment.

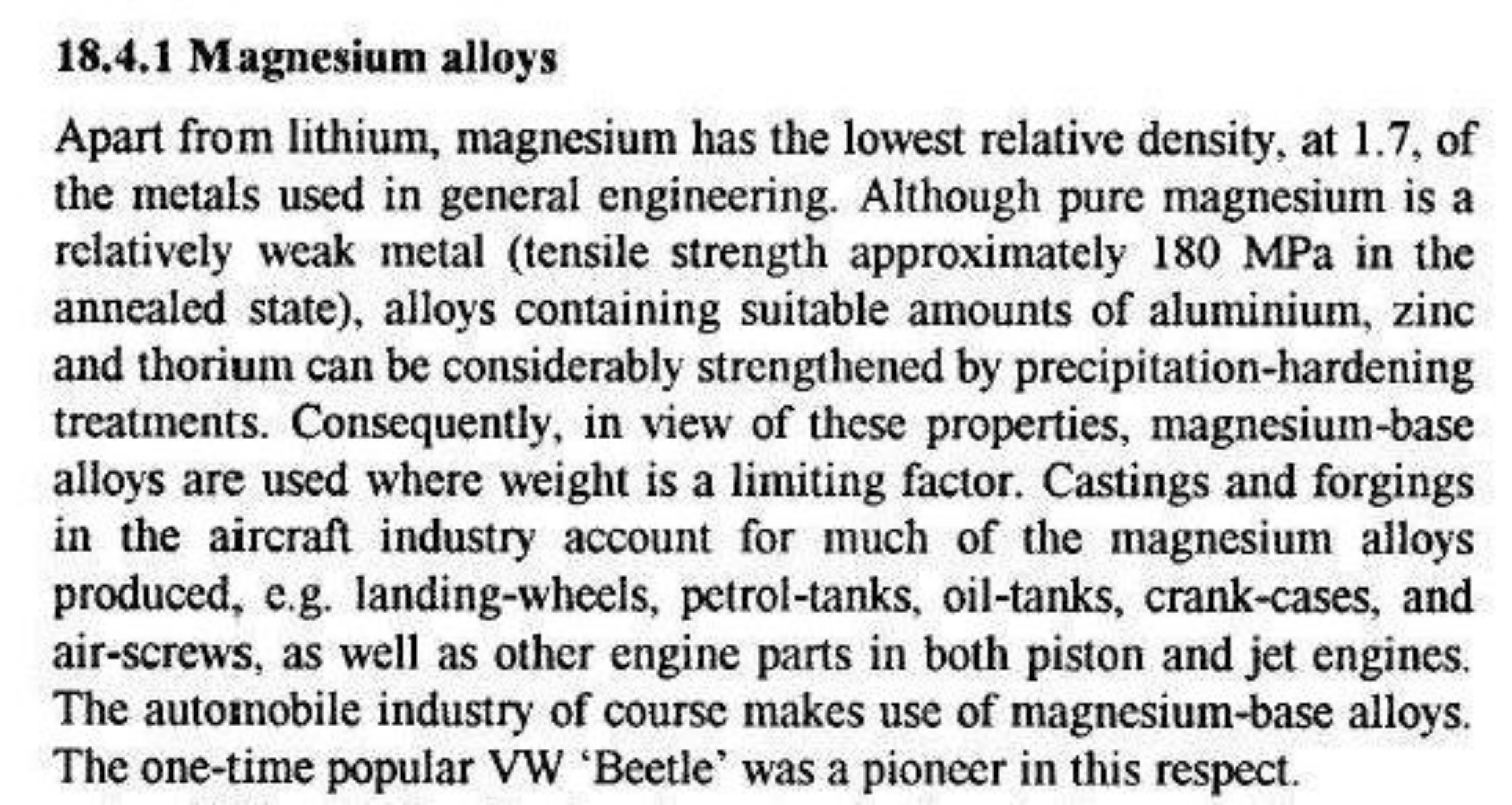
* The trade name for these alloys, coined by Messrs Henry Wiggin.



Titanium is probably the most important and most widely used of those metals whose technology was developed in the latter half of the twentieth century. As well as being strong and corrosion-resistant, it is also a very light metal and since it has a relative density of 4.5, only just half that of steel, this gives it an excellent strength-to-weight ratio (termed '*specific strength*'). It is as corrosion-resistant as 18/8 stainless steel but will also withstand the extreme corrosiveness of salt water. It has a high melting-point of 1668°C. It is this combination of high strength, low density and excellent corrrosion resistance which has led to the expansion of the use of titanium in the aerospace, chemical and engineering industries since the late 1940s. It is now no longer a 'new' metal but quite a commonly used metal.

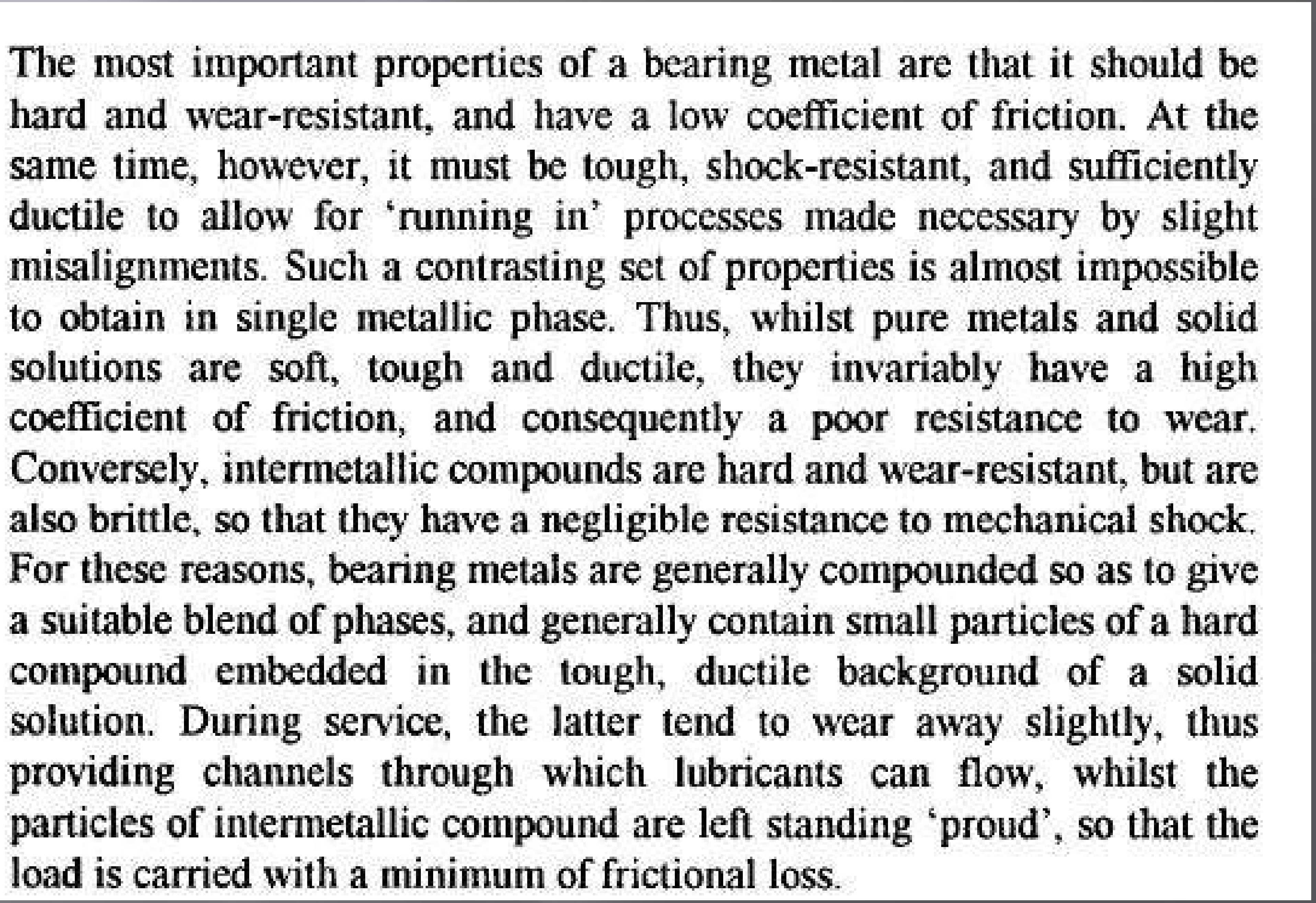


Titanium is a white metal with a fracture surface like that of steel. In the pure state, it has a maximum tensile strength of no more than 400 MPa, but, when alloyed with small amounts of other metals such as aluminium, tin and molybdenum, strengths of 1400 MPa or more can be obtained, and, most important, maintained at much higher temperatures than is possible with aluminium alloys. In view of the properties mentioned above – low relative density, high strength-to-weight ratio, good corrosion resistance and good strength at high temperatures – it is obvious that titanium will be used in increasing amounts in both aircraft and spacecraft. Titanium alloys have been used for some time for parts in jet engines, and in some modern aircraft about a quarter of the weight of the engine is taken up by titanium alloys. In structural members of aircraft, too, these alloys are finding increasing use because of their high strength-to-weight ratio, e.g. the four engines of Concorde used some 16 tonnes of titanium alloys.

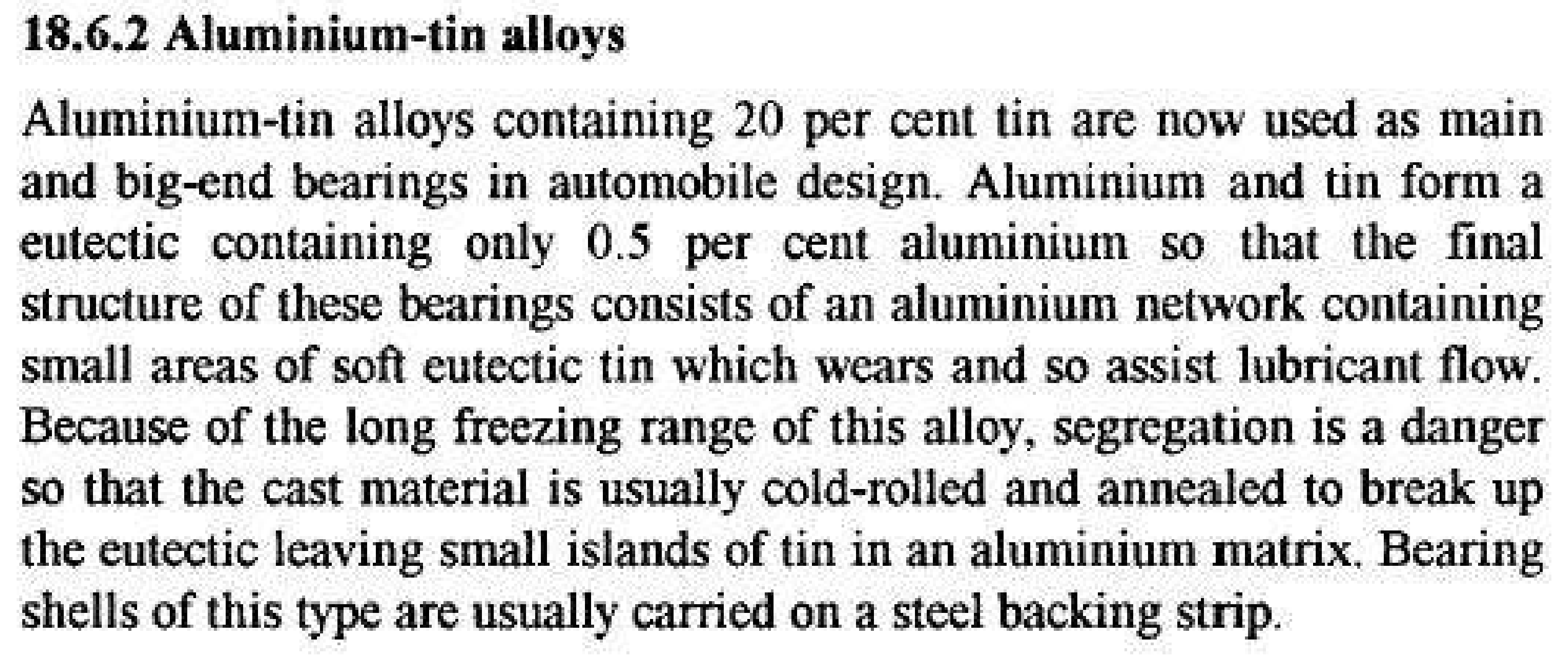


18.4.1 Magnesium alloys

Apart from lithium, magnesium has the lowest relative density, at 1.7, of the metals used in general engineering. Although pure magnesium is a relatively weak metal (tensile strength approximately 180 MPa in the annealed state), alloys containing suitable amounts of aluminium, zinc and thorium can be considerably strengthened by precipitation-hardening treatments. Consequently, in view of these properties, magnesium-base alloys are used where weight is a limiting factor. Castings and forgings in the aircraft industry account for much of the magnesium alloys produced, e.g. landing-wheels, petrol-tanks, oil-tanks, crank-cases, and air-screws, as well as other engine parts in both piston and jet engines. The automobile industry of course makes use of magnesium-base alloys. The one-time popular VW ‘Beetle’ was a pioneer in this respect.

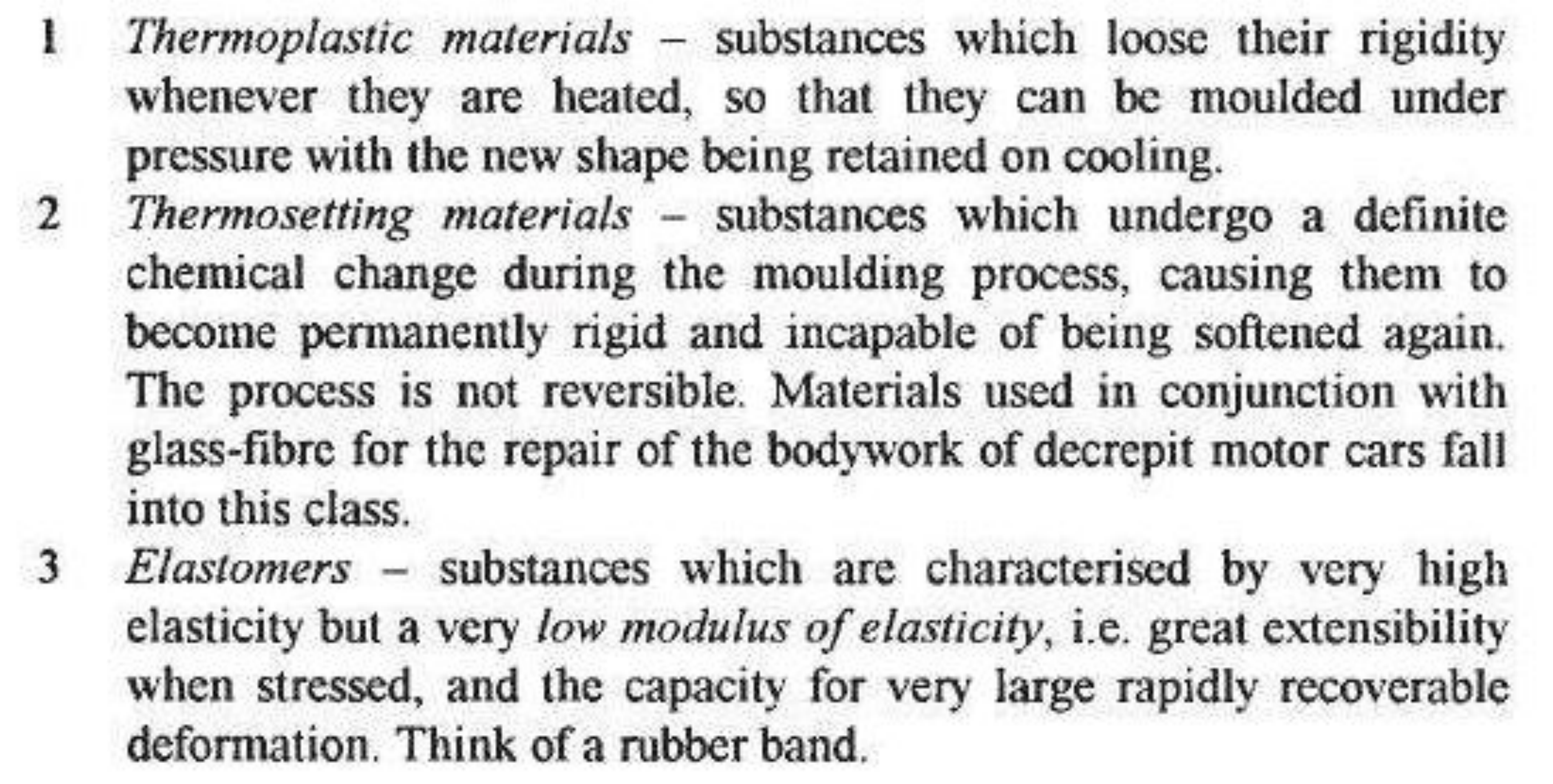


The most important properties of a bearing metal are that it should be hard and wear-resistant, and have a low coefficient of friction. At the same time, however, it must be tough, shock-resistant, and sufficiently ductile to allow for 'running in' processes made necessary by slight misalignments. Such a contrasting set of properties is almost impossible to obtain in single metallic phase. Thus, whilst pure metals and solid solutions are soft, tough and ductile, they invariably have a high coefficient of friction, and consequently a poor resistance to wear. Conversely, intermetallic compounds are hard and wear-resistant, but are also brittle, so that they have a negligible resistance to mechanical shock. For these reasons, bearing metals are generally compounded so as to give a suitable blend of phases, and generally contain small particles of a hard compound embedded in the tough, ductile background of a solid solution. During service, the latter tend to wear away slightly, thus providing channels through which lubricants can flow, whilst the particles of intermetallic compound are left standing 'proud', so that the load is carried with a minimum of frictional loss.



18.6.2 Aluminium-tin alloys

Aluminium-tin alloys containing 20 per cent tin are now used as main and big-end bearings in automobile design. Aluminium and tin form a eutectic containing only 0.5 per cent aluminium so that the final structure of these bearings consists of an aluminium network containing small areas of soft eutectic tin which wears and so assist lubricant flow. Because of the long freezing range of this alloy, segregation is a danger so that the cast material is usually cold-rolled and annealed to break up the eutectic leaving small islands of tin in an aluminium matrix. Bearing shells of this type are usually carried on a steel backing strip.



1. *Thermoplastic materials* – substances which loose their rigidity whenever they are heated, so that they can be moulded under pressure with the new shape being retained on cooling.
2. *Thermosetting materials* – substances which undergo a definite chemical change during the moulding process, causing them to become permanently rigid and incapable of being softened again. The process is not reversible. Materials used in conjunction with glass-fibre for the repair of the bodywork of decrepit motor cars fall into this class.
3. *Elastomers* – substances which are characterised by very high elasticity but a very *low modulus of elasticity*, i.e. great extensibility when stressed, and the capacity for very large rapidly recoverable deformation. Think of a rubber band.

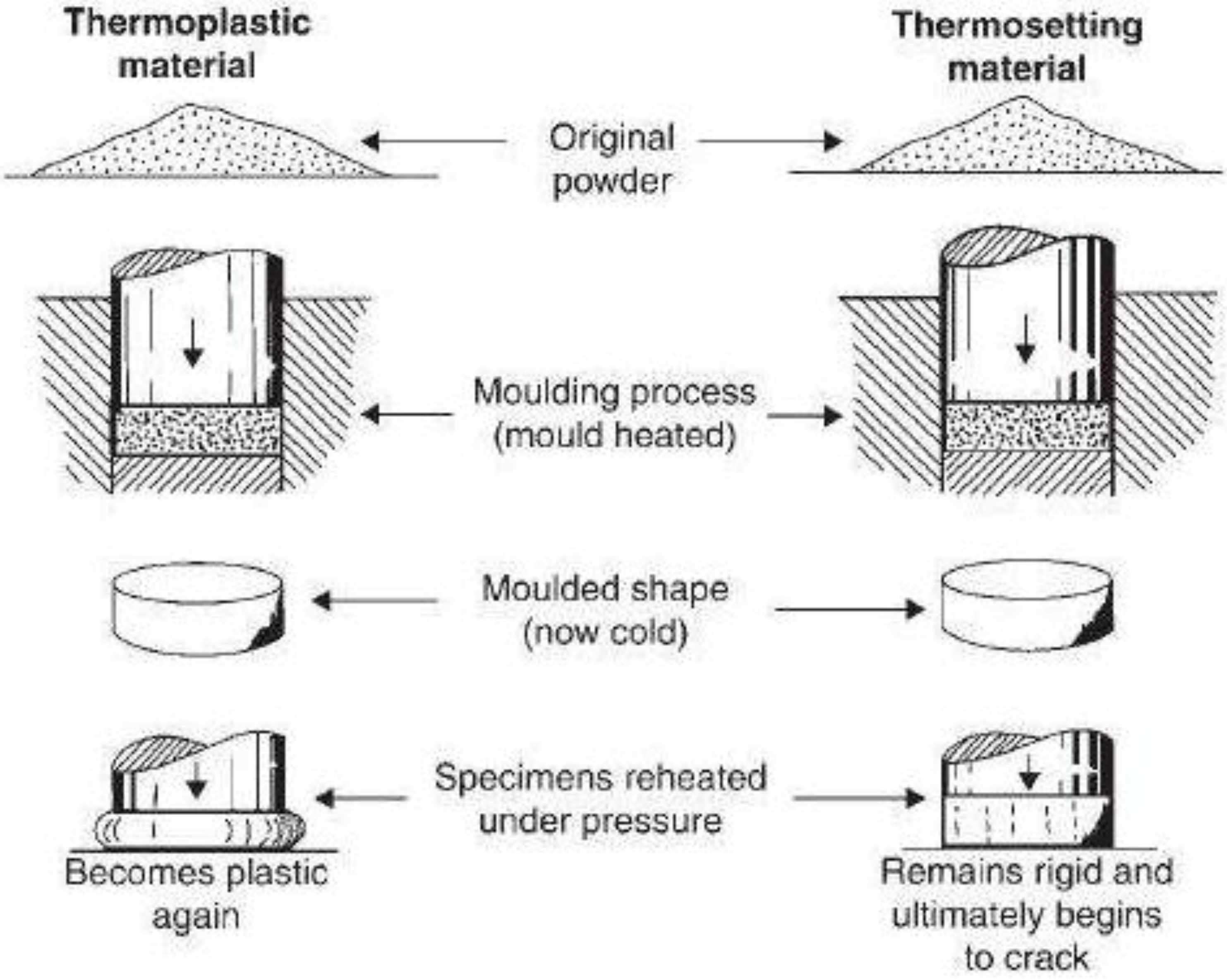
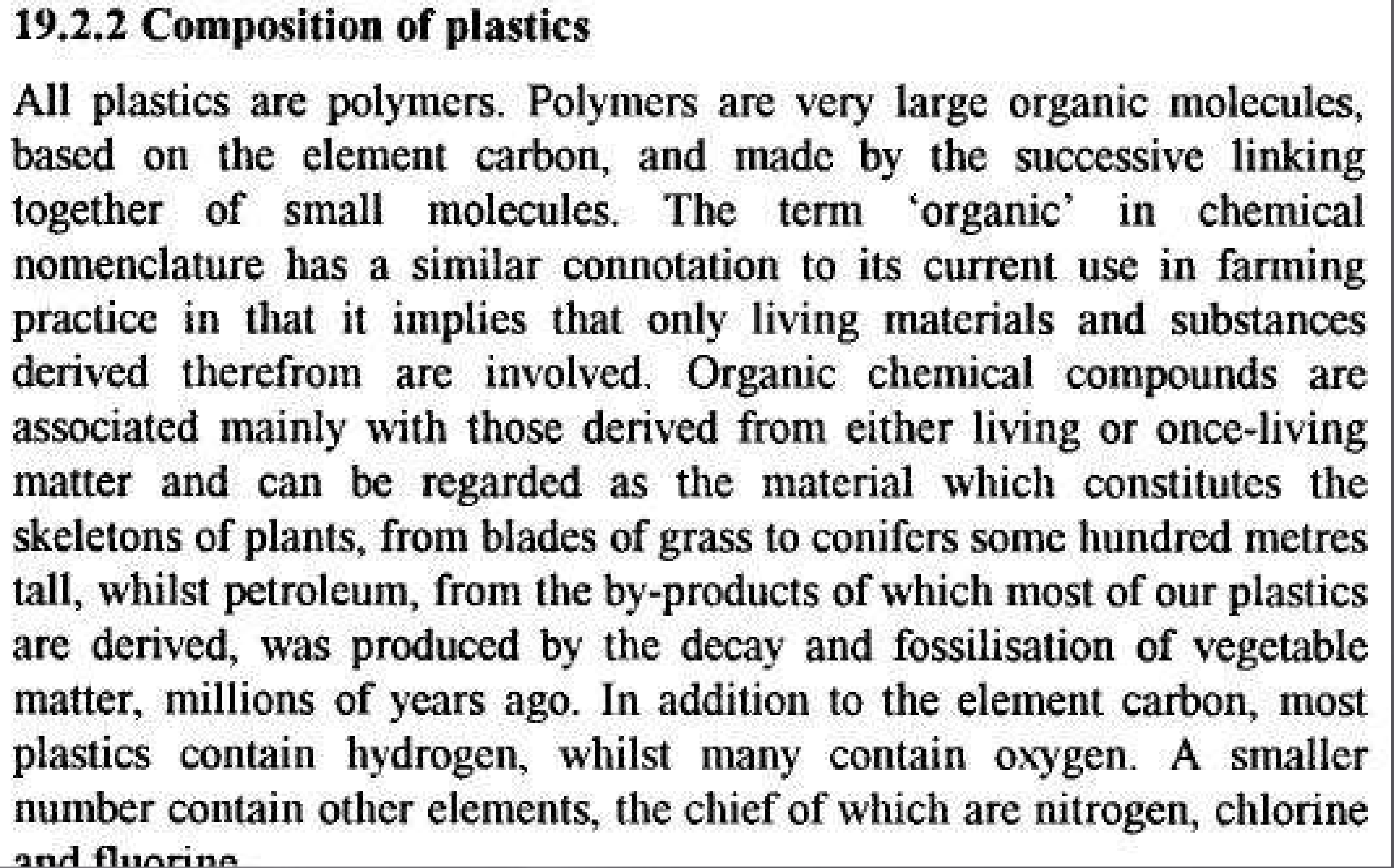
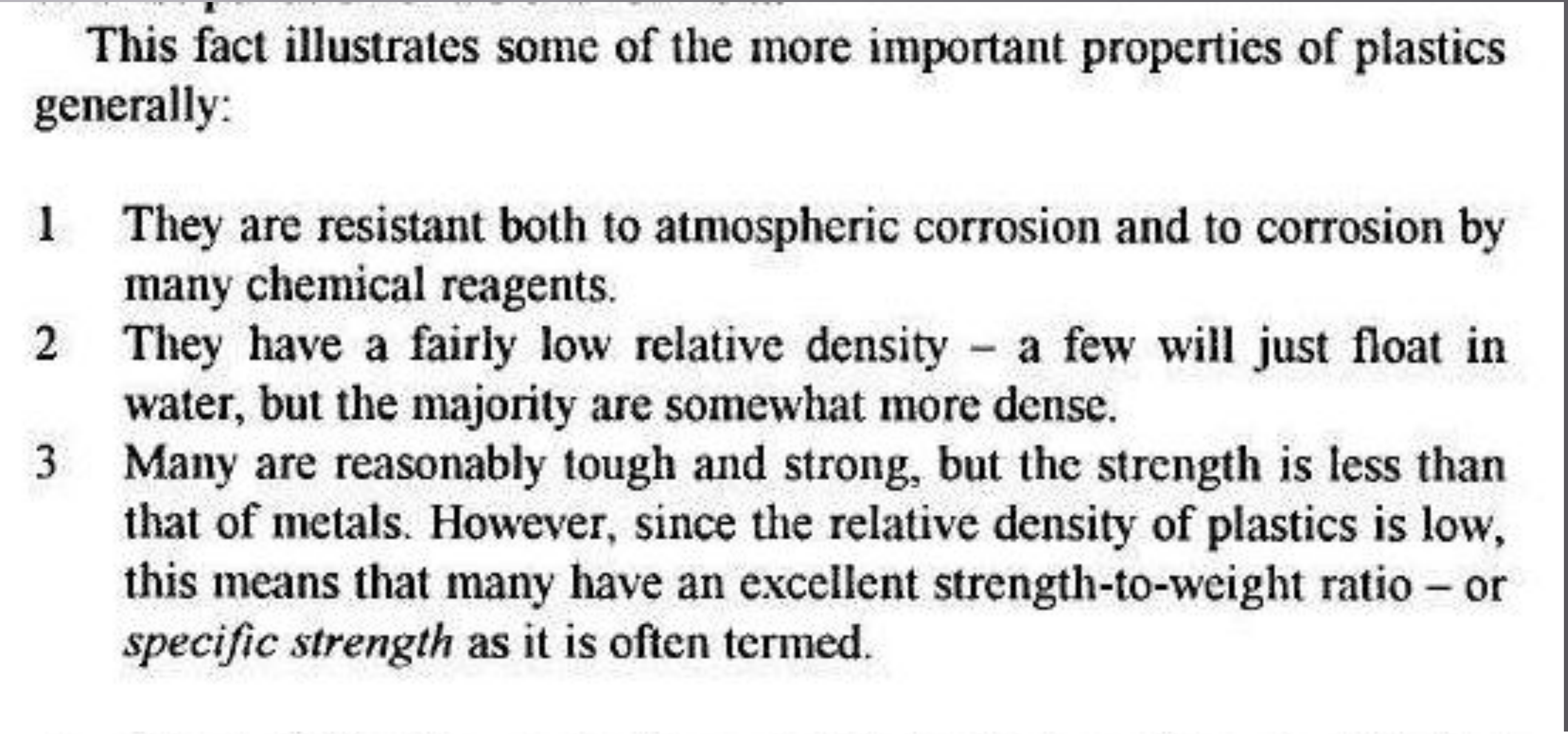


Figure 19.1 *The behaviour of thermoplastic and thermosetting materials when reheated under pressure.*



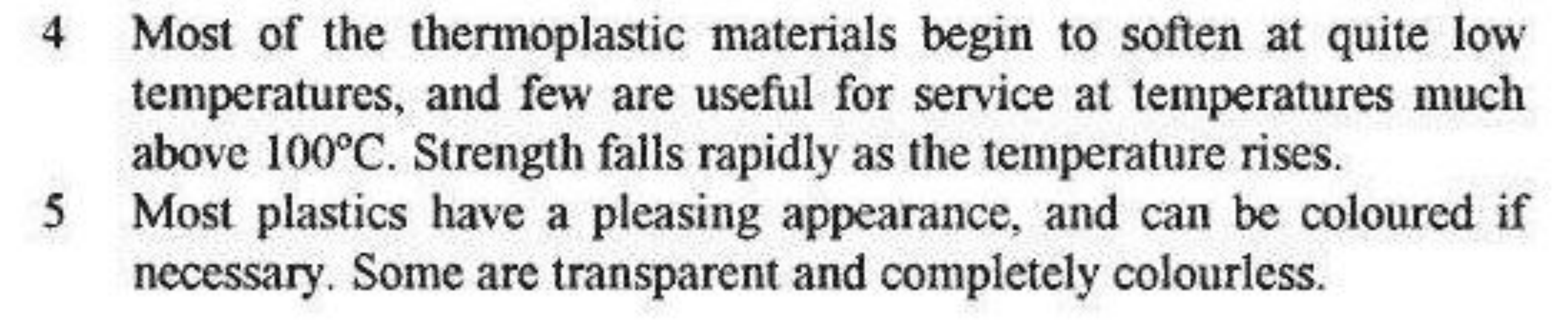
19.2.2 Composition of plastics

All plastics are polymers. Polymers are very large organic molecules, based on the element carbon, and made by the successive linking together of small molecules. The term ‘organic’ in chemical nomenclature has a similar connotation to its current use in farming practice in that it implies that only living materials and substances derived therefrom are involved. Organic chemical compounds are associated mainly with those derived from either living or once-living matter and can be regarded as the material which constitutes the skeletons of plants, from blades of grass to conifers some hundred metres tall, whilst petroleum, from the by-products of which most of our plastics are derived, was produced by the decay and fossilisation of vegetable matter, millions of years ago. In addition to the element carbon, most plastics contain hydrogen, whilst many contain oxygen. A smaller number contain other elements, the chief of which are nitrogen, chlorine and fluorine



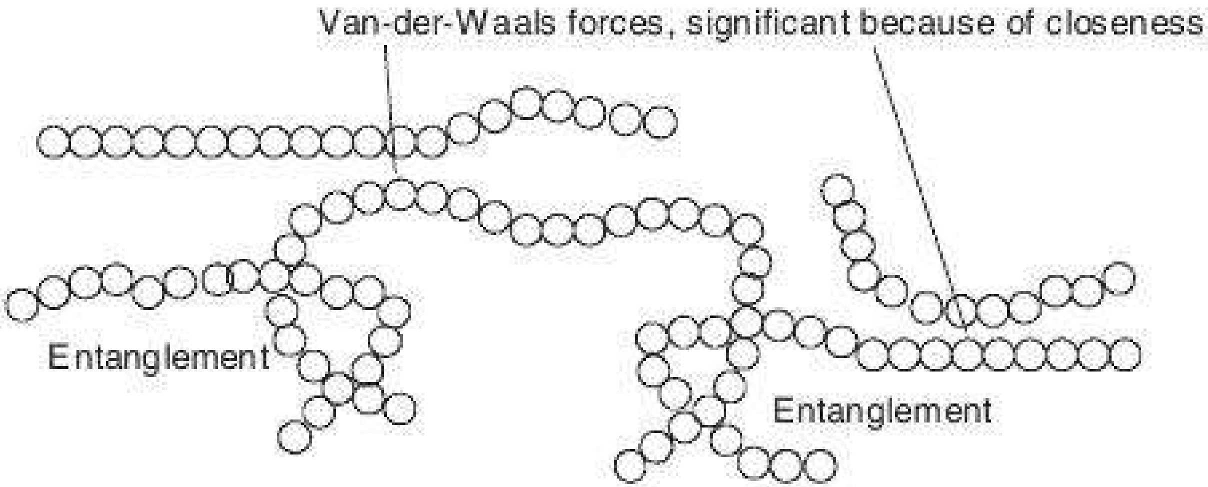
This fact illustrates some of the more important properties of plastics generally:

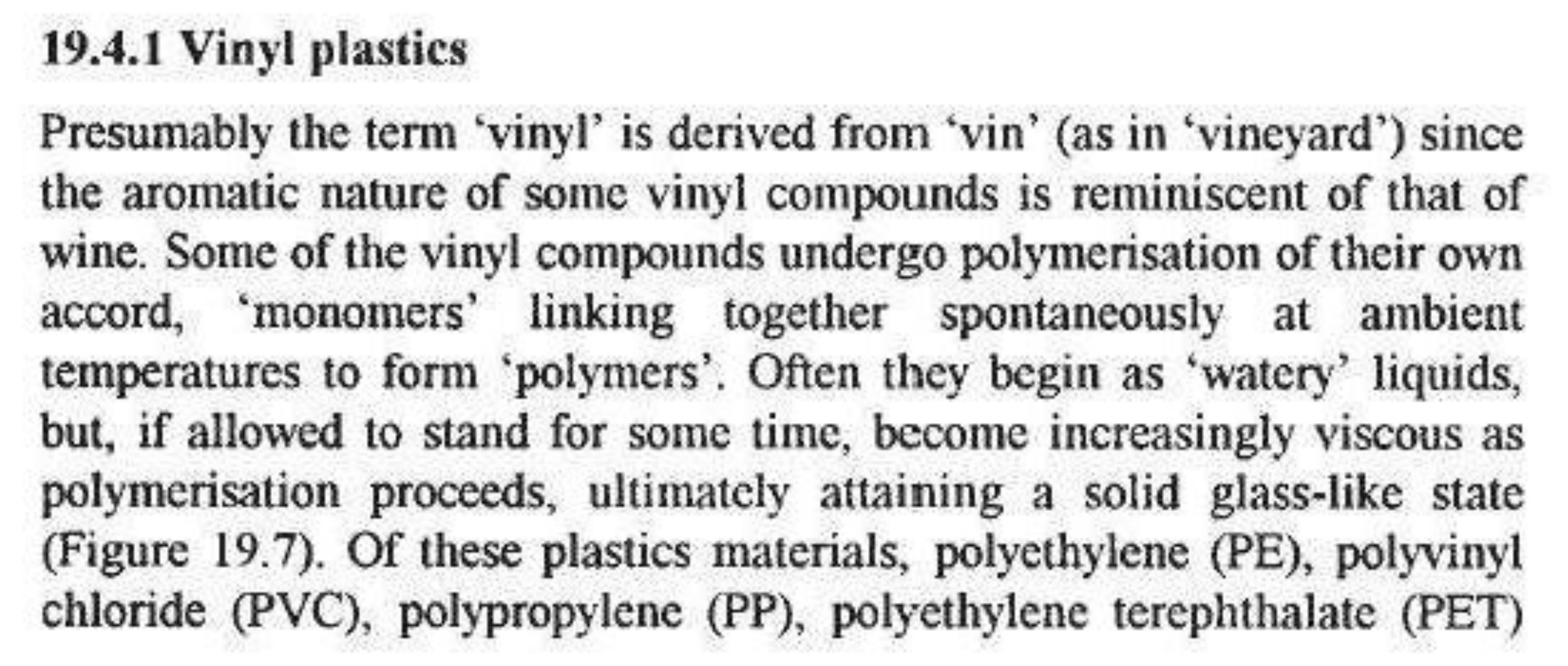
1 They are resistant both to atmospheric corrosion and to corrosion by many chemical reagents.
2 They have a fairly low relative density – a few will just float in water, but the majority are somewhat more dense.
3 Many are reasonably tough and strong, but the strength is less than that of metals. However, since the relative density of plastics is low, this means that many have an excellent strength-to-weight ratio – or *specific strength* as it is often termed.



4 Most of the thermoplastic materials begin to soften at quite low temperatures, and few are useful for service at temperatures much above 100°C. Strength falls rapidly as the temperature rises.
5 Most plastics have a pleasing appearance, and can be coloured if necessary. Some are transparent and completely colourless.

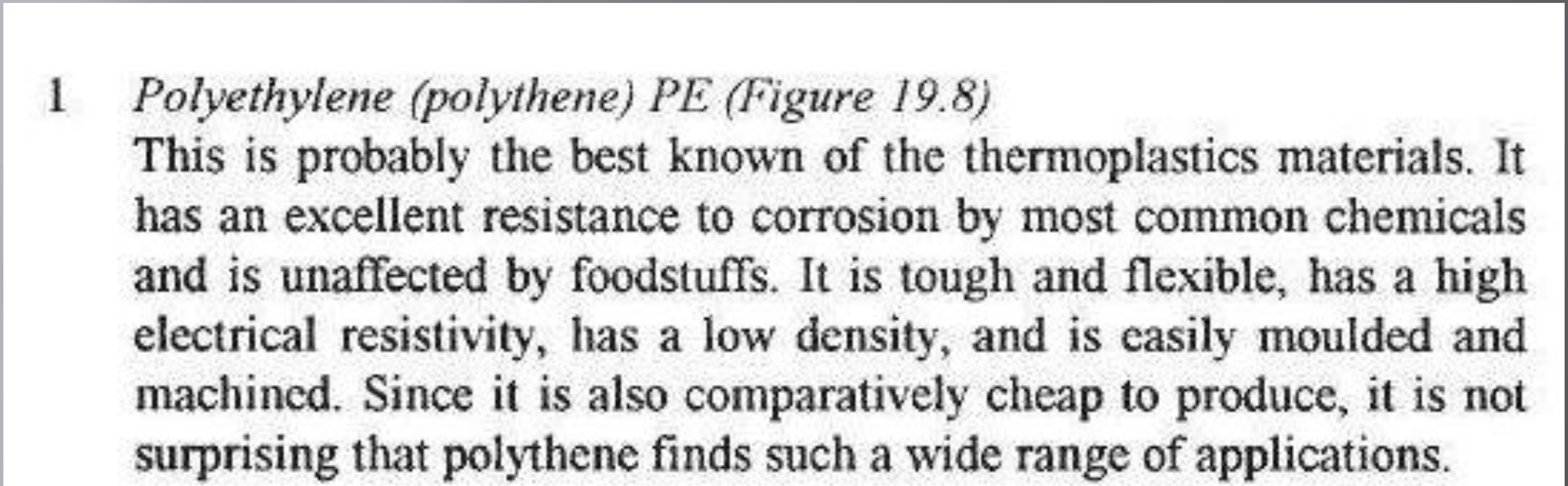
In thermoplastics materials, the carbon atoms are attached to each other by covalent bonds in the form of a long chain – this in polythene is a chain of about 1200 carbon atoms in length. Strong binding forces operate between the molecules in the chains with just van der Waals forces between chains. These van der Waals forces will be stronger the closer the molecules are together. Furthermore, it is easy to imagine that a considerable amount of entanglement will exist among these long chain-like molecules (Figure 19.2). When such a solid is heated, vibration within the molecules becomes greater so that the distances between molecules becomes greater and so the forces of attraction between them will decrease (in a similar way, the force acting between two magnets becomes smaller the further they are moved apart). Then such a material will be weaker and less rigid, so that it can be moulded more easily – hence the term thermoplastic for such materials.





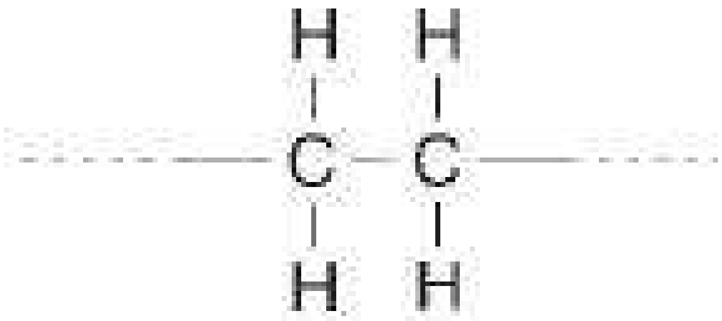
19.4.1 Vinyl plastics

Presumably the term ‘vinyl’ is derived from ‘vin’ (as in ‘vineyard’) since the aromatic nature of some vinyl compounds is reminiscent of that of wine. Some of the vinyl compounds undergo polymerisation of their own accord, ‘monomers’ linking together spontaneously at ambient temperatures to form ‘polymers’. Often they begin as ‘watery’ liquids, but, if allowed to stand for some time, become increasingly viscous as polymerisation proceeds, ultimately attaining a solid glass-like state (Figure 19.7). Of these plastics materials, polyethylene (PE), polyvinyl chloride (PVC), polypropylene (PP), polyethylene terephthalate (PET)



1 *Polyethylene (polythene) PE (Figure 19.8)*

This is probably the best known of the thermoplastics materials. It has an excellent resistance to corrosion by most common chemicals and is unaffected by foodstuffs. It is tough and flexible, has a high electrical resistivity, has a low density, and is easily moulded and machined. Since it is also comparatively cheap to produce, it is not surprising that polythene finds such a wide range of applications.

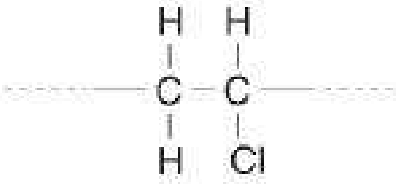


$$\cdots - \mathrm{CH_2} - \mathrm{CH_2} - \cdots$$

Figure 19.8 *Polyethylene.*

2 *Polyvinyl chloride (PVC) (Figure 19.10)*

The gas vinyl chloride was discovered more than a century ago. It was found that, on heating, it changed to a hard, white solid, later identified as polyvinyl chloride. Having rather a high softening temperature, PVC was difficult to mould, and it was not until the late 1920s that it was discovered that it could be plasticised. By adjusting the proportion of liquid plasticiser used, a thermoplastic material can be produced which varies in properties from a hard rigid substance to a soft rubbery one. Consequently, during the Second World War, and since then, PVC has been used in many instances to replace rubber. Protective gloves, raincoats and garden hose are examples of such use. PVC can be shaped by injection moulding, extrusion, and the normal thermoplastic processes. It can



$$-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{Cl}{C}}-$$

Figure 19.10 *Polyvinyl chloride.*

Table 19.1 *Mechanical properties (average) of PVC related to the degree of plasticisation*

Degree of plasticisation	*Tensile strength MPa*	*Elongation %*
None	55	20
Low	35	200
High	17	400

3 *Polyvinyl acetate (PVA) (Figure 19.11)*

This polymer softens at too low a temperature for it to be much use as a mouldable plastic, but it is useful as an adhesive, since it will stick effectively to almost any surface. It is supplied as an emulsion with water; when used in the manner of glue, the water dries off, leaving a strong adhesive polyvinyl acetate film for bonding the parts together. It is possibly best known as an emulsion with water, as the basis for 'vinyl emulsion paints'. The introduction of these was certainly a boon to those of us who, in our earlier days, battled with 'glue-size' based 'distemper' for our home decoration.

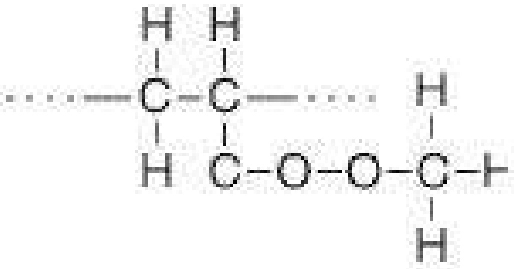


Figure 19.11 *Polyvinyl acetate.*

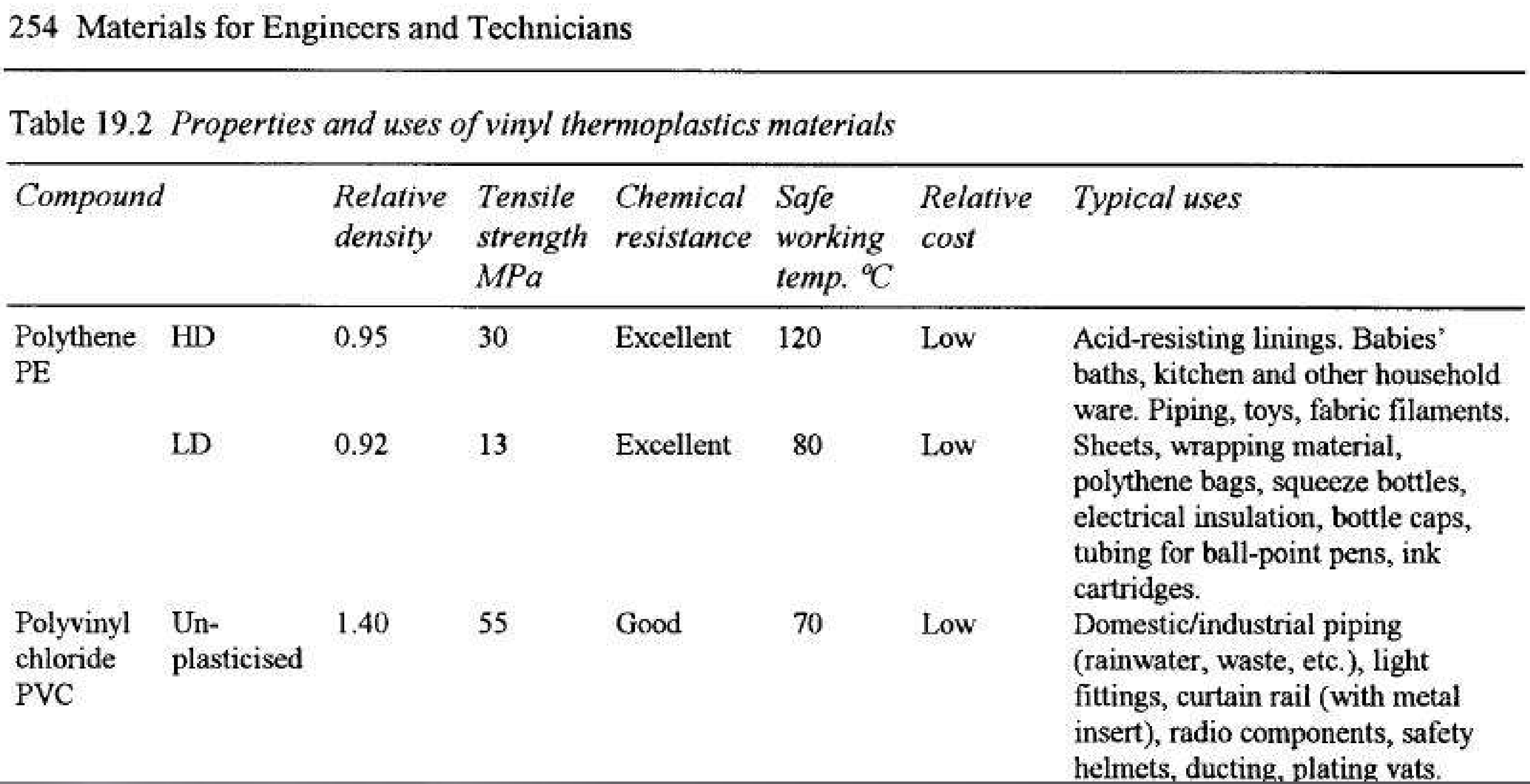
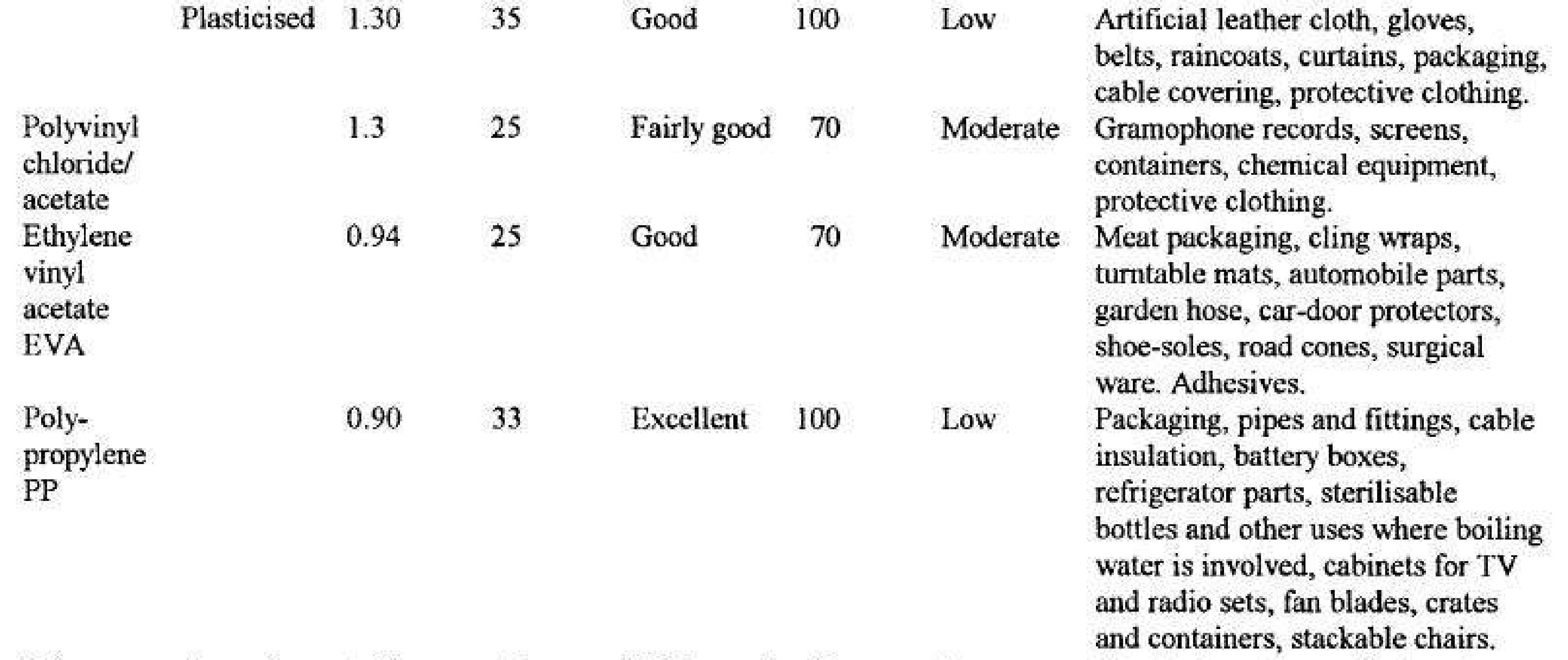
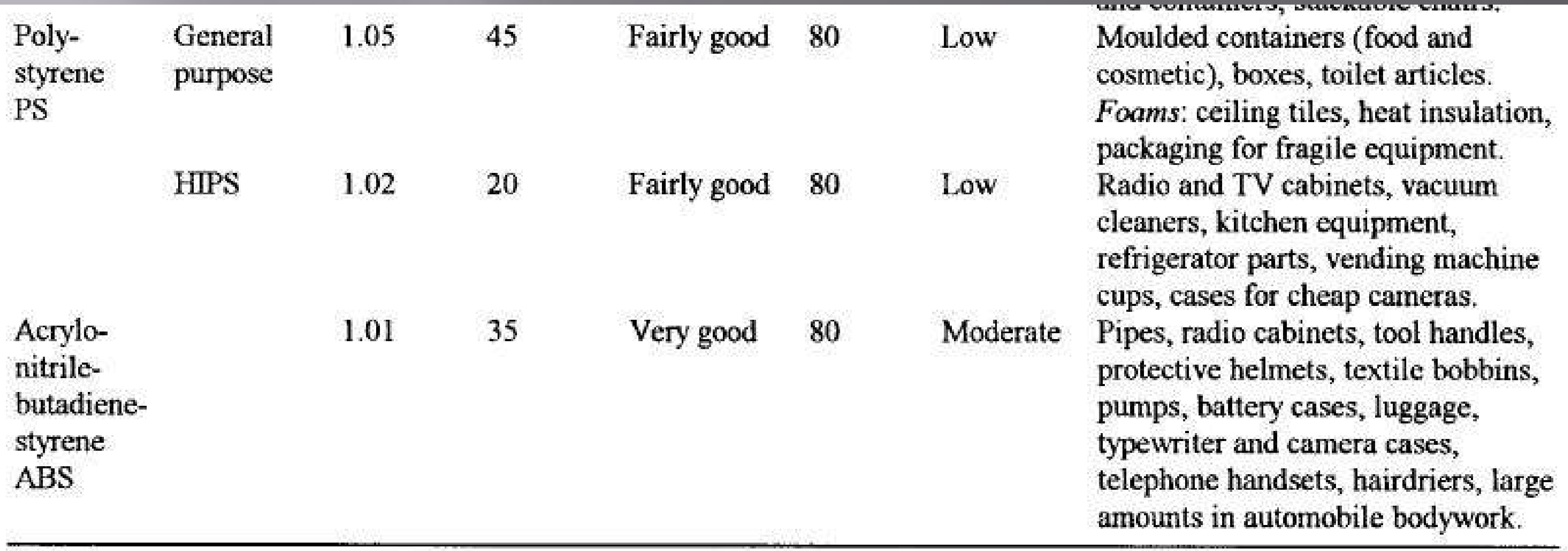


Table 19.2 *Properties and uses of vinyl thermoplastics materials*

Compound		*Relative density*	*Tensile strength MPa*	*Chemical resistance*	*Safe working temp. °C*	*Relative cost*	*Typical uses*
Polythene PE	HD	0.95	30	Excellent	120	Low	Acid-resisting linings. Babies' baths, kitchen and other household ware. Piping, toys, fabric filaments.
	LD	0.92	13	Excellent	80	Low	Sheets, wrapping material, polythene bags, squeeze bottles, electrical insulation, bottle caps, tubing for ball-point pens, ink cartridges.
Polyvinyl chloride PVC	Un-plasticised	1.40	55	Good	70	Low	Domestic/industrial piping (rainwater, waste, etc.), light fittings, curtain rail (with metal insert), radio components, safety helmets, ducting, plating vats.



	Plasticised	1.30	35	Good	100	Low	Artificial leather cloth, gloves, belts, raincoats, curtains, packaging, cable covering, protective clothing.
Polyvinyl chloride/ acetate		1.3	25	Fairly good	70	Moderate	Gramophone records, screens, containers, chemical equipment, protective clothing.
Ethylene vinyl acetate EVA		0.94	25	Good	70	Moderate	Meat packaging, cling wraps, turntable mats, automobile parts, garden hose, car-door protectors, shoe-soles, road cones, surgical ware. Adhesives.
Poly-propylene PP		0.90	33	Excellent	100	Low	Packaging, pipes and fittings, cable insulation, battery boxes, refrigerator parts, sterilisable bottles and other uses where boiling water is involved, cabinets for TV and radio sets, fan blades, crates and containers, stackable chairs.



Poly-styrene PS	General purpose	1.05	45	Fairly good	80	Low	Moulded containers (food and cosmetic), boxes, toilet articles. *Foams*: ceiling tiles, heat insulation, packaging for fragile equipment.
	HIPS	1.02	20	Fairly good	80	Low	Radio and TV cabinets, vacuum cleaners, kitchen equipment, refrigerator parts, vending machine cups, cases for cheap cameras.
Acrylo-nitrile-butadiene-styrene ABS		1.01	35	Very good	80	Moderate	Pipes, radio cabinets, tool handles, protective helmets, textile bobbins, pumps, battery cases, luggage, typewriter and camera cases, telephone handsets, hairdriers, large amounts in automobile bodywork.

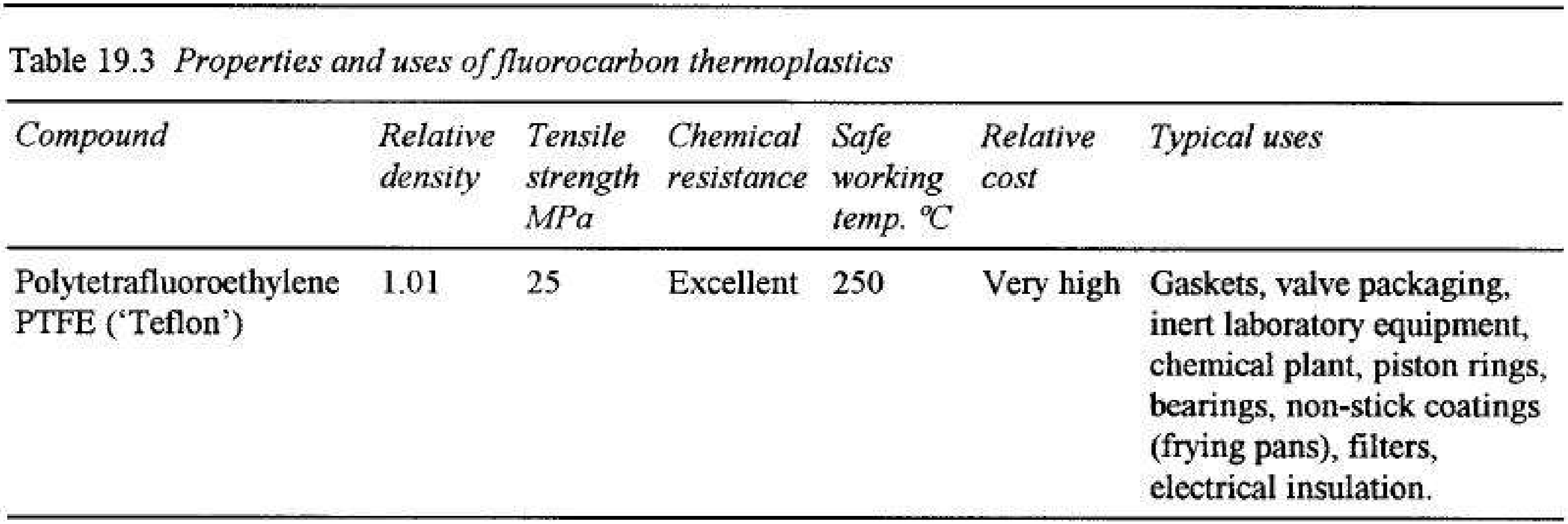


Table 19.3 *Properties and uses of fluorocarbon thermoplastics*

Compound	*Relative density*	*Tensile strength MPa*	*Chemical resistance*	*Safe working temp. °C*	*Relative cost*	*Typical uses*
Polytetrafluoroethylene PTFE ('Teflon')	1.01	25	Excellent	250	Very high	Gaskets, valve packaging, inert laboratory equipment, chemical plant, piston rings, bearings, non-stick coatings (frying pans), filters, electrical insulation.

Table 19.4 *Properties and uses of cellulosic thermoplastics*

Compound	*Relative density*	*Tensile strength MPa*	*Chemical resistance*	*Safe working temp. °C*	*Relative cost*	*Typical uses*
Cellulose acetate CA	1.3	35	Fair	70	Fairly high	Artificial leather, brush backs, combs, spectacle frames, photographic film base, mixing bowls, lamp-shades, toys, laminated luggage, knobs, wire- and cable-covering.
Cellulose acetate-butyrate CAB	1.18	35	Fair	70	Fairly high	Illuminated road signs, extruded pipe, containers.
Cellulose acetate-propionate CAP	1.21	55	Fair	70	Fairly high	Steering wheels, packaging, toothbrushes, door knobs.

Table 19.5 *Properties and uses of polyamide thermoplastics*

Compound	*Relative density*	*Tensile strength MPa*	*Chemical resistance*	*Safe working temp. °C*	*Relative cost*	*Typical uses*
Nylon 66 (PA66)	1.12	Moulded 60 Filaments 350	Good	140	High	Raincoats, yarn (clothing), containers, cable-covering, gears, bearings, cams, spectacle frames, combs, bristles for brushes, climbing ropes, fishing lines, shock absorbers.

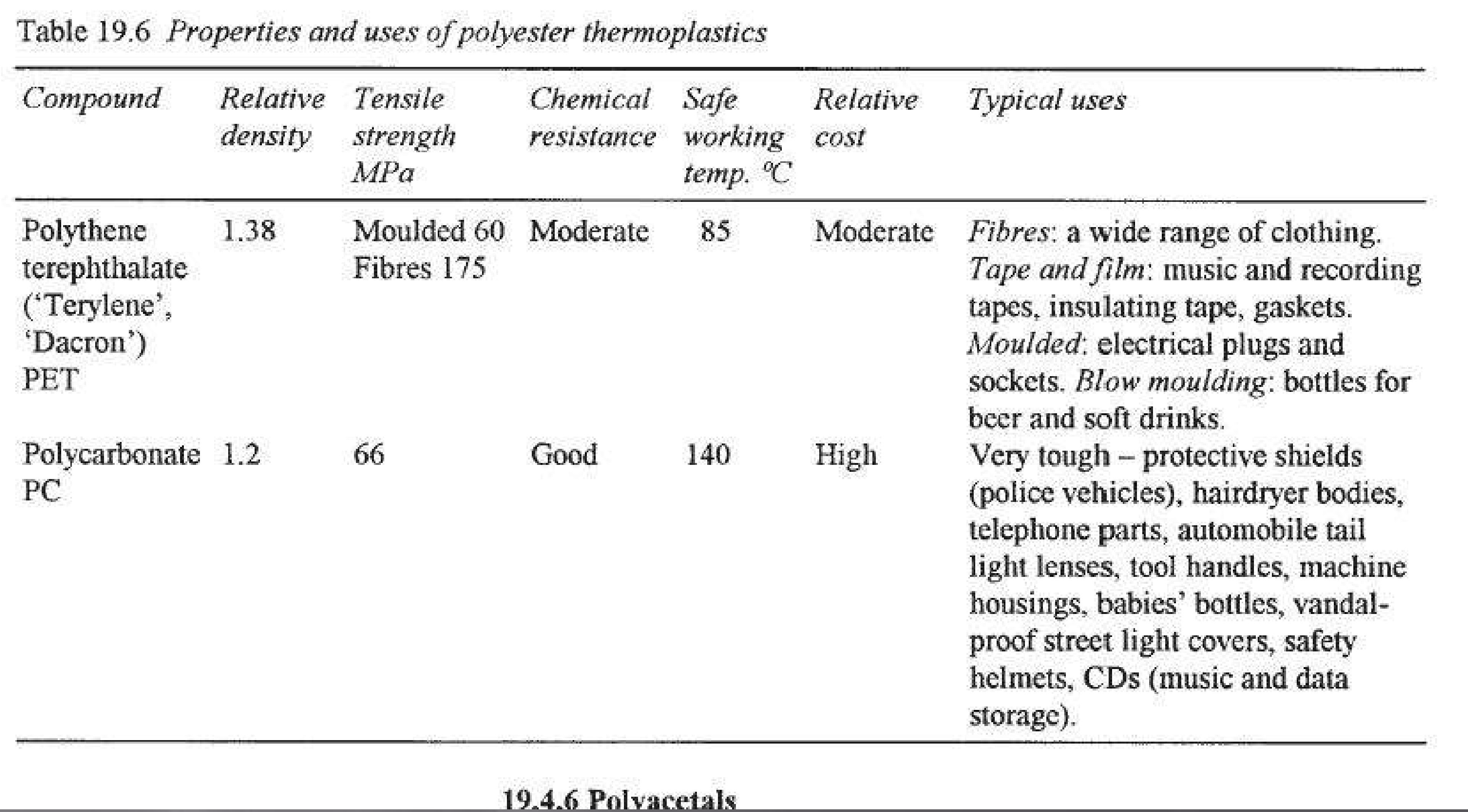


Table 19.6 *Properties and uses of polyester thermoplastics*

Compound	*Relative density*	*Tensile strength MPa*	*Chemical resistance*	*Safe working temp. °C*	*Relative cost*	*Typical uses*
Polythene terephthalate ('Terylene', 'Dacron') PET	1.38	Moulded 60 Fibres 175	Moderate	85	Moderate	*Fibres*: a wide range of clothing. *Tape and film*: music and recording tapes, insulating tape, gaskets. *Moulded*: electrical plugs and sockets. *Blow moulding*: bottles for beer and soft drinks.
Polycarbonate PC	1.2	66	Good	140	High	Very tough – protective shields (police vehicles), hairdryer bodies, telephone parts, automobile tail light lenses, tool handles, machine housings, babies' bottles, vandal-proof street light covers, safety helmets, CDs (music and data storage).

19.4.6 Polyacetals

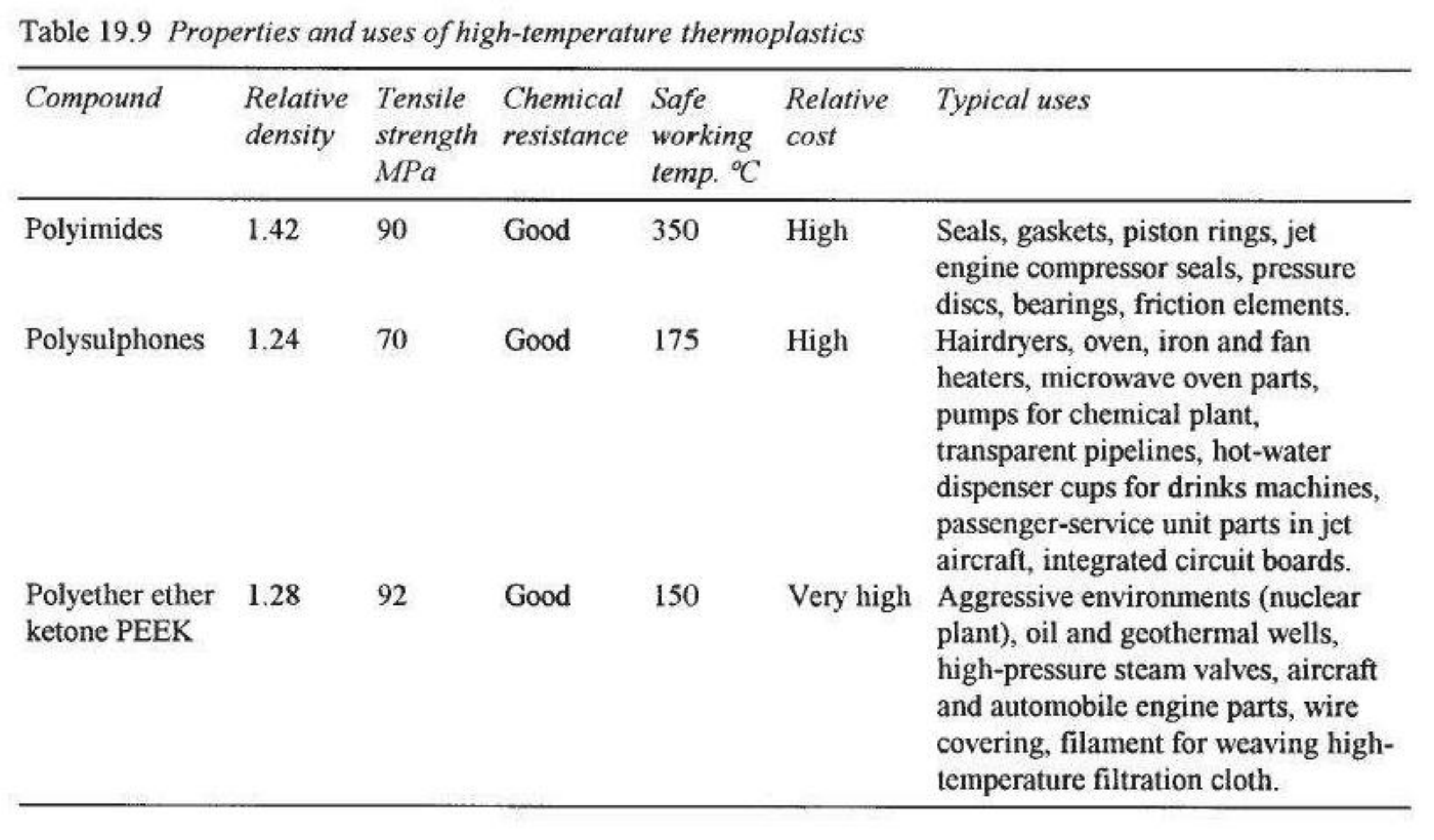


Table 19.9 *Properties and uses of high-temperature thermoplastics*

Compound	*Relative density*	*Tensile strength MPa*	*Chemical resistance*	*Safe working temp. °C*	*Relative cost*	*Typical uses*
Polyimides	1.42	90	Good	350	High	Seals, gaskets, piston rings, jet engine compressor seals, pressure discs, bearings, friction elements.
Polysulphones	1.24	70	Good	175	High	Hairdryers, oven, iron and fan heaters, microwave oven parts, pumps for chemical plant, transparent pipelines, hot-water dispenser cups for drinks machines, passenger-service unit parts in jet aircraft, integrated circuit boards.
Polyether ether ketone PEEK	1.28	92	Good	150	Very high	Aggressive environments (nuclear plant), oil and geothermal wells, high-pressure steam valves, aircraft and automobile engine parts, wire covering, filament for weaving high-temperature filtration cloth.

Table 19.10 *Properties and uses of phenolics thermosetting materials*

Compound	*Relative density*	*Tensile strength MPa*	*Chemical resistance*	*Safe working temp. °C*	*Relative cost*	*Uses*
Phenol formaldehyde ('bakelite, 'phenolic') PF	1.45	50	Very good	120	Low	Electrical equipment, radio-cabinets, vacuum-cleaners, ashtrays, buttons, cheap cameras, automobile ignition systems, ornaments, handles, instrument-panels, advertising displays, novelties and games, dies, gears, bearings (laminates), washing-machine agitators.
Urea formaldehyde ('urea') UF	1.48	45	Fair	80	Moderate	Adhesives, plugs and switches, buckles, buttons, bottle-tops, cups, saucers, plates, radio-cabinets, knobs, clock-cases, kitchen equipment, electric light-fittings, surface coatings, bond for foundry sand.
Melamine formaldehyde ('melamine') MF	1.49	50	Good	130	Moderate	Electrical equipment, handles, knobs, cups, saucers, plates, refrigerator coatings, trays, washing-machine agitators, radio-cabinets, light-fixtures, lamp-pedestals, switches, buttons, building-panels, automotive ignition-blocks, manufacture of laminates.

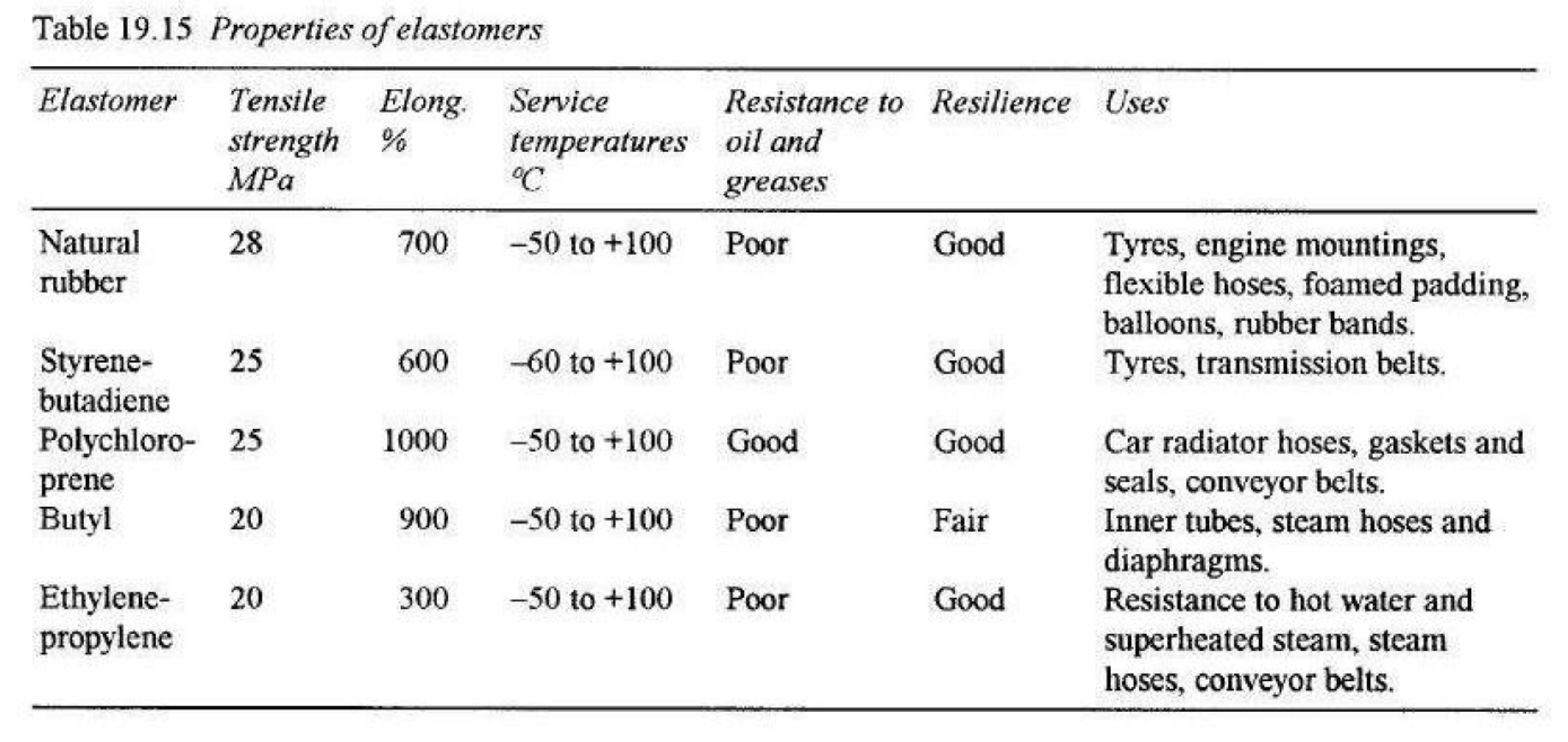
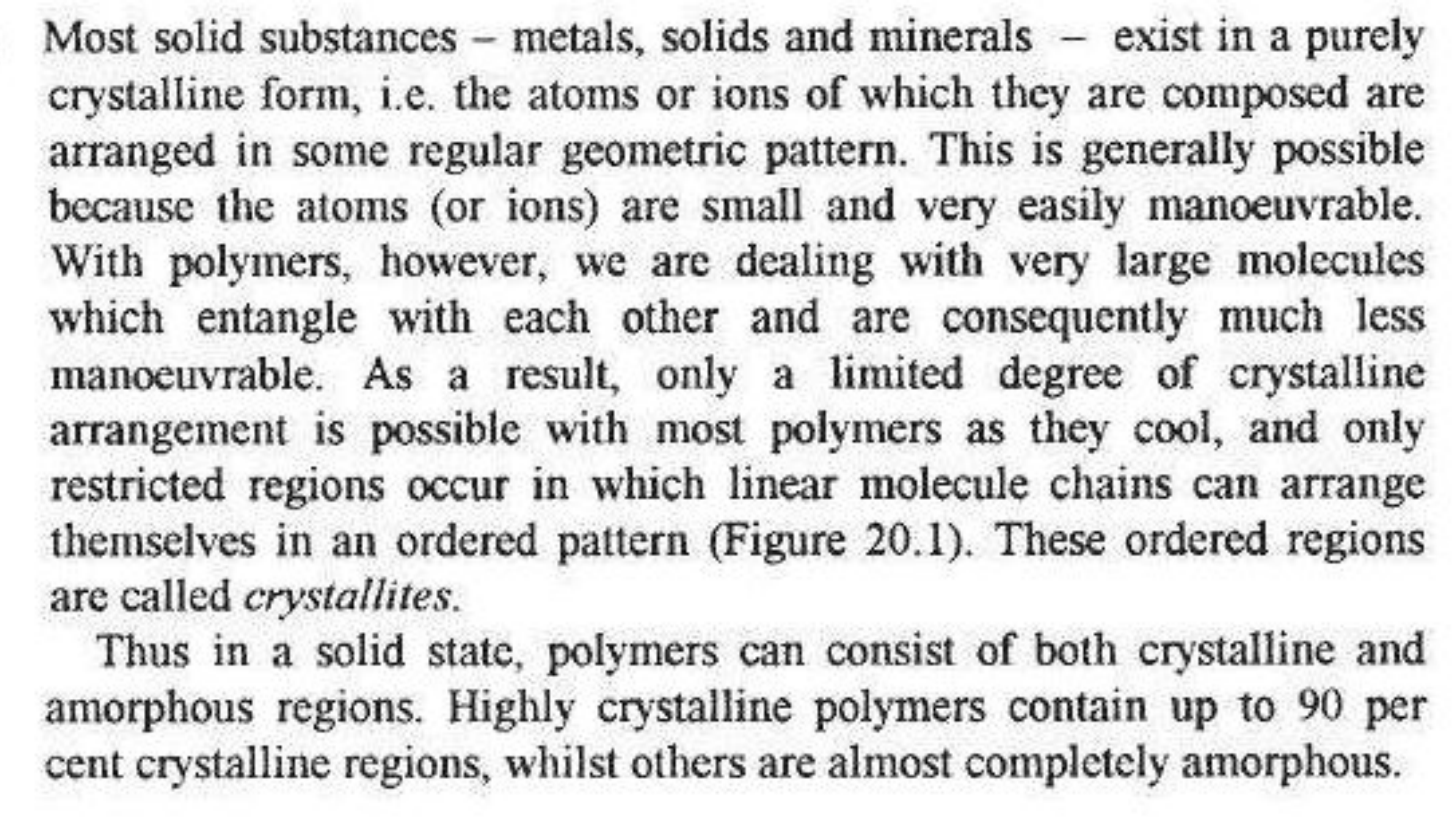


Table 19.15 *Properties of elastomers*

Elastomer	*Tensile strength MPa*	*Elong. %*	*Service temperatures °C*	*Resistance to oil and greases*	*Resilience*	*Uses*
Natural rubber	28	700	–50 to +100	Poor	Good	Tyres, engine mountings, flexible hoses, foamed padding, balloons, rubber bands.
Styrene-butadiene	25	600	–60 to +100	Poor	Good	Tyres, transmission belts.
Polychloroprene	25	1000	–50 to +100	Good	Good	Car radiator hoses, gaskets and seals, conveyor belts.
Butyl	20	900	–50 to +100	Poor	Fair	Inner tubes, steam hoses and diaphragms.
Ethylene-propylene	20	300	–50 to +100	Poor	Good	Resistance to hot water and superheated steam, steam hoses, conveyor belts.



Most solid substances – metals, solids and minerals – exist in a purely crystalline form, i.e. the atoms or ions of which they are composed are arranged in some regular geometric pattern. This is generally possible because the atoms (or ions) are small and very easily manoeuvrable. With polymers, however, we are dealing with very large molecules which entangle with each other and are consequently much less manoeuvrable. As a result, only a limited degree of crystalline arrangement is possible with most polymers as they cool, and only restricted regions occur in which linear molecule chains can arrange themselves in an ordered pattern (Figure 20.1). These ordered regions are called *crystallites*.

Thus in a solid state, polymers can consist of both crystalline and amorphous regions. Highly crystalline polymers contain up to 90 per cent crystalline regions, whilst others are almost completely amorphous.

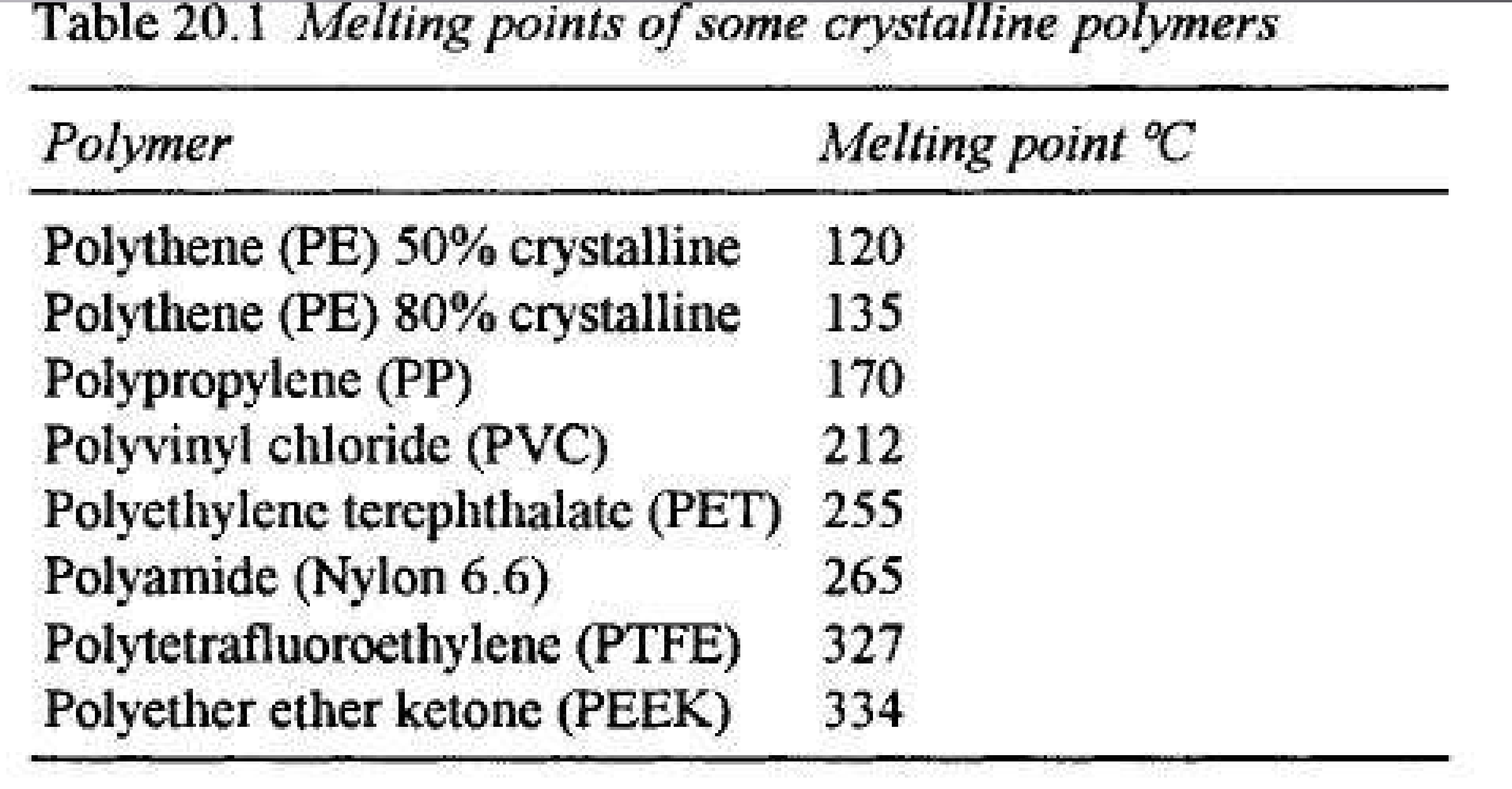


Table 20.1 *Melting points of some crystalline polymers*

Polymer	*Melting point °C*
Polythene (PE) 50% crystalline	120
Polythene (PE) 80% crystalline	135
Polypropylene (PP)	170
Polyvinyl chloride (PVC)	212
Polyethylene terephthalate (PET)	255
Polyamide (Nylon 6.6)	265
Polytetrafluoroethylene (PTFE)	327
Polyether ether ketone (PEEK)	334

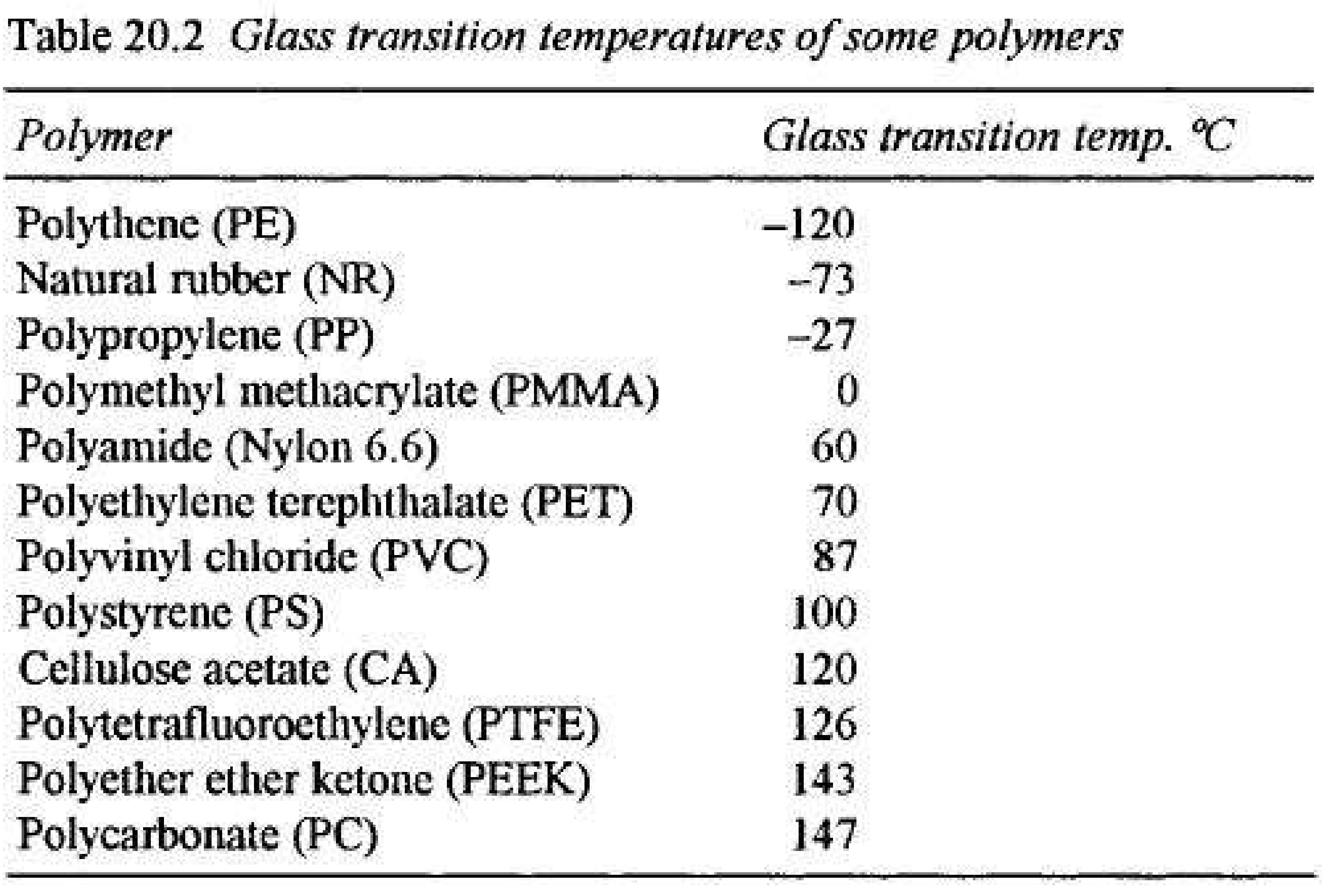


Table 20.2 *Glass transition temperatures of some polymers*

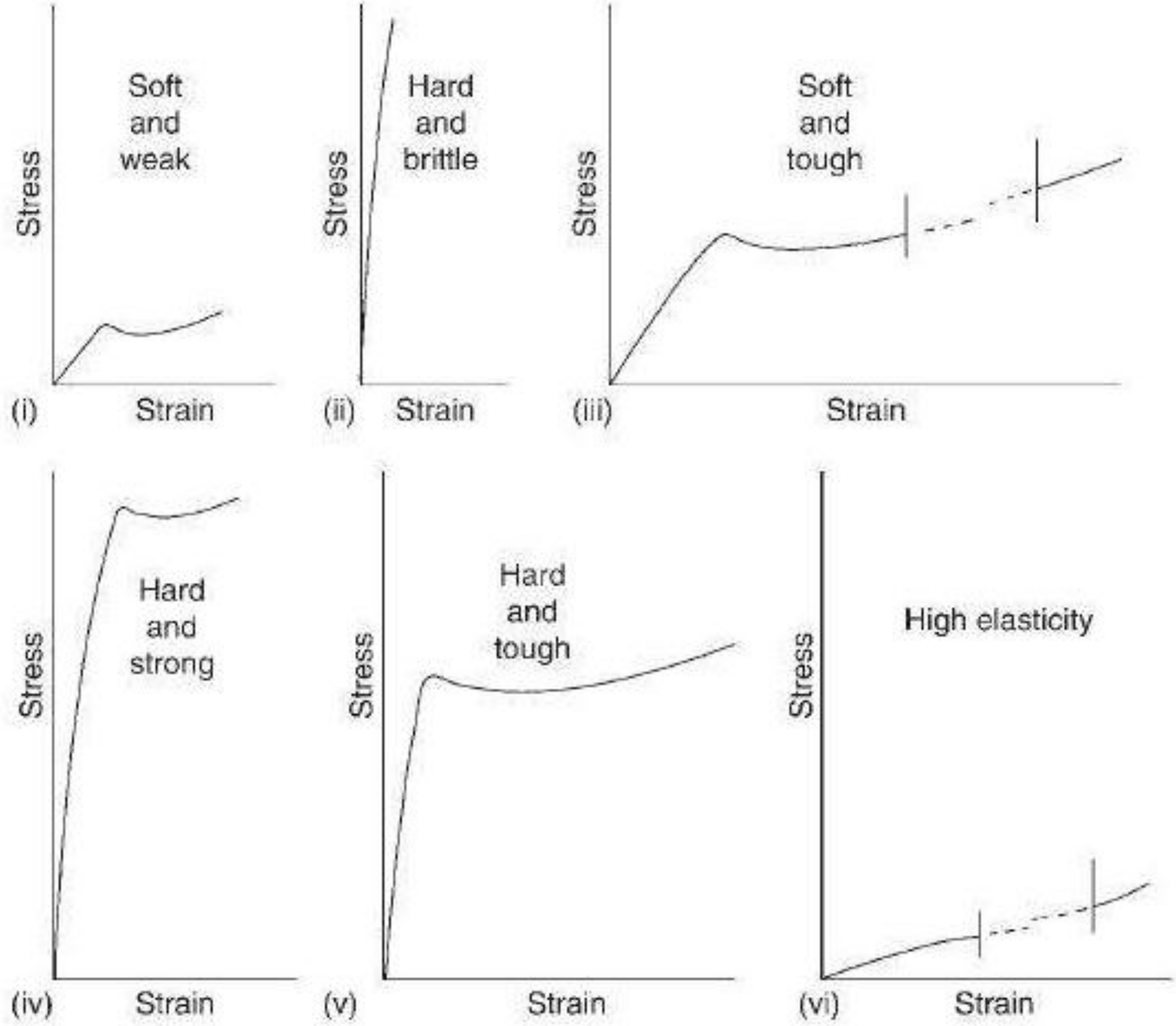
Polymer	*Glass transition temp. °C*
Polythene (PE)	–120
Natural rubber (NR)	–73
Polypropylene (PP)	–27
Polymethyl methacrylate (PMMA)	0
Polyamide (Nylon 6.6)	60
Polyethylene terephthalate (PET)	70
Polyvinyl chloride (PVC)	87
Polystyrene (PS)	100
Cellulose acetate (CA)	120
Polytetrafluoroethylene (PTFE)	126
Polyether ether ketone (PEEK)	143
Polycarbonate (PC)	147

Table 20.3 *Vicat temperatures for some polymers*

Polymer	*Vicat softening temp. °C*
Ethylene vinyl acetate (EVA)	51
Cellulose acetate (CA)	72
Polyvinyl chloride (PVC)	83
Low-density polythene (LDPE)	85
Polymethyl methacrylate (PMMA)	90
Polystyrene (HIPS)	94
Polystyrene (PS)	99
Acrylonitrile-butadiene-styrene (ABS)	104
High density polythene (HDPE)	125
Polypropylene (PP)	150
Polycarbonate (PC)	165
Polyacetal	185
Polyamide (Nylon 6.6)	185

The strength of plastics materials is generally much lower than that of most other constructional materials. Nevertheless, plastics are light materials with a relative density between 0.9 and 2.0 so that when considered in terms of strength/weight ratio they compare favourably with some metals and alloys. Figure 20.2 indicates the types of stress/strain relationship obtained for different groups of polymers.

The mechanical properties of most engineering materials and alloys vary very little within the range of ambient temperatures encountered in service. This is to be expected since no structural changes occur (other than thermal expansion) until the recystallisation temperature (see Section 6.3.2) is reached and this is usually well above 100°C. However, with many polymer materials – particularly thermoplastic – mechanical properties vary considerably with temperature in the ambient region. The gradual reduction in van der Waals forces with rise in temperature will affect mechanical properties; at both T_g and T_m mechanical properties change. Thus, a thermoplastic polymer may have a tensile strength of, say, 70 MPa at 0°C, falling to 40 MPa at 25°C and to no more than 10 MPa at 80°C. As tensile strength falls with rise in temperature, there is a corresponding increase in percentage elongation (Figure 20.3).


Soft and weak
Stress
Strain
(i)
Hard and brittle
Stress
Strain
(ii)
Soft and tough
Stress
Strain
(iii)
Hard and strong
Stress
Strain
(iv)
Hard and tough
Stress
Strain
(v)
High elasticity
Stress
Strain
(vi)

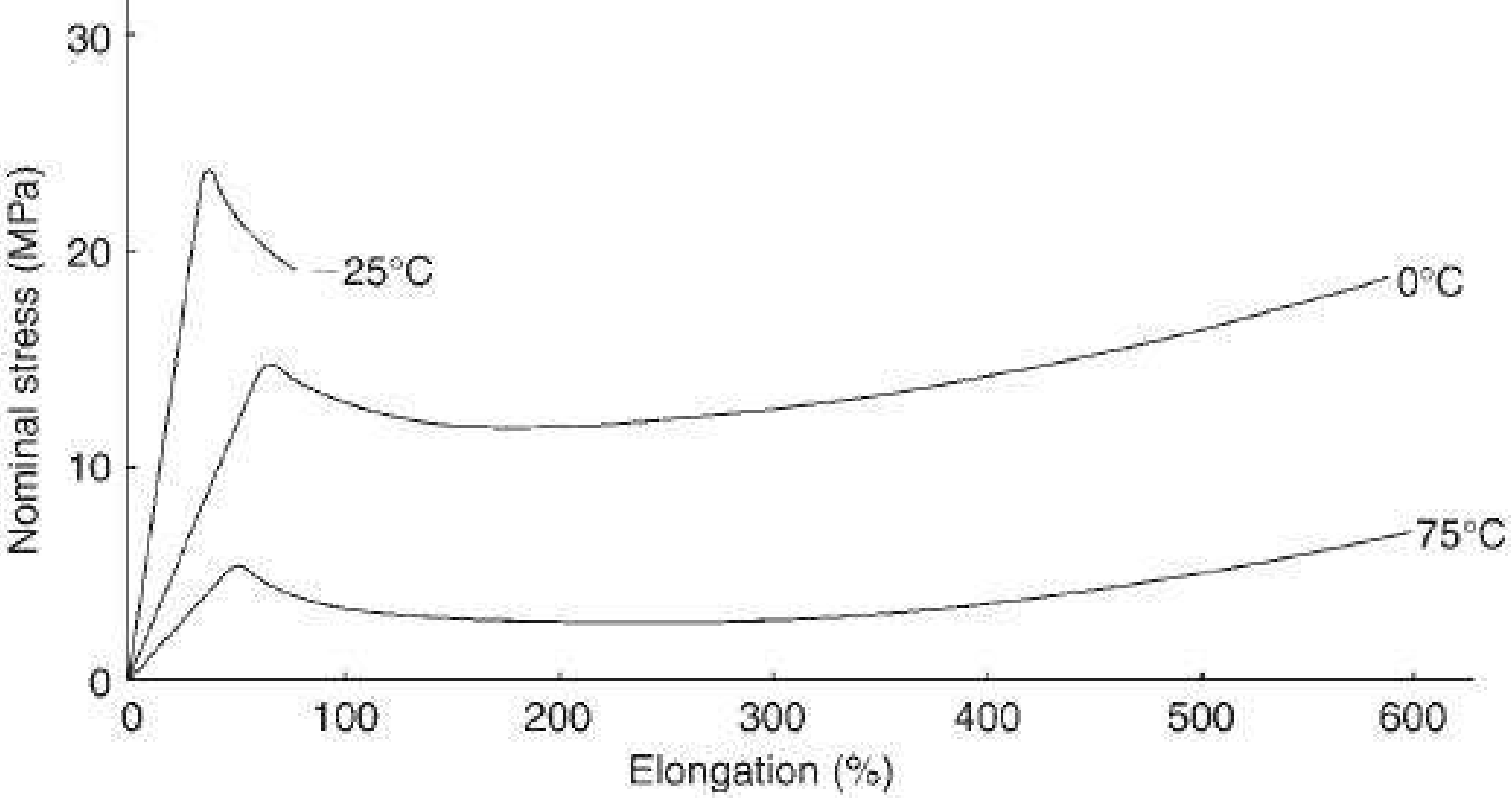


Figure 20.3 *Tensile stress-strain curves for low-density polythene at –25°C, 0°C and 75°C.*

Plastics materials are also very time-sensitive as far as mechanical testing is concerned. This is because the total deformation depends upon:

1 Bond bending of the carbon-carbon covalent bonds in the polymer chain – this is manifested as the ordinary elasticity and is an *instantaneous* deformation.
2 Uncoiling of the polymer chains – this gives rise to high elasticity and is *very time dependent*.
3 Slipping of polymer chains past each other – this produces *irreversible* plastic flow and is also *very time dependent*.

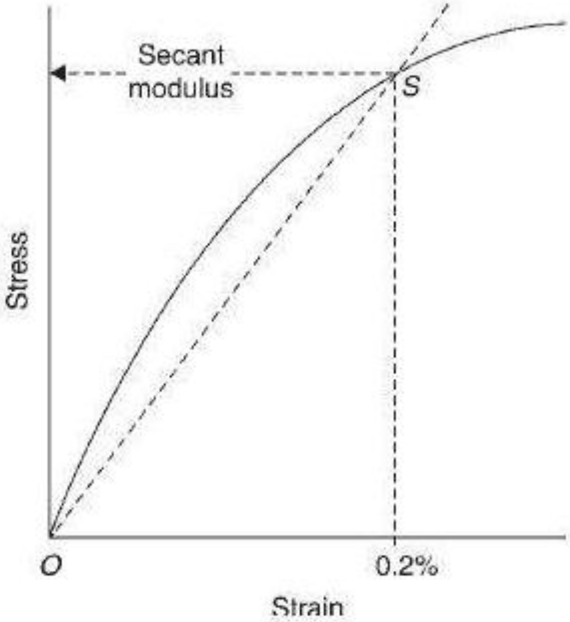
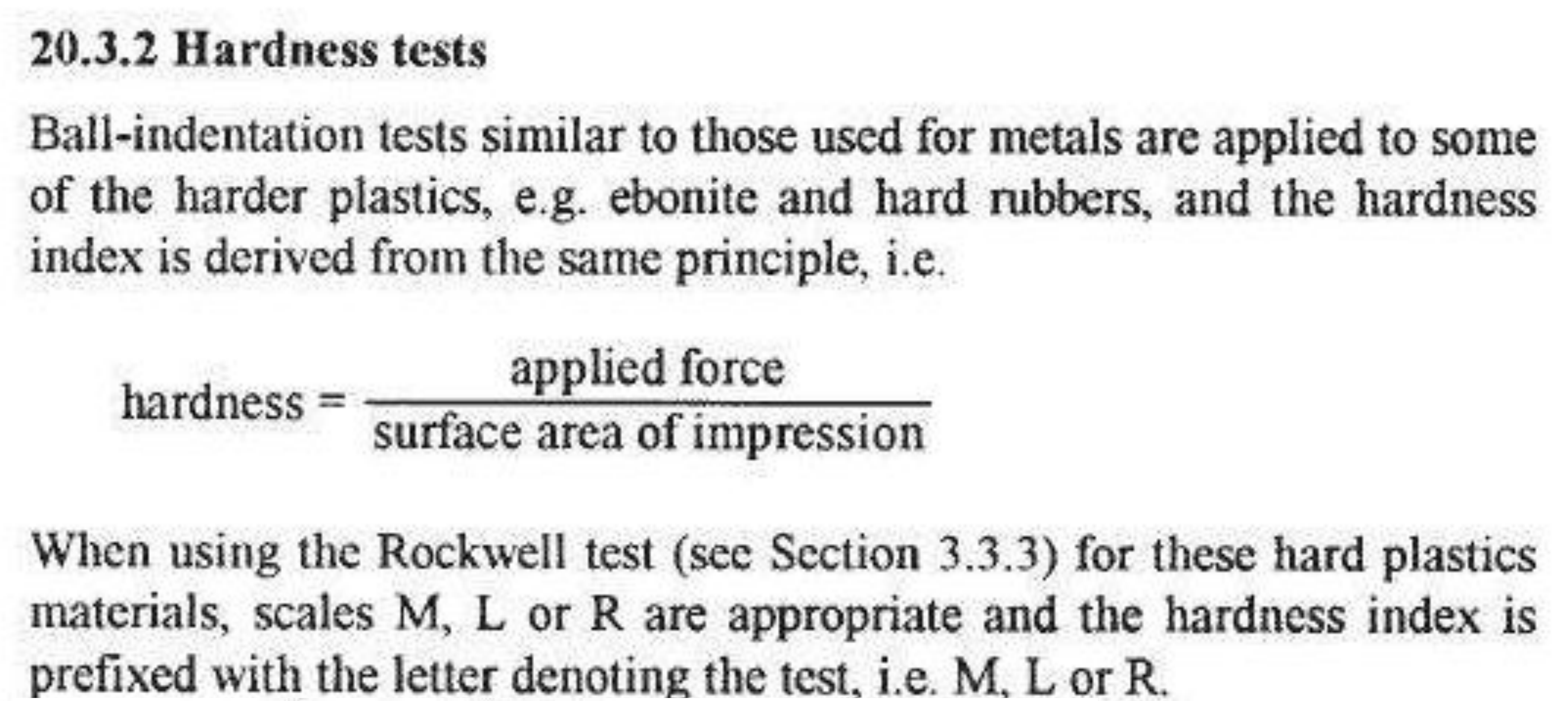


Figure 20.5 *The secant modulus for non-Hookean polymer materials.*



20.3.2 Hardness tests

Ball-indentation tests similar to those used for metals are applied to some of the harder plastics, e.g. ebonite and hard rubbers, and the hardness index is derived from the same principle, i.e.

$$\text{hardness} = \frac{\text{applied force}}{\text{surface area of impression}}$$

When using the Rockwell test (see Section 3.3.3) for these hard plastics materials, scales M, L or R are appropriate and the hardness index is prefixed with the letter denoting the test, i.e. M, L or R.

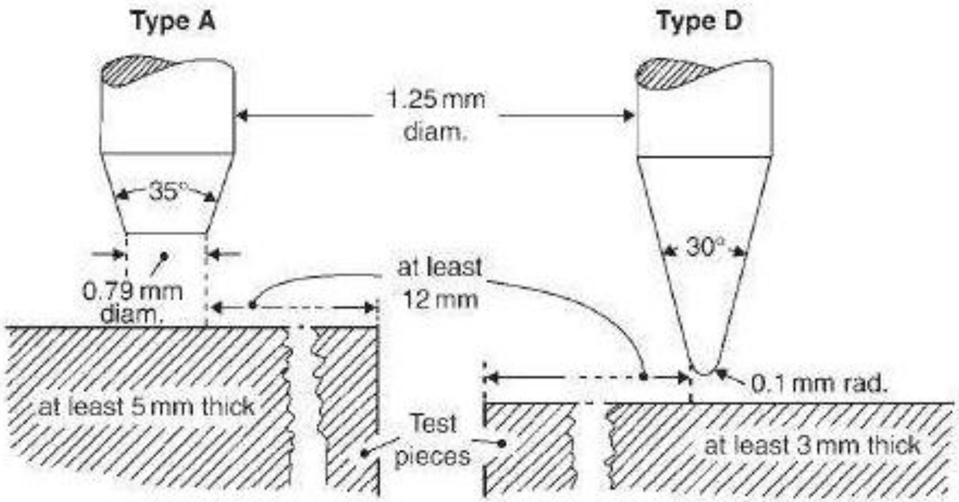


Figure 20.6 *Indentors used in the durometer (Shore hardness).*

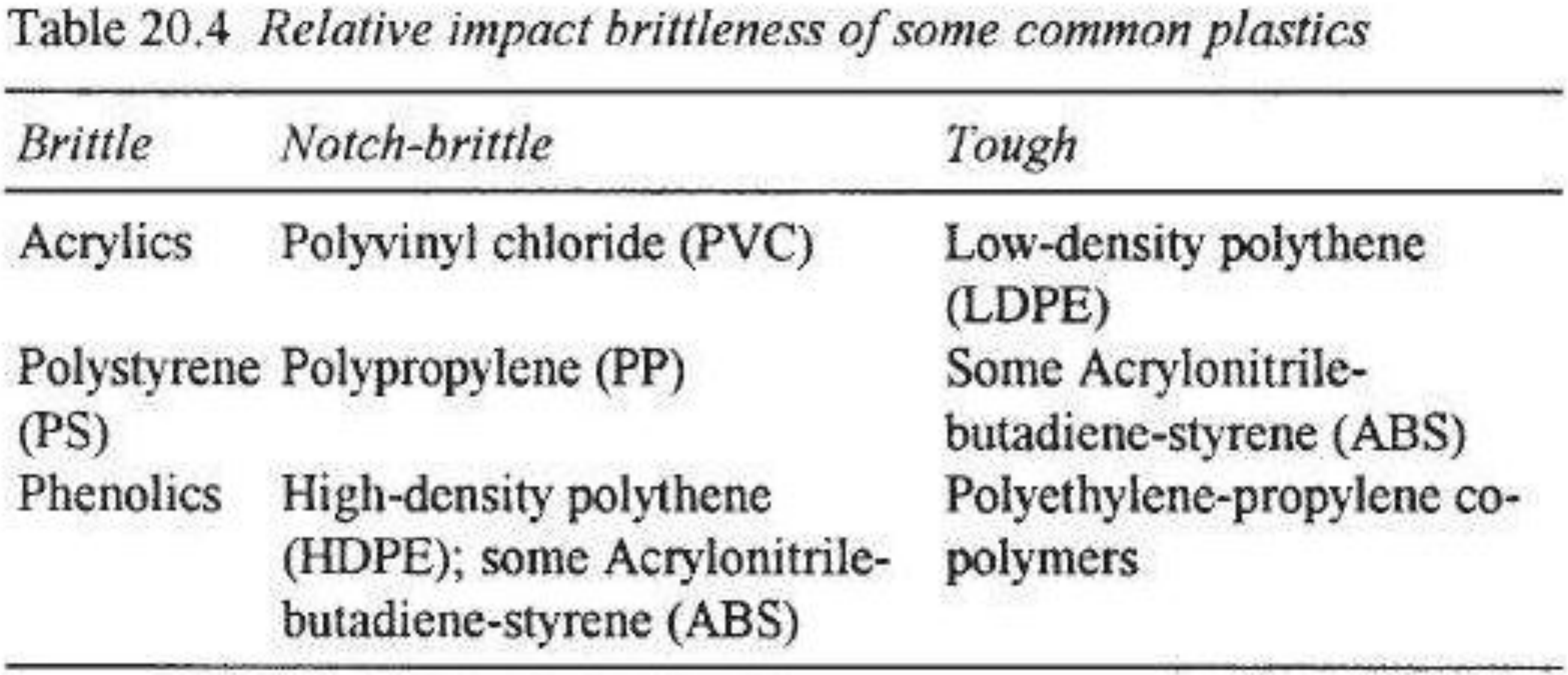


Table 20.4 *Relative impact brittleness of some common plastics*

Brittle	*Notch-brittle*	*Tough*
Acrylics	Polyvinyl chloride (PVC)	Low-density polythene (LDPE)
Polystyrene (PS)	Polypropylene (PP)	Some Acrylonitrile-butadiene-styrene (ABS)
Phenolics	High-density polythene (HDPE); some Acrylonitrile-butadiene-styrene (ABS)	Polyethylene-propylene co-polymers

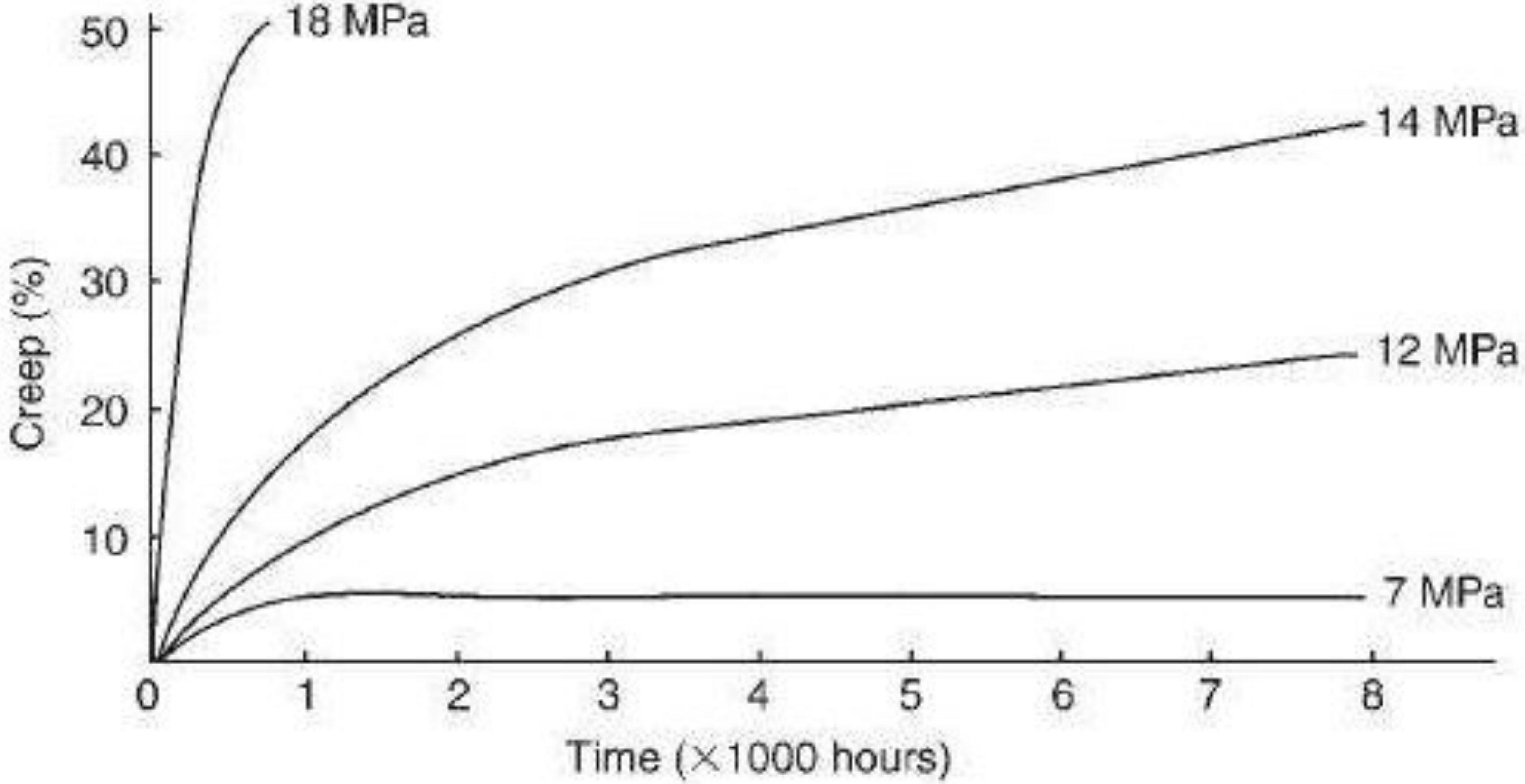


Figure 20.8 *Creep curves for cellulose acetate at 25°C. At a stress of 18 MPa, rapid creep soon leads to catastrophic failure, whilst at a stress of 7 MPa a small initial amount of creep ceases after about 1000 hours and no further measurable creep occurs.*

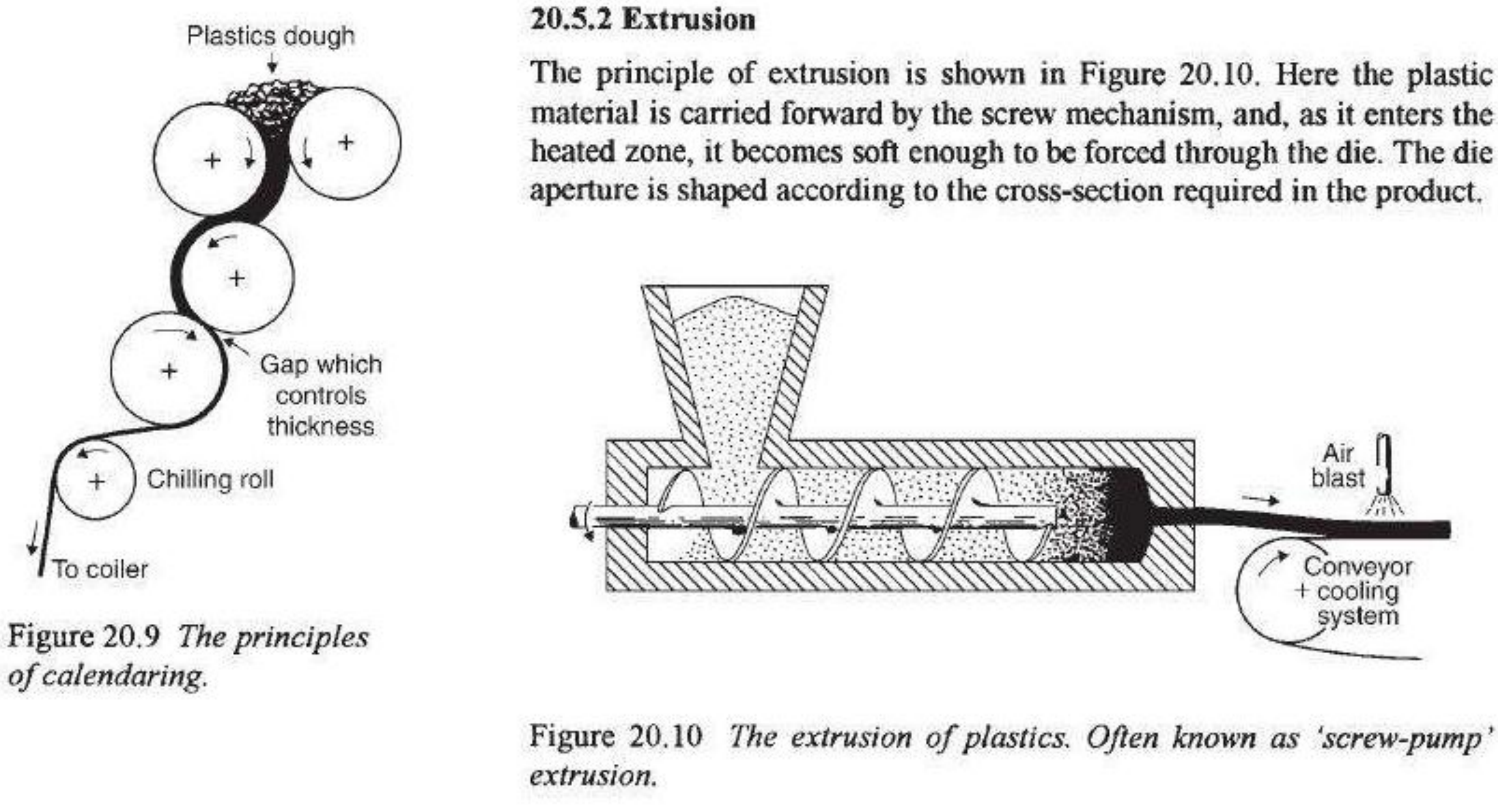


Figure 20.9 *The principles of calendaring.*

20.5.2 Extrusion

The principle of extrusion is shown in Figure 20.10. Here the plastic material is carried forward by the screw mechanism, and, as it enters the heated zone, it becomes soft enough to be forced through the die. The die aperture is shaped according to the cross-section required in the product.

Figure 20.10 *The extrusion of plastics. Often known as 'screw-pump' extrusion.*

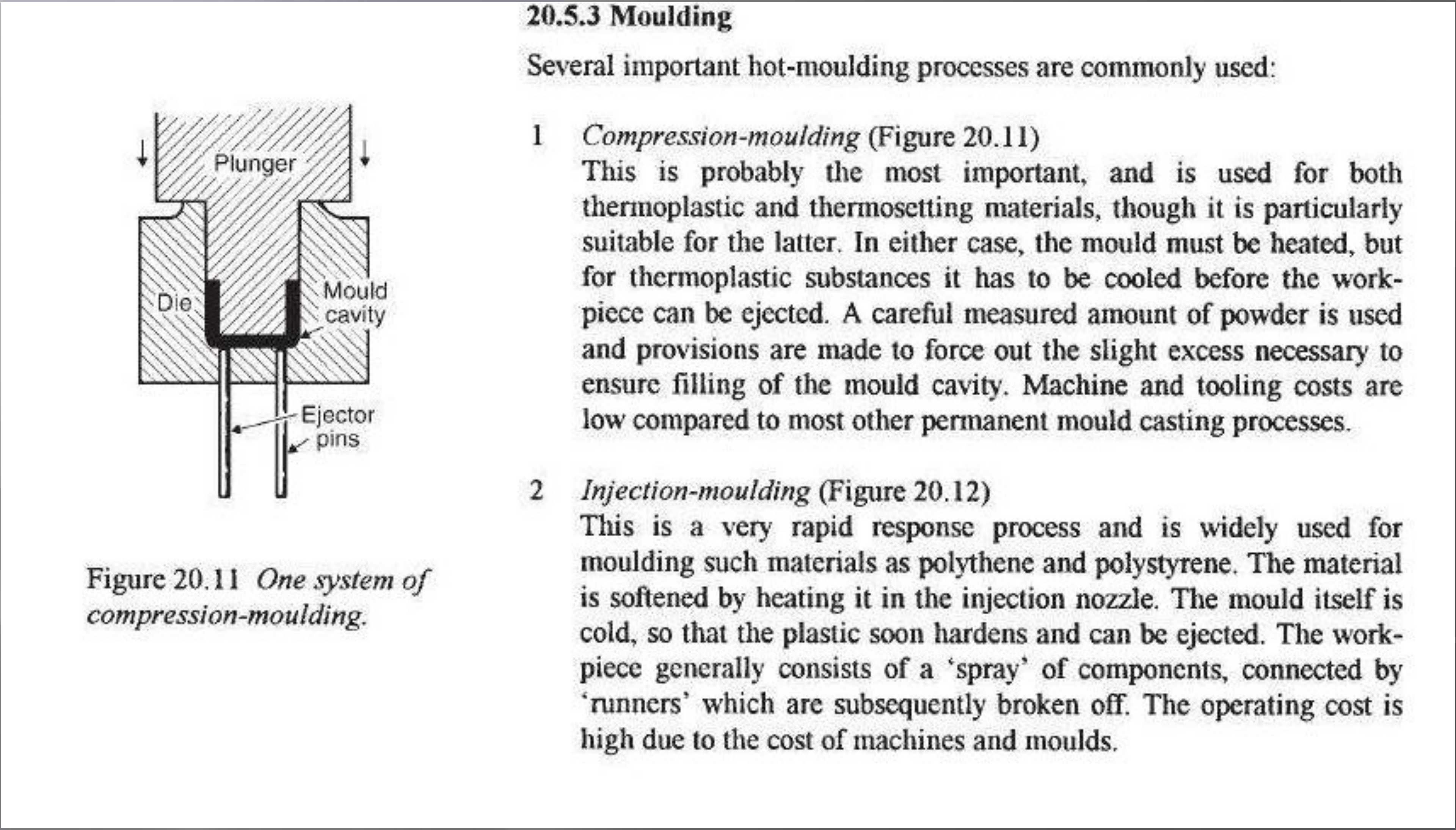


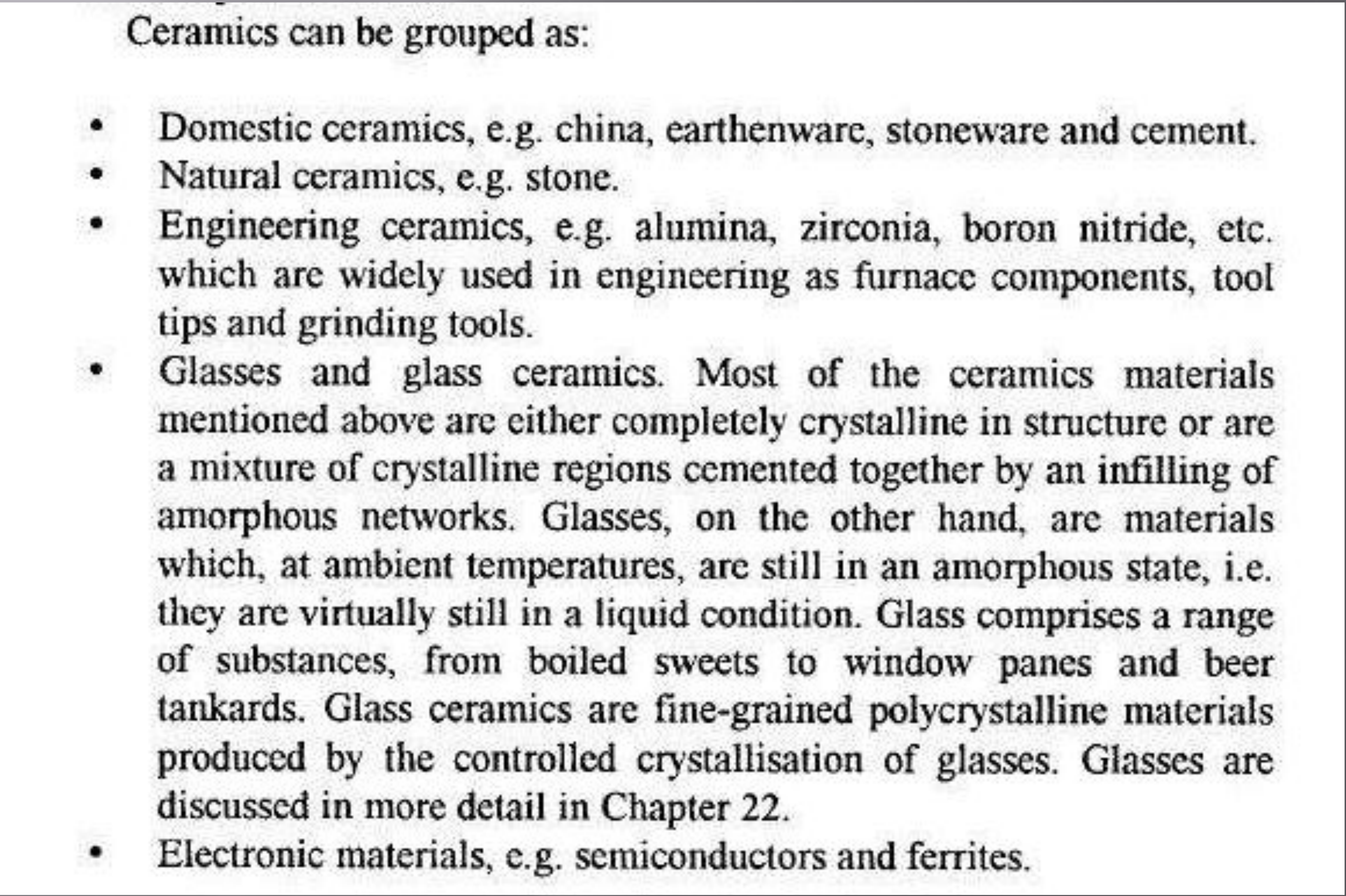
Figure 20.11 *One system of compression-moulding.*

20.5.3 Moulding

Several important hot-moulding processes are commonly used:

1 *Compression-moulding* (Figure 20.11)
This is probably the most important, and is used for both thermoplastic and thermosetting materials, though it is particularly suitable for the latter. In either case, the mould must be heated, but for thermoplastic substances it has to be cooled before the workpiece can be ejected. A careful measured amount of powder is used and provisions are made to force out the slight excess necessary to ensure filling of the mould cavity. Machine and tooling costs are low compared to most other permanent mould casting processes.

2 *Injection-moulding* (Figure 20.12)
This is a very rapid response process and is widely used for moulding such materials as polythene and polystyrene. The material is softened by heating it in the injection nozzle. The mould itself is cold, so that the plastic soon hardens and can be ejected. The workpiece generally consists of a 'spray' of components, connected by 'runners' which are subsequently broken off. The operating cost is high due to the cost of machines and moulds.



Ceramics can be grouped as:

- Domestic ceramics, e.g. china, earthenware, stoneware and cement.
- Natural ceramics, e.g. stone.
- Engineering ceramics, e.g. alumina, zirconia, boron nitride, etc. which are widely used in engineering as furnace components, tool tips and grinding tools.
- Glasses and glass ceramics. Most of the ceramics materials mentioned above are either completely crystalline in structure or are a mixture of crystalline regions cemented together by an infilling of amorphous networks. Glasses, on the other hand, are materials which, at ambient temperatures, are still in an amorphous state, i.e. they are virtually still in a liquid condition. Glass comprises a range of substances, from boiled sweets to window panes and beer tankards. Glass ceramics are fine-grained polycrystalline materials produced by the controlled crystallisation of glasses. Glasses are discussed in more detail in Chapter 22.
- Electronic materials, e.g. semiconductors and ferrites.

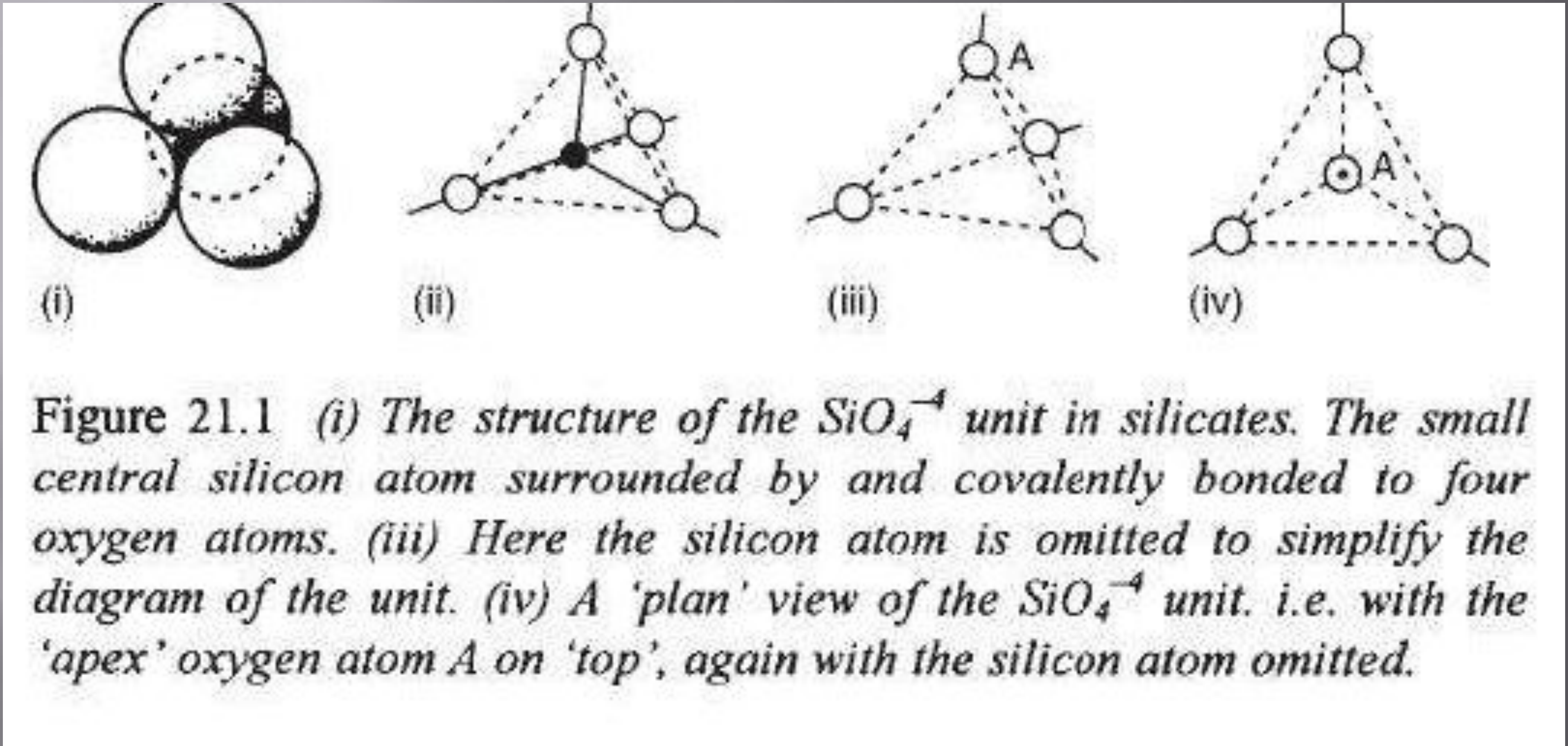
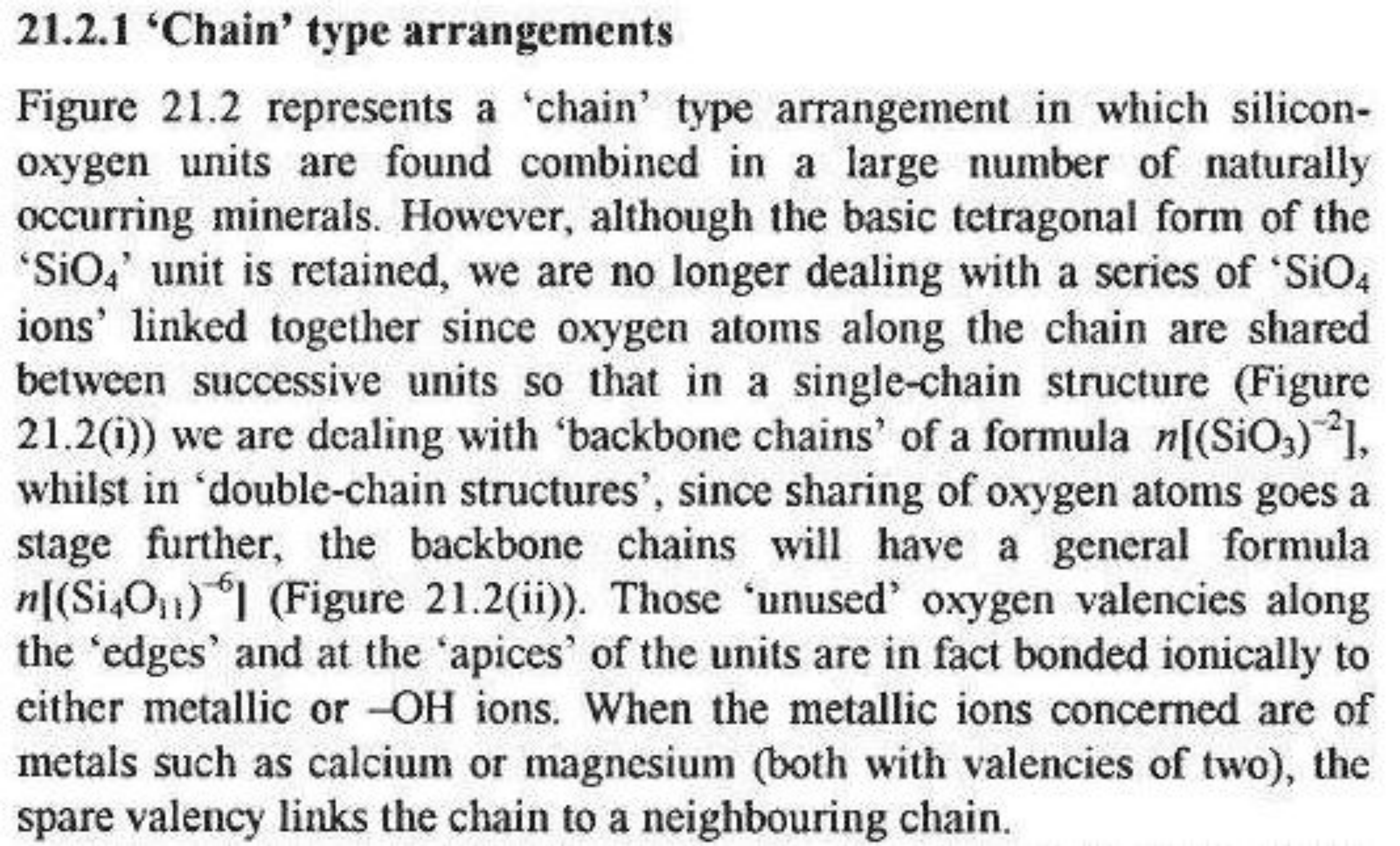


Figure 21.1 *(i) The structure of the SiO_4^{-4} unit in silicates. The small central silicon atom surrounded by and covalently bonded to four oxygen atoms. (iii) Here the silicon atom is omitted to simplify the diagram of the unit. (iv) A 'plan' view of the SiO_4^{-4} unit. i.e. with the 'apex' oxygen atom A on 'top', again with the silicon atom omitted.*



21.2.1 ‘Chain’ type arrangements

Figure 21.2 represents a ‘chain’ type arrangement in which silicon-oxygen units are found combined in a large number of naturally occurring minerals. However, although the basic tetragonal form of the ‘SiO_4’ unit is retained, we are no longer dealing with a series of ‘SiO_4 ions’ linked together since oxygen atoms along the chain are shared between successive units so that in a single-chain structure (Figure 21.2(i)) we are dealing with ‘backbone chains’ of a formula $n[(SiO_3)^{-2}]$, whilst in ‘double-chain structures’, since sharing of oxygen atoms goes a stage further, the backbone chains will have a general formula $n[(Si_4O_{11})^{-6}]$ (Figure 21.2(ii)). Those ‘unused’ oxygen valencies along the ‘edges’ and at the ‘apices’ of the units are in fact bonded ionically to either metallic or –OH ions. When the metallic ions concerned are of metals such as calcium or magnesium (both with valencies of two), the spare valency links the chain to a neighbouring chain.

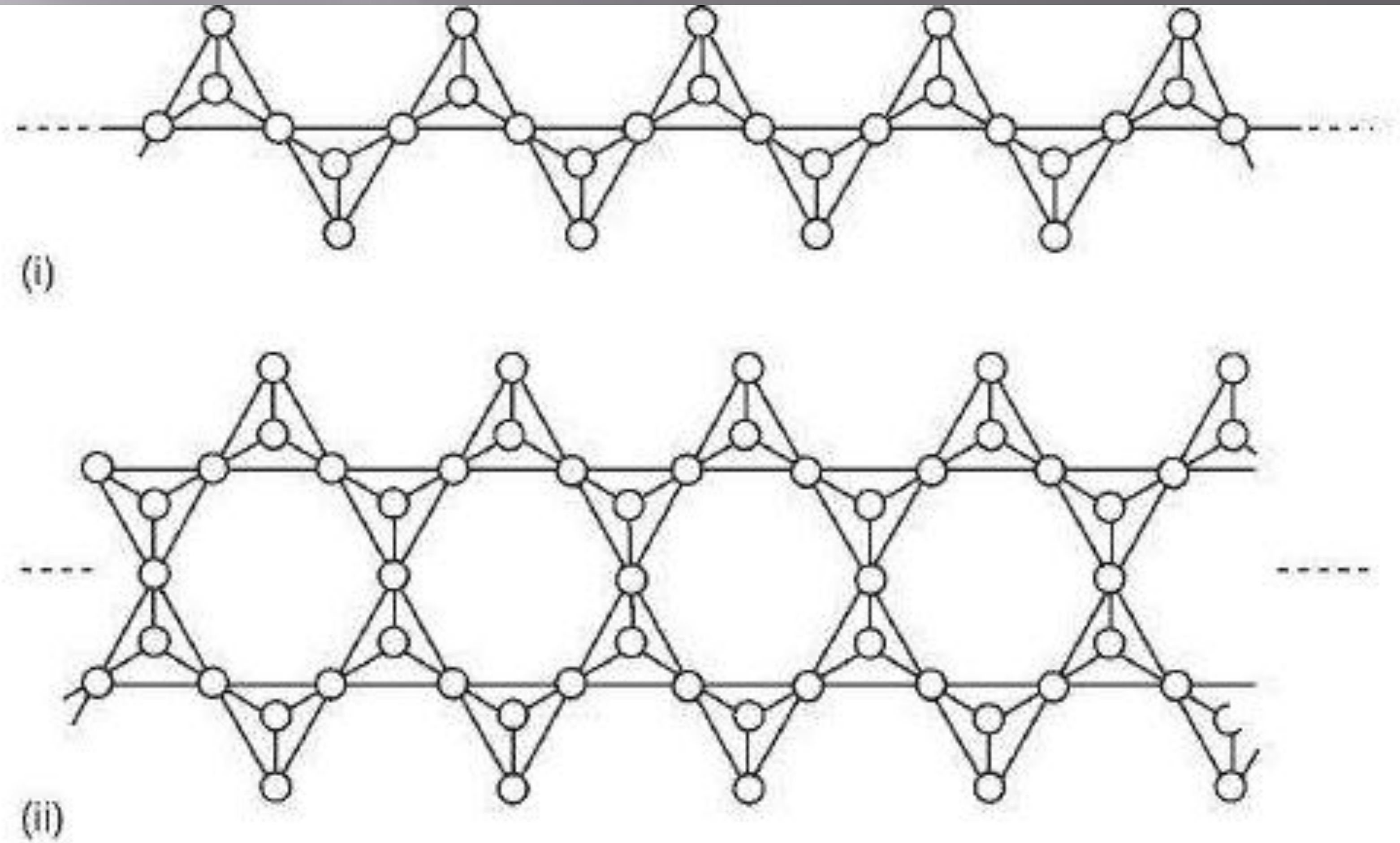


Figure 21.2 *This shows how the structure of chain-type 'giant ions' can be formed from '*SiO_4 *groups'. In fact, because oxygen atoms are shared between two units in a chain, the basic formula of the chain is n[*$(SiO_3)^{-2}$*]. 'Unused' oxygen valencies along the chain attach themselves to metallic ions.*

21.2.2 'Sheet' type arrangements

In another very large group of naturally occurring silicates, the tetragonal silicon-oxygen units are covalently linked in a two-dimensional *sheet* form (Figure 21.3) and the basic (empirical) formula becomes $n[(Si_2O_5)^{-2}]$. This type of structure is found in naturally occurring minerals such as *talc* and some *clays*.

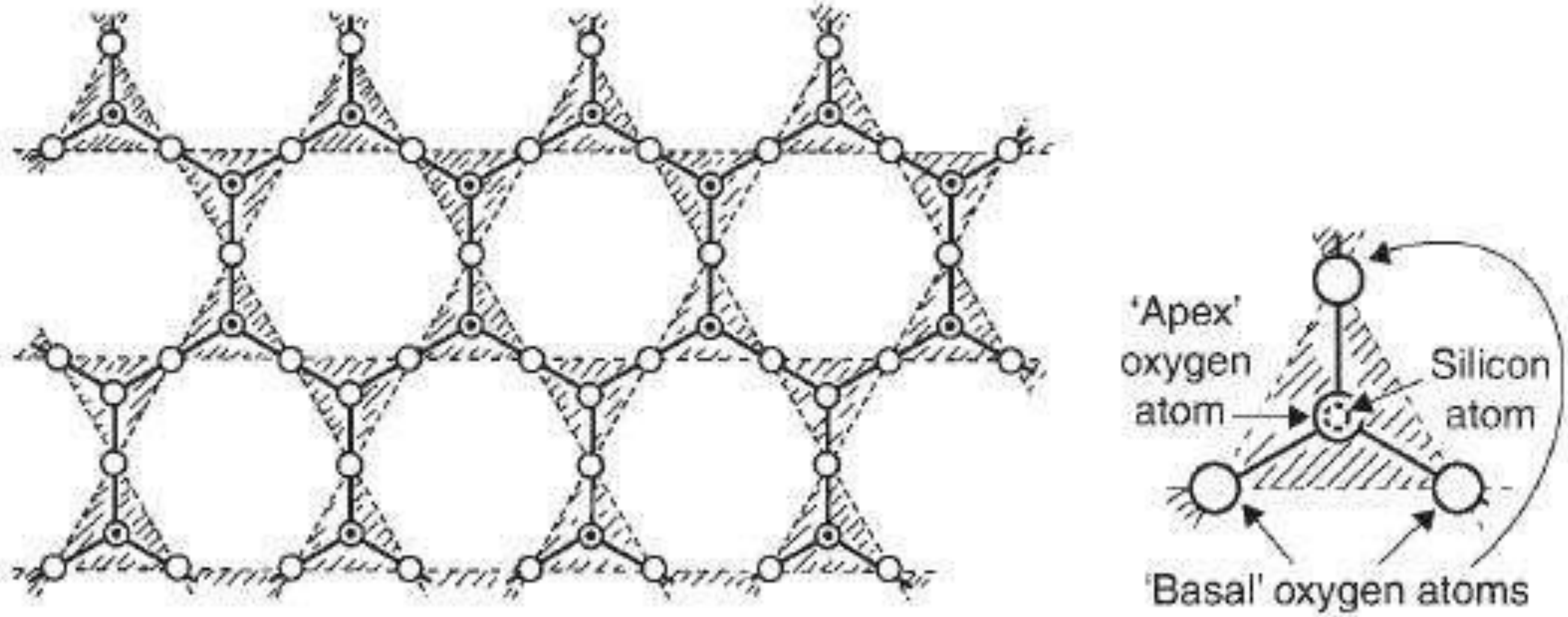


Figure 21.3 *The 'sheet' structure of silicate tetrahedra.*

21.2.2 'Sheet' type arrangements

In another very large group of naturally occurring silicates, the tetragonal silicon-oxygen units are covalently linked in a two-dimensional *sheet* form (Figure 21.3) and the basic (empirical) formula becomes $n[(Si_2O_5)^{-2}]$. This type of structure is found in naturally occurring minerals such as *talc* and some *clays*.

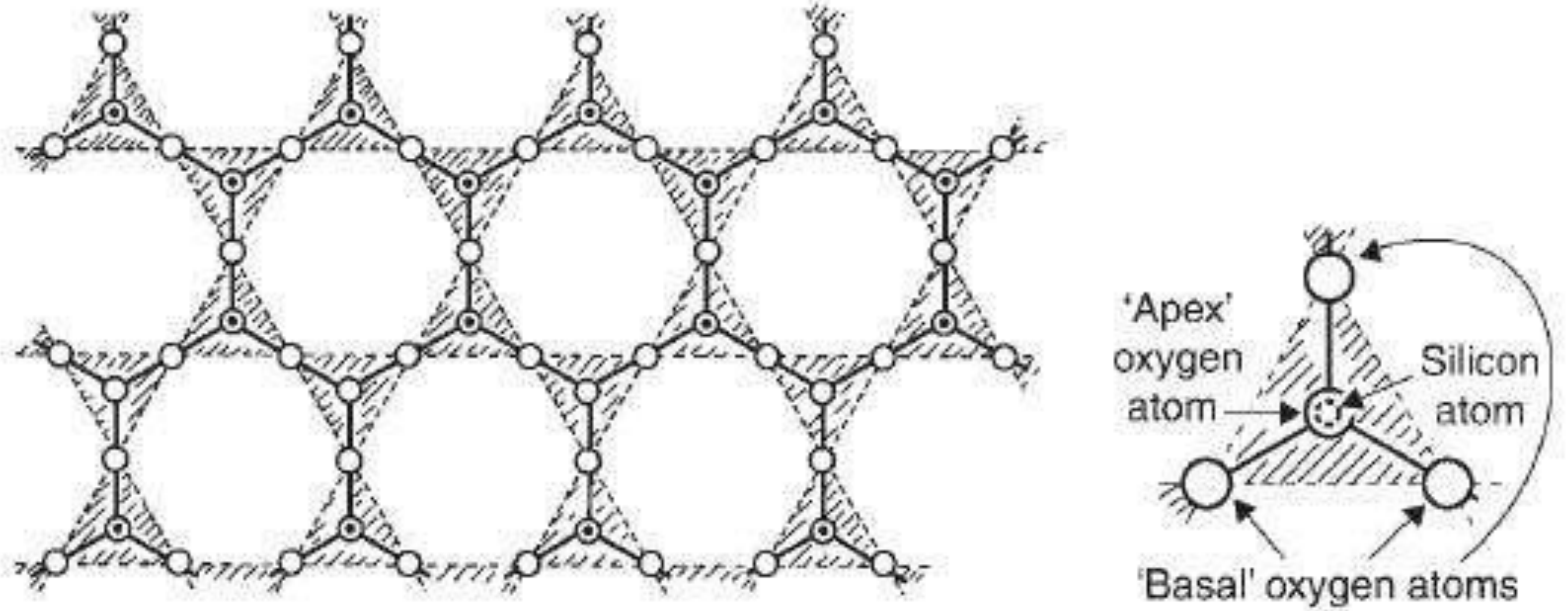
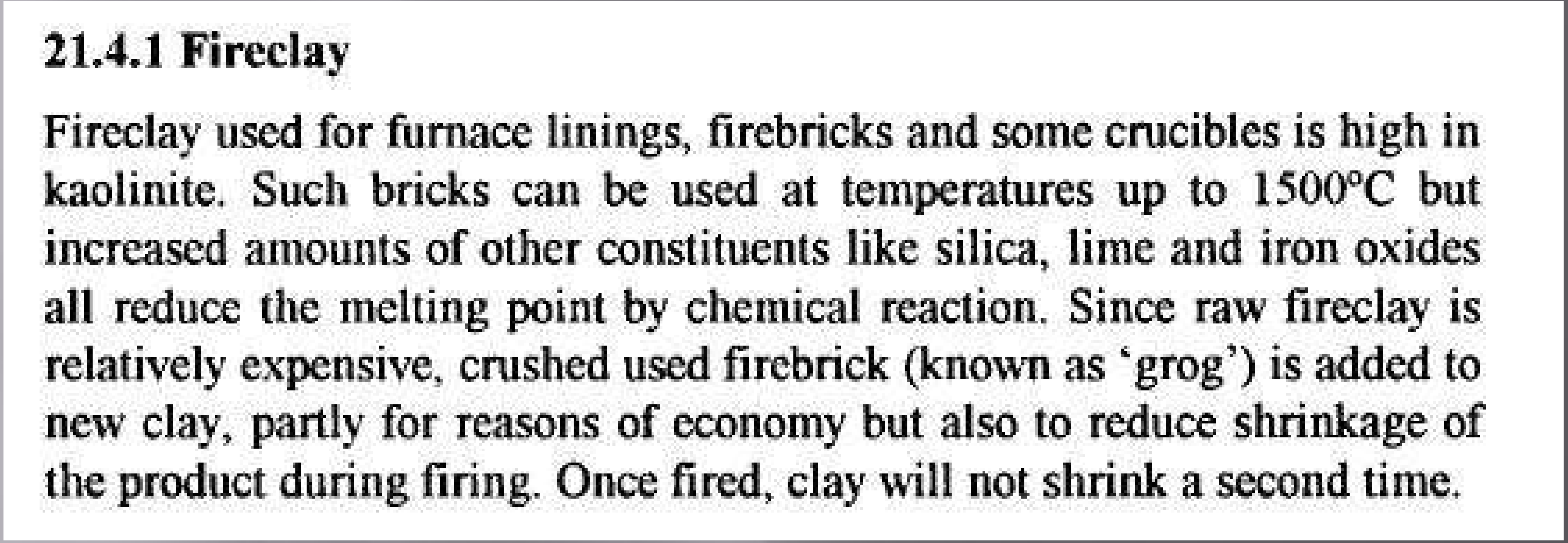


Figure 21.3 *The 'sheet' structure of silicate tetrahedra.*



21.4.1 Fireclay

Fireclay used for furnace linings, firebricks and some crucibles is high in kaolinite. Such bricks can be used at temperatures up to 1500°C but increased amounts of other constituents like silica, lime and iron oxides all reduce the melting point by chemical reaction. Since raw fireclay is relatively expensive, crushed used firebrick (known as 'grog') is added to new clay, partly for reasons of economy but also to reduce shrinkage of the product during firing. Once fired, clay will not shrink a second time.

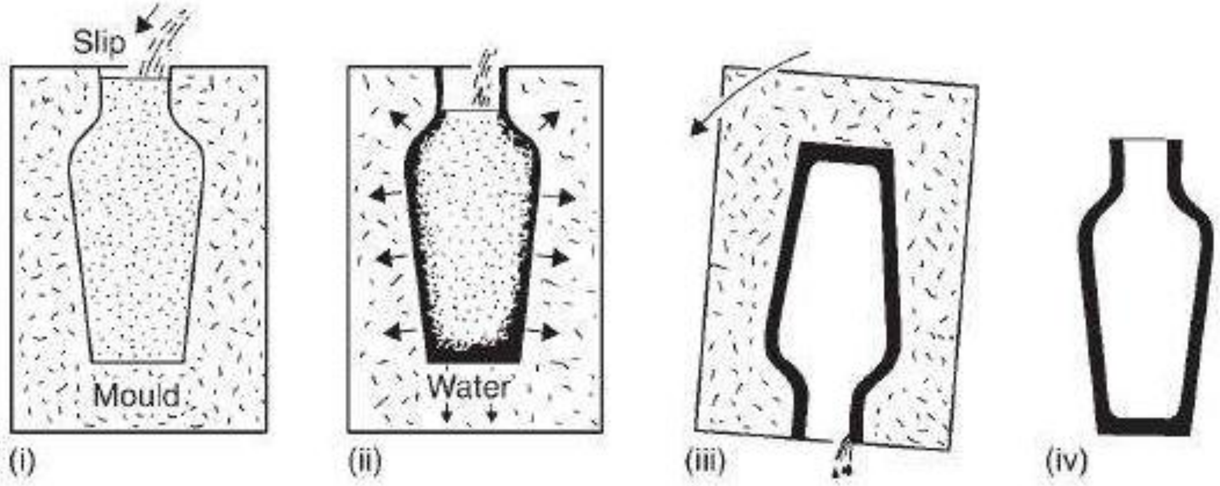
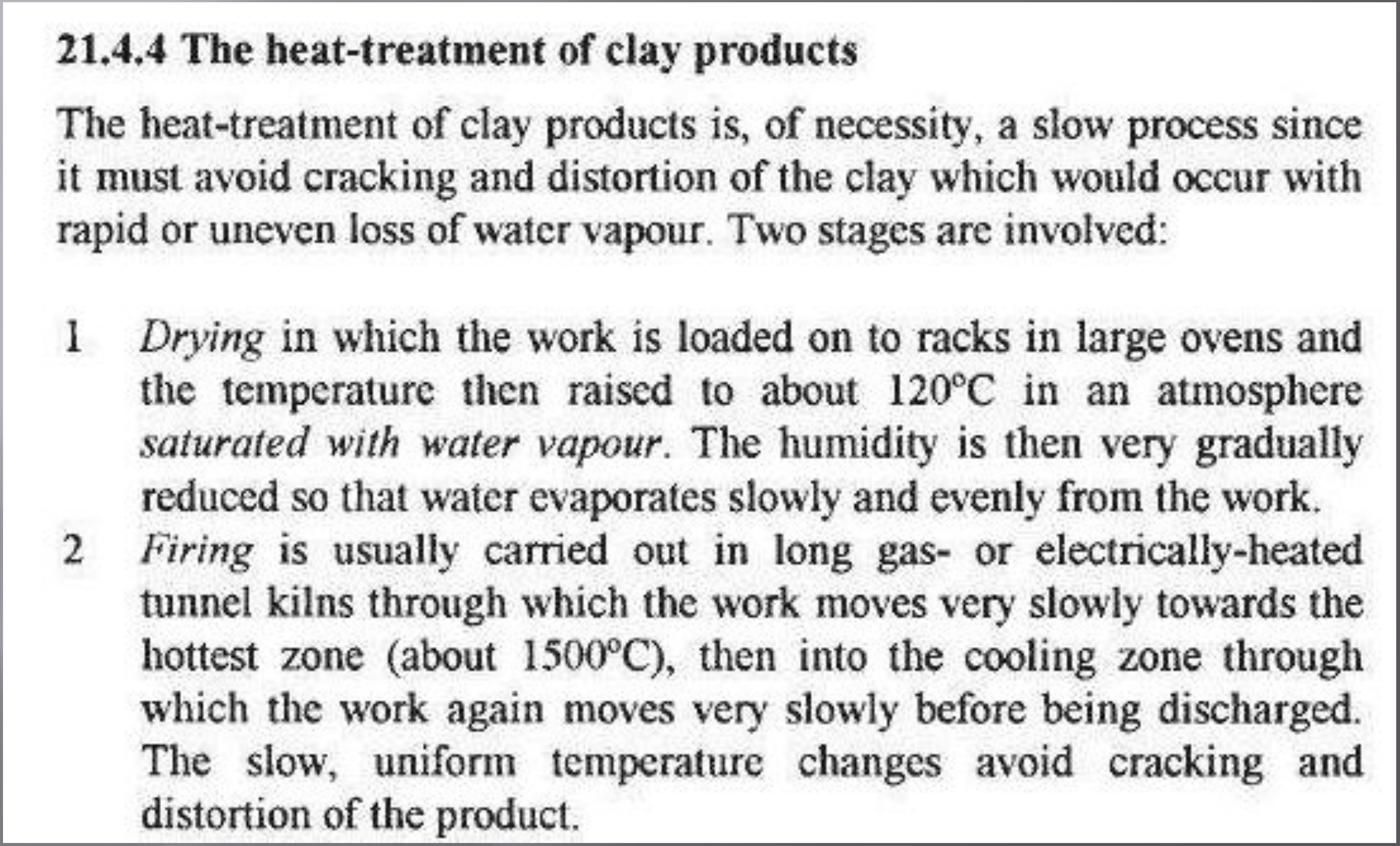


Figure 21.5 *Slip casting of pottery. (i) The plaster mould is filled with slip, (ii) a layer of clay particles collects on the mould surface as water is absorbed by the mould, (iii) when the shell is thick enough, excess slip is poured away, (iv) the resultant 'casting' is removed from the dry mould before being further dried and 'fired'.*

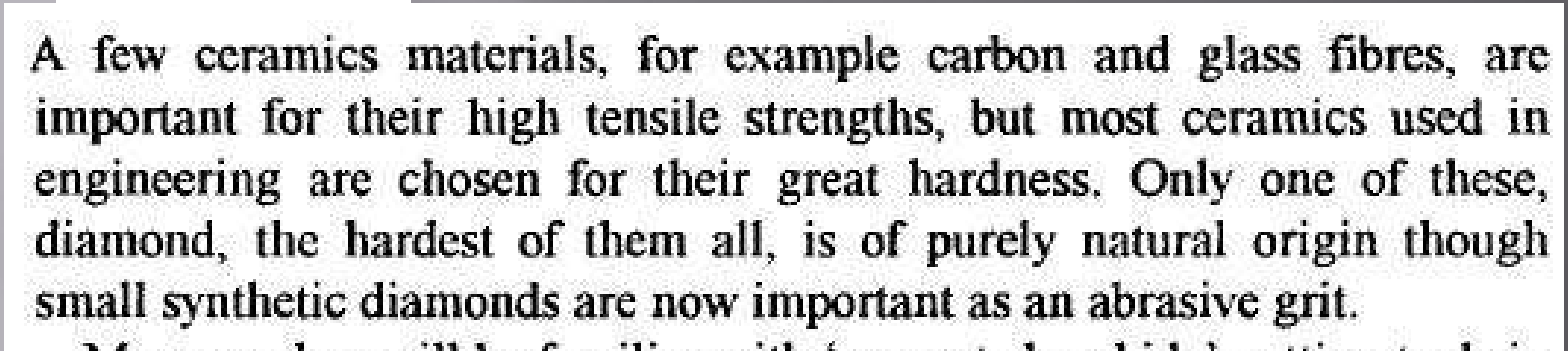


21.4.4 The heat-treatment of clay products

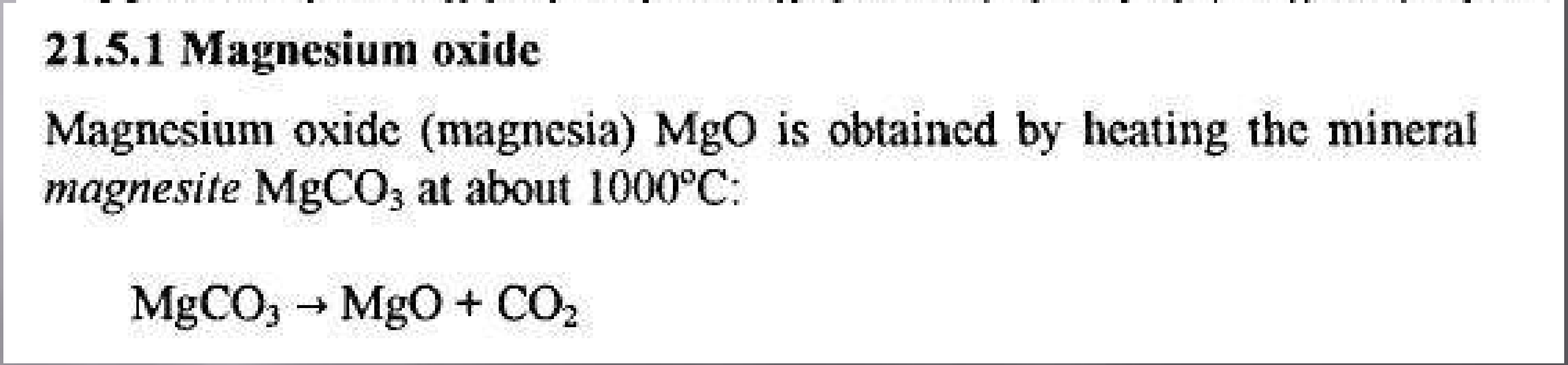
The heat-treatment of clay products is, of necessity, a slow process since it must avoid cracking and distortion of the clay which would occur with rapid or uneven loss of water vapour. Two stages are involved:

1 *Drying* in which the work is loaded on to racks in large ovens and the temperature then raised to about 120°C in an atmosphere *saturated with water vapour*. The humidity is then very gradually reduced so that water evaporates slowly and evenly from the work.
2 *Firing* is usually carried out in long gas- or electrically-heated tunnel kilns through which the work moves very slowly towards the hottest zone (about 1500°C), then into the cooling zone through which the work again moves very slowly before being discharged. The slow, uniform temperature changes avoid cracking and distortion of the product.

Engineering ceramics



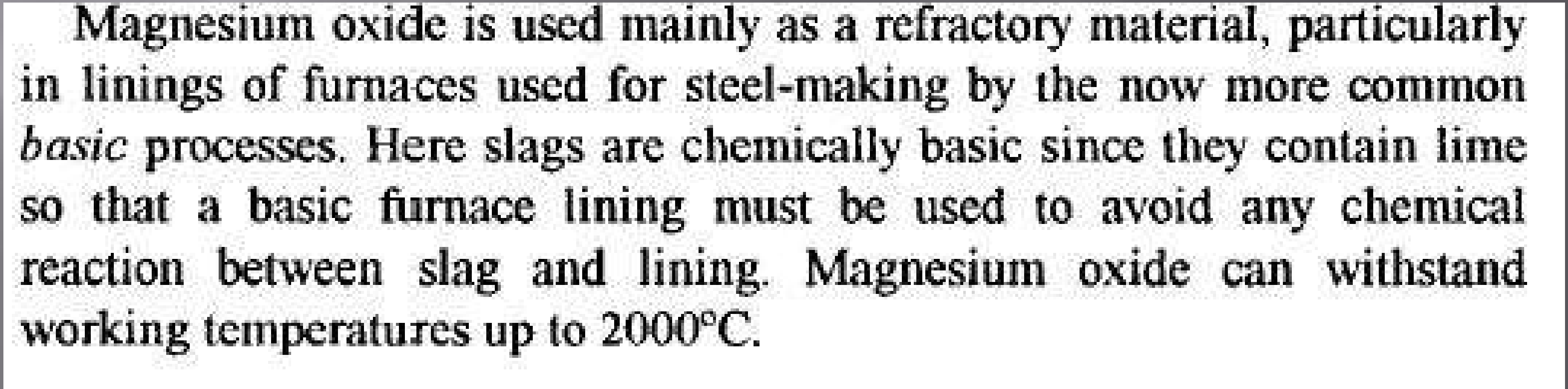
A few ceramics materials, for example carbon and glass fibres, are important for their high tensile strengths, but most ceramics used in engineering are chosen for their great hardness. Only one of these, diamond, the hardest of them all, is of purely natural origin though small synthetic diamonds are now important as an abrasive grit.



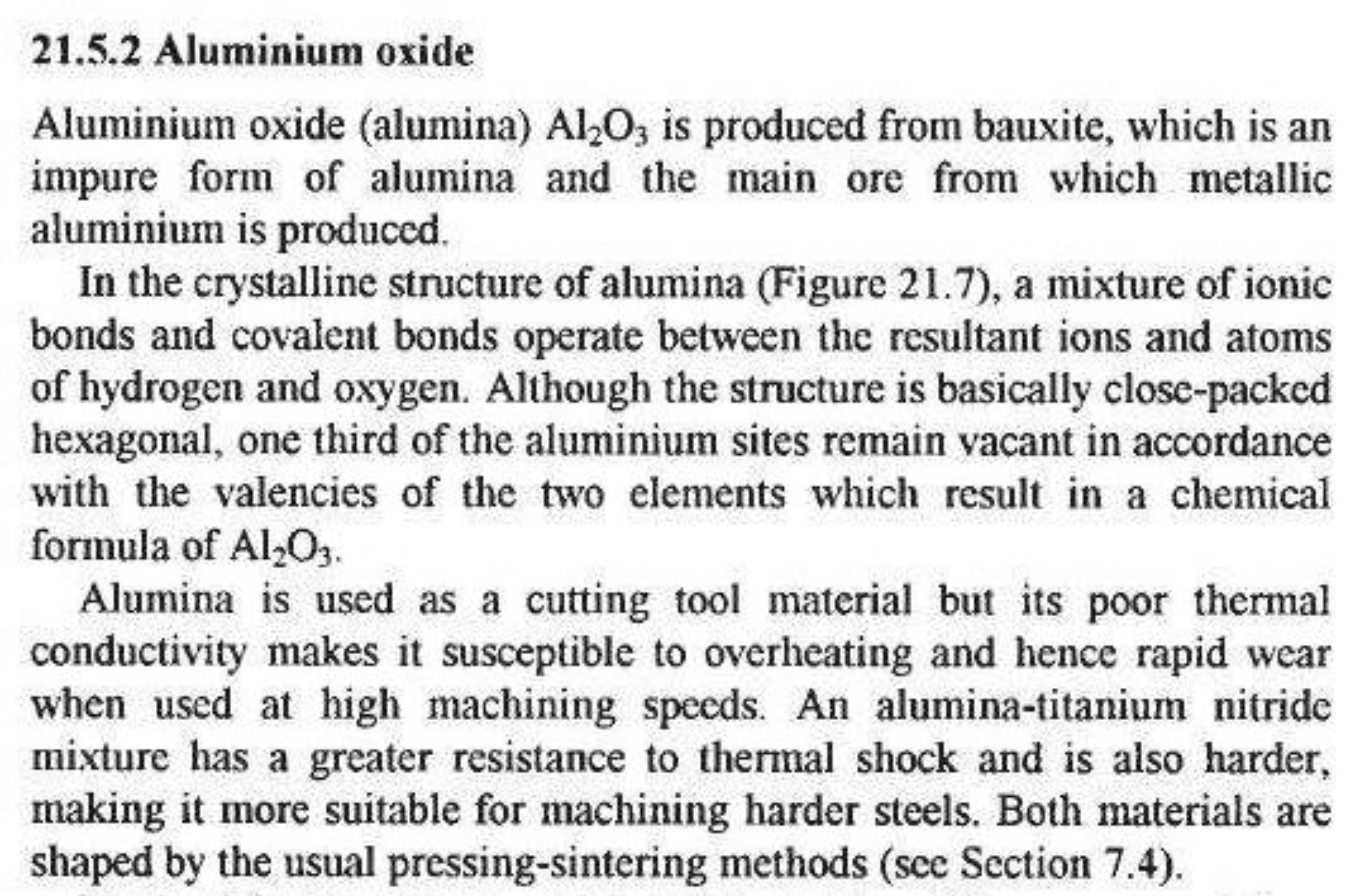
21.5.1 Magnesium oxide

Magnesium oxide (magnesia) MgO is obtained by heating the mineral *magnesite* $MgCO_3$ at about 1000°C:

$$MgCO_3 \rightarrow MgO + CO_2$$



Magnesium oxide is used mainly as a refractory material, particularly in linings of furnaces used for steel-making by the now more common *basic* processes. Here slags are chemically basic since they contain lime so that a basic furnace lining must be used to avoid any chemical reaction between slag and lining. Magnesium oxide can withstand working temperatures up to 2000°C.



21.5.2 Aluminium oxide

Aluminium oxide (alumina) Al_2O_3 is produced from bauxite, which is an impure form of alumina and the main ore from which metallic aluminium is produced.

In the crystalline structure of alumina (Figure 21.7), a mixture of ionic bonds and covalent bonds operate between the resultant ions and atoms of hydrogen and oxygen. Although the structure is basically close-packed hexagonal, one third of the aluminium sites remain vacant in accordance with the valencies of the two elements which result in a chemical formula of Al_2O_3.

Alumina is used as a cutting tool material but its poor thermal conductivity makes it susceptible to overheating and hence rapid wear when used at high machining speeds. An alumina-titanium nitride mixture has a greater resistance to thermal shock and is also harder, making it more suitable for machining harder steels. Both materials are shaped by the usual pressing-sintering methods (see Section 7.4).

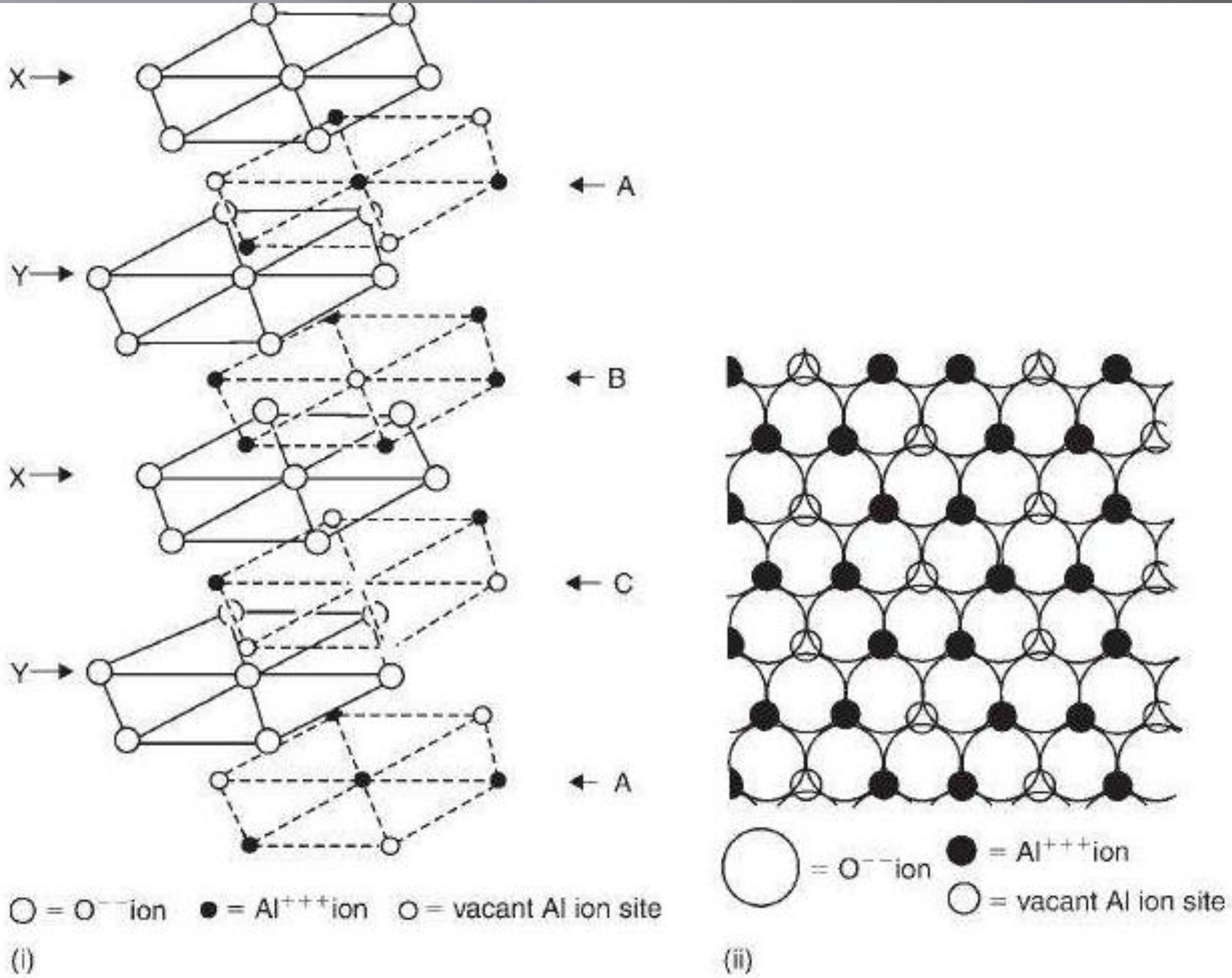
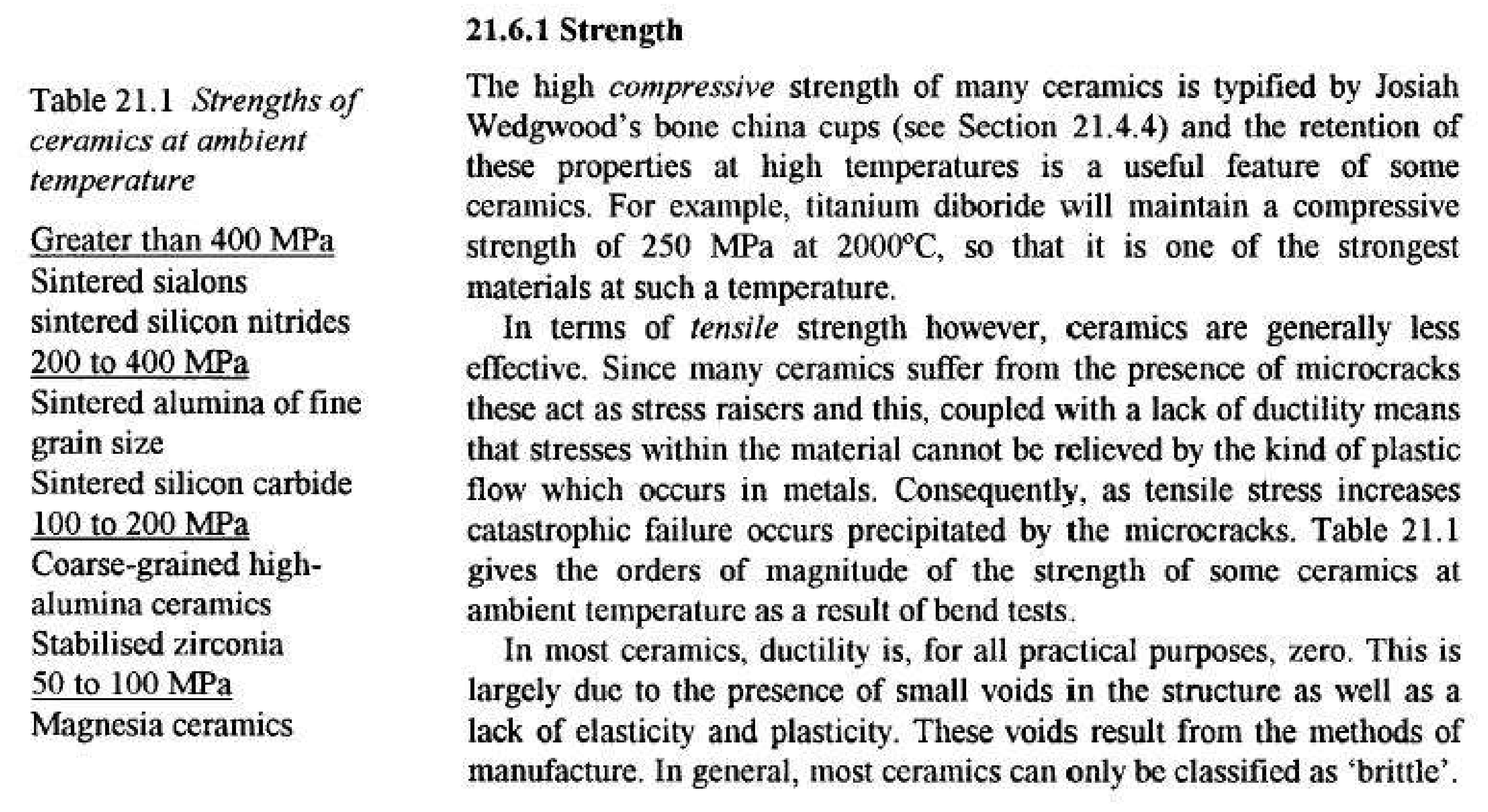


Figure 21.7 *The crystal structure of alpha alumina: (i) represents a spatial arrangement of the positions of aluminium and oxygen atom/ion sites, (ii) represents a 'plan' view of the structure along plane X showing that only two-thirds of the aluminium atom/ion sites are occupied.*



21.6.1 Strength

The high *compressive* strength of many ceramics is typified by Josiah Wedgwood's bone china cups (see Section 21.4.4) and the retention of these properties at high temperatures is a useful feature of some ceramics. For example, titanium diboride will maintain a compressive strength of 250 MPa at 2000°C, so that it is one of the strongest materials at such a temperature.

In terms of *tensile* strength however, ceramics are generally less effective. Since many ceramics suffer from the presence of microcracks these act as stress raisers and this, coupled with a lack of ductility means that stresses within the material cannot be relieved by the kind of plastic flow which occurs in metals. Consequently, as tensile stress increases catastrophic failure occurs precipitated by the microcracks. Table 21.1 gives the orders of magnitude of the strength of some ceramics at ambient temperature as a result of bend tests.

In most ceramics, ductility is, for all practical purposes, zero. This is largely due to the presence of small voids in the structure as well as a lack of elasticity and plasticity. These voids result from the methods of manufacture. In general, most ceramics can only be classified as 'brittle'.

Table 21.1 *Strengths of ceramics at ambient temperature*

Greater than 400 MPa
Sintered sialons
sintered silicon nitrides
200 to 400 MPa
Sintered alumina of fine grain size
Sintered silicon carbide
100 to 200 MPa
Coarse-grained high-alumina ceramics
Stabilised zirconia
50 to 100 MPa
Magnesia ceramics

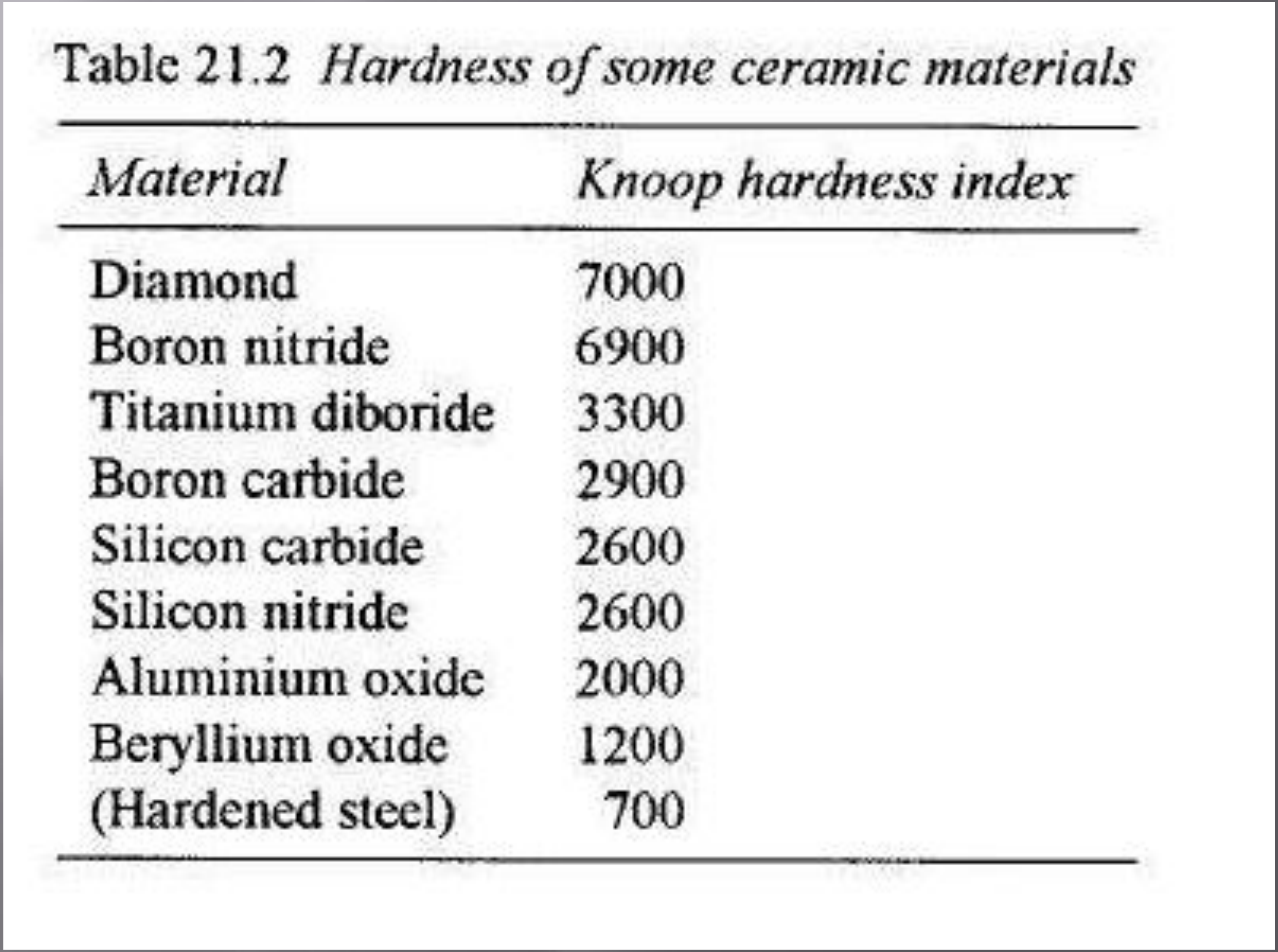


Table 21.2 *Hardness of some ceramic materials*

Material	*Knoop hardness index*
Diamond	7000
Boron nitride	6900
Titanium diboride	3300
Boron carbide	2900
Silicon carbide	2600
Silicon nitride	2600
Aluminium oxide	2000
Beryllium oxide	1200
(Hardened steel)	700

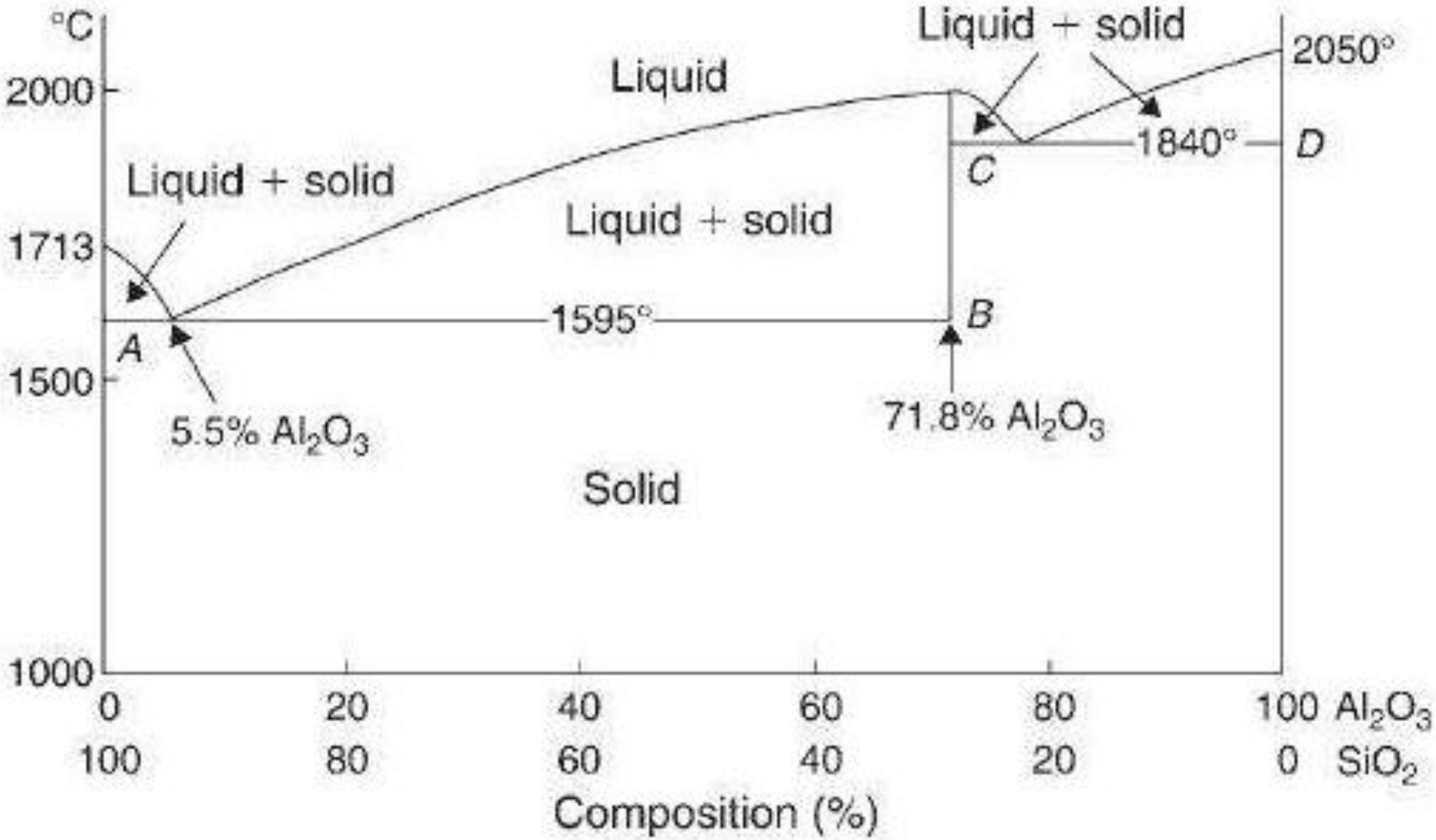


Figure 21.8 *Part of the Al_2O_3–SiO_2 equilibrium diagram showing the liquidus-solidus range.*

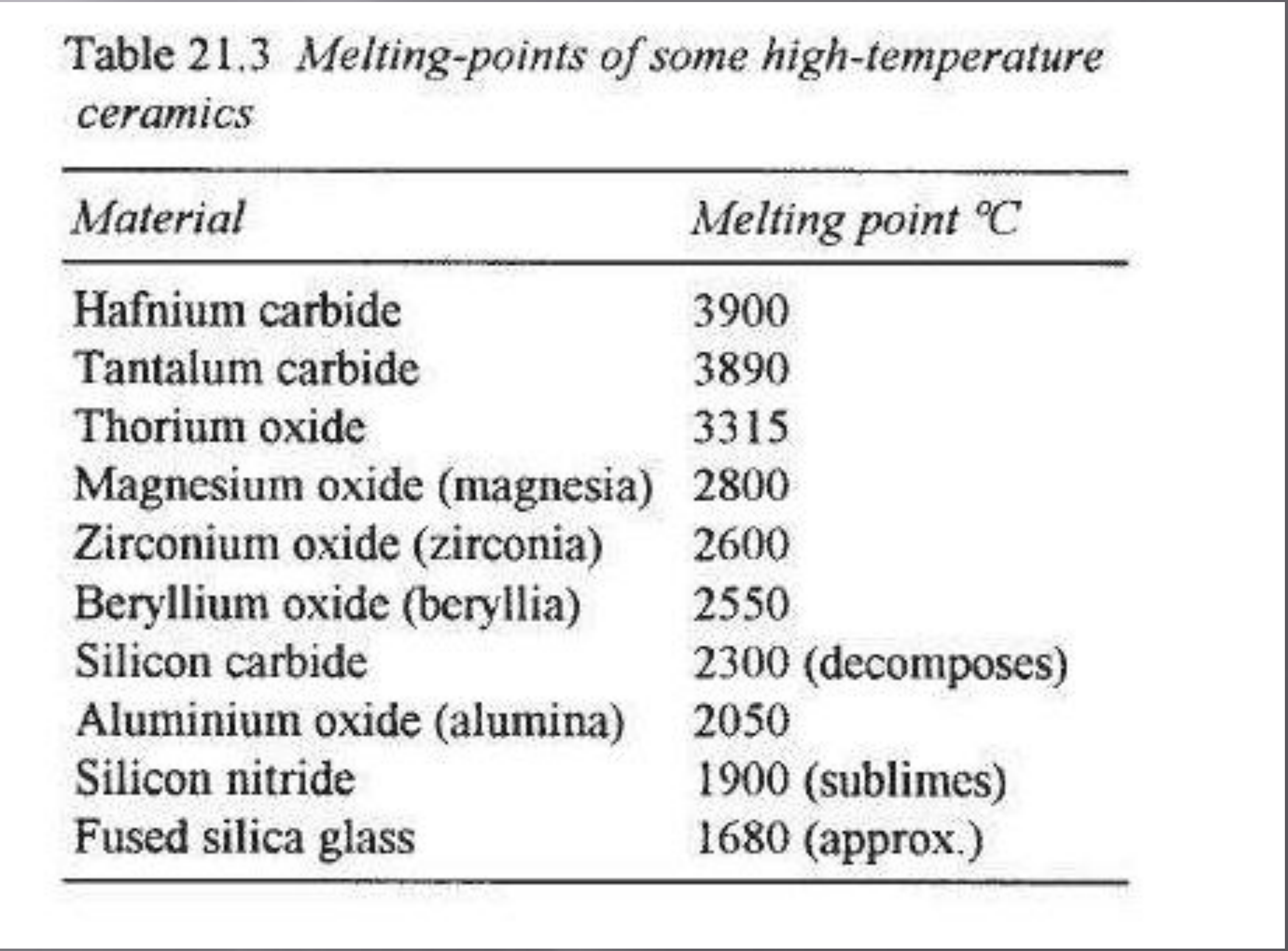
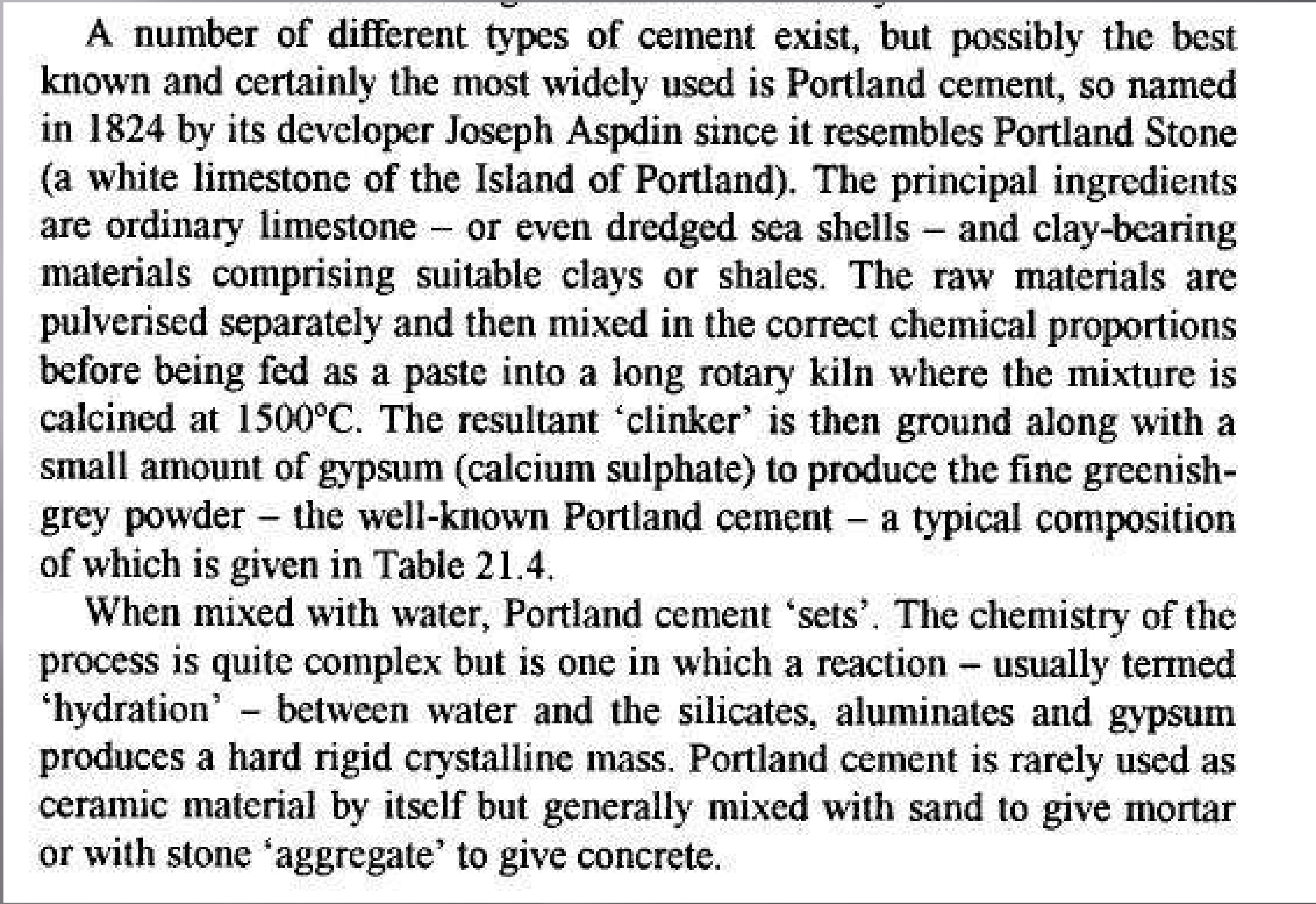


Table 21.3 *Melting-points of some high-temperature ceramics*

Material	*Melting point ℃*
Hafnium carbide	3900
Tantalum carbide	3890
Thorium oxide	3315
Magnesium oxide (magnesia)	2800
Zirconium oxide (zirconia)	2600
Beryllium oxide (beryllia)	2550
Silicon carbide	2300 (decomposes)
Aluminium oxide (alumina)	2050
Silicon nitride	1900 (sublimes)
Fused silica glass	1680 (approx.)



A number of different types of cement exist, but possibly the best known and certainly the most widely used is Portland cement, so named in 1824 by its developer Joseph Aspdin since it resembles Portland Stone (a white limestone of the Island of Portland). The principal ingredients are ordinary limestone – or even dredged sea shells – and clay-bearing materials comprising suitable clays or shales. The raw materials are pulverised separately and then mixed in the correct chemical proportions before being fed as a paste into a long rotary kiln where the mixture is calcined at 1500°C. The resultant 'clinker' is then ground along with a small amount of gypsum (calcium sulphate) to produce the fine greenish-grey powder – the well-known Portland cement – a typical composition of which is given in Table 21.4.

When mixed with water, Portland cement 'sets'. The chemistry of the process is quite complex but is one in which a reaction – usually termed 'hydration' – between water and the silicates, aluminates and gypsum produces a hard rigid crystalline mass. Portland cement is rarely used as ceramic material by itself but generally mixed with sand to give mortar or with stone 'aggregate' to give concrete.

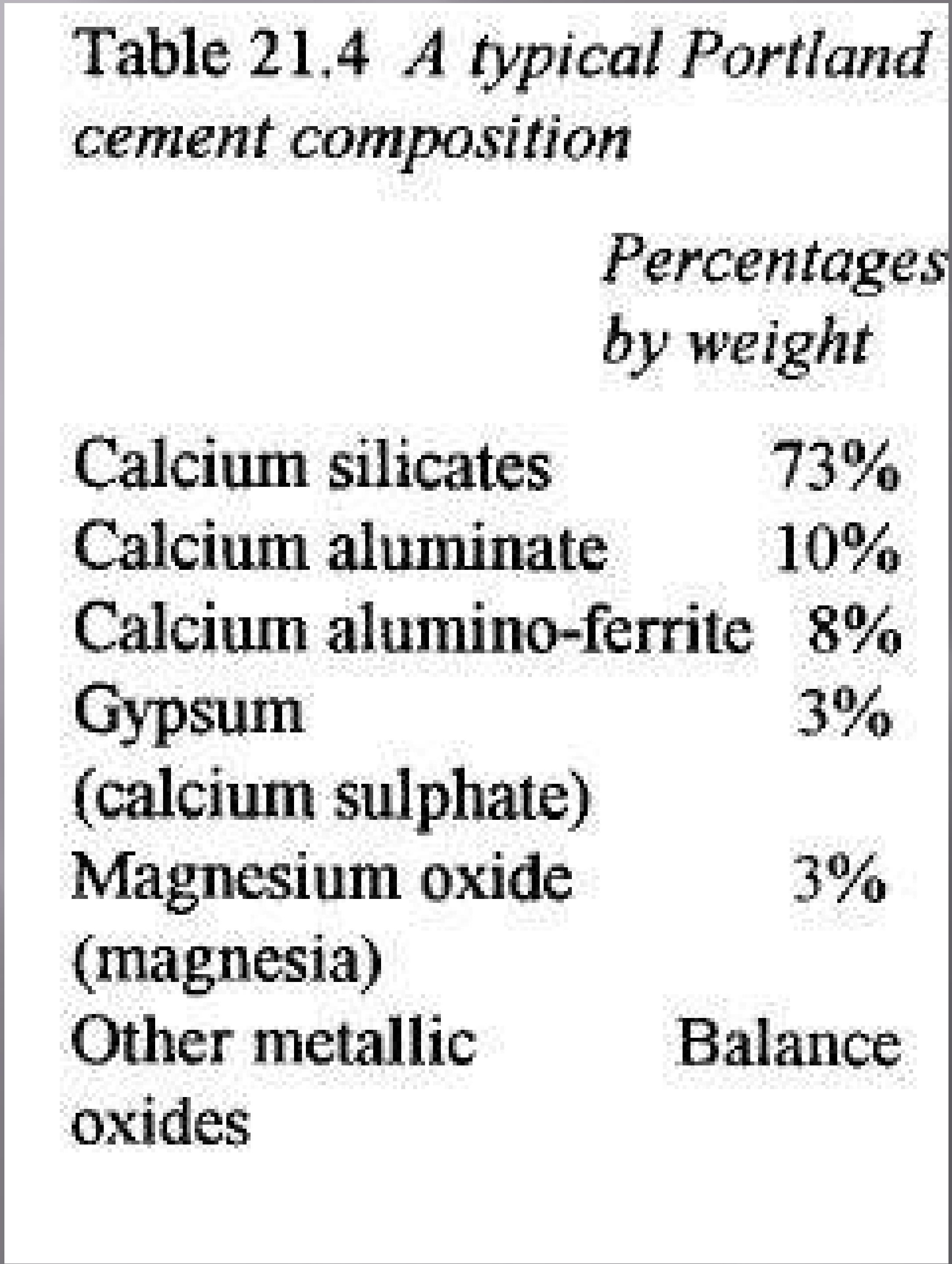
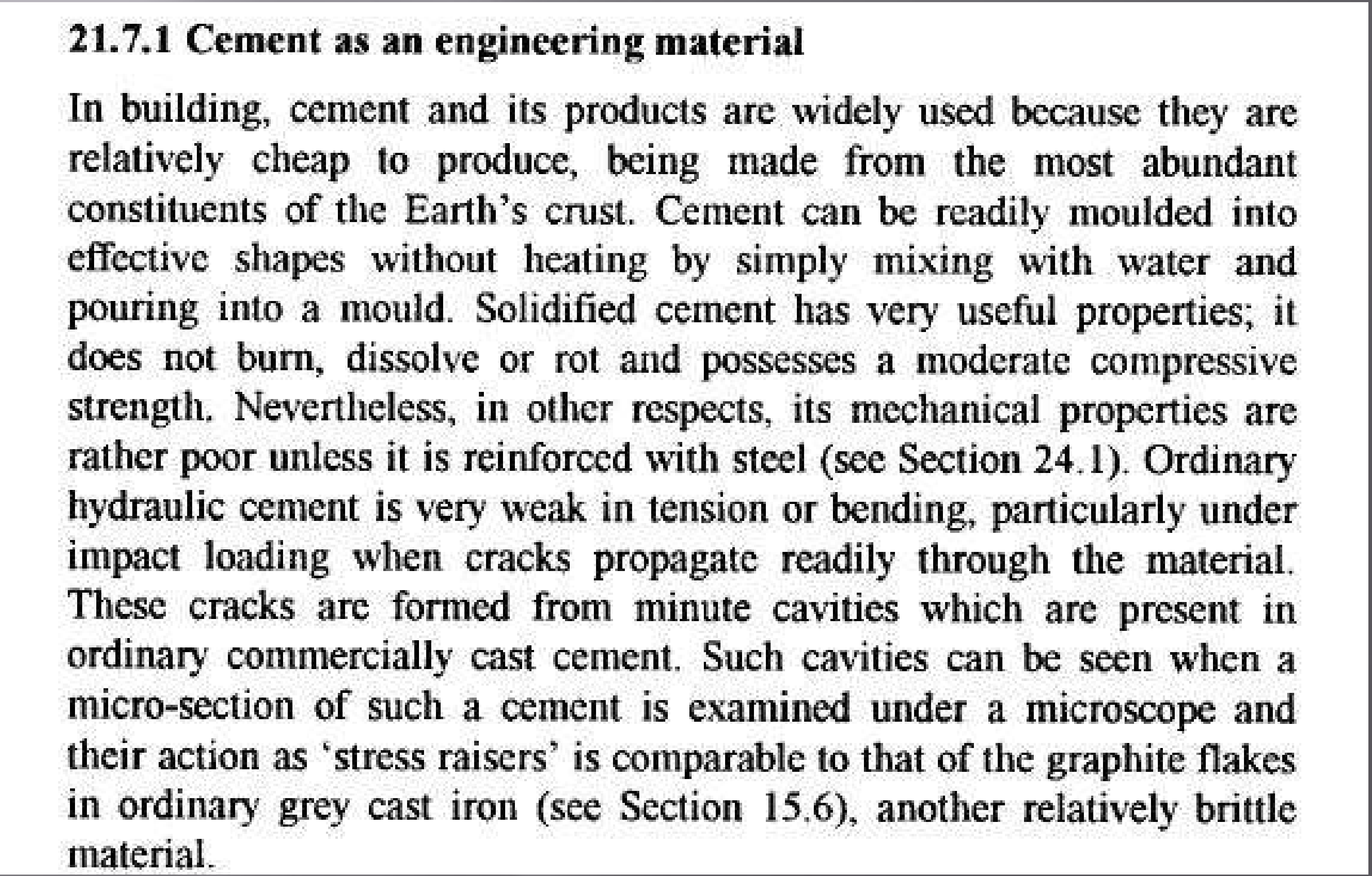


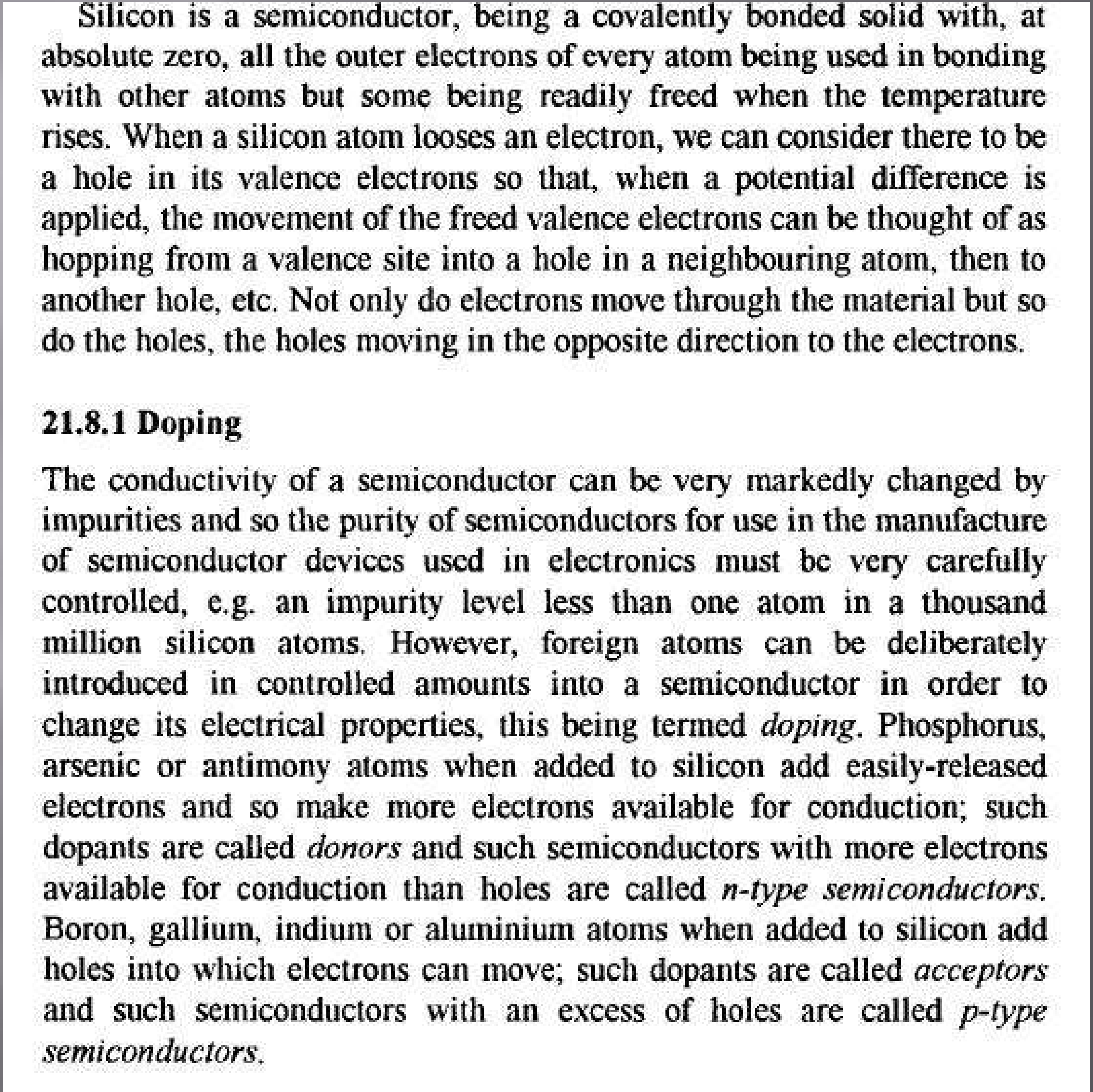
Table 21.4 *A typical Portland cement composition*

	Percentages by weight
Calcium silicates	73%
Calcium aluminate	10%
Calcium alumino-ferrite	8%
Gypsum (calcium sulphate)	3%
Magnesium oxide (magnesia)	3%
Other metallic oxides	Balance



21.7.1 Cement as an engineering material

In building, cement and its products are widely used because they are relatively cheap to produce, being made from the most abundant constituents of the Earth's crust. Cement can be readily moulded into effective shapes without heating by simply mixing with water and pouring into a mould. Solidified cement has very useful properties; it does not burn, dissolve or rot and possesses a moderate compressive strength. Nevertheless, in other respects, its mechanical properties are rather poor unless it is reinforced with steel (see Section 24.1). Ordinary hydraulic cement is very weak in tension or bending, particularly under impact loading when cracks propagate readily through the material. These cracks are formed from minute cavities which are present in ordinary commercially cast cement. Such cavities can be seen when a micro-section of such a cement is examined under a microscope and their action as 'stress raisers' is comparable to that of the graphite flakes in ordinary grey cast iron (see Section 15.6), another relatively brittle material.

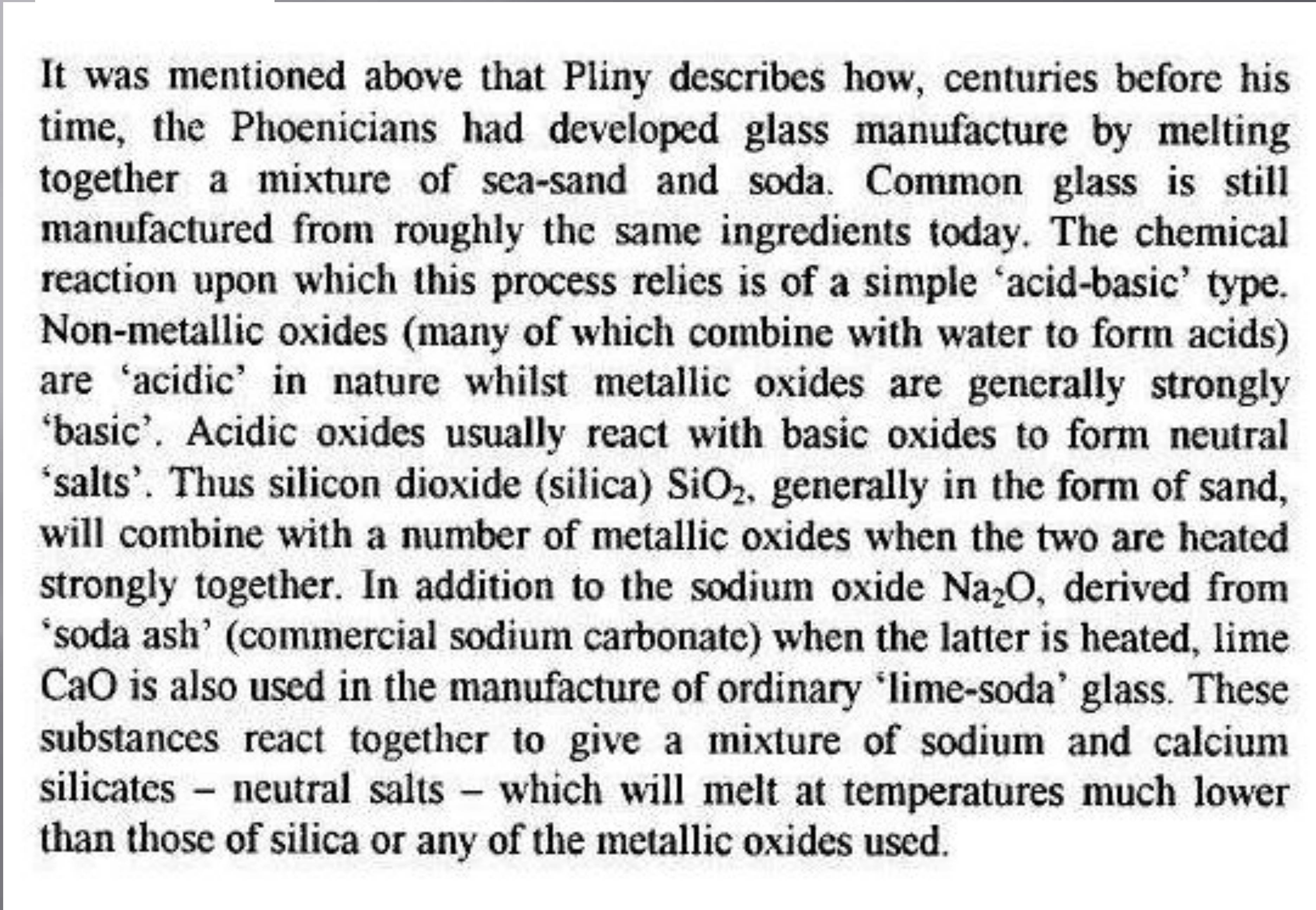


Silicon is a semiconductor, being a covalently bonded solid with, at absolute zero, all the outer electrons of every atom being used in bonding with other atoms but some being readily freed when the temperature rises. When a silicon atom looses an electron, we can consider there to be a hole in its valence electrons so that, when a potential difference is applied, the movement of the freed valence electrons can be thought of as hopping from a valence site into a hole in a neighbouring atom, then to another hole, etc. Not only do electrons move through the material but so do the holes, the holes moving in the opposite direction to the electrons.

21.8.1 Doping

The conductivity of a semiconductor can be very markedly changed by impurities and so the purity of semiconductors for use in the manufacture of semiconductor devices used in electronics must be very carefully controlled, e.g. an impurity level less than one atom in a thousand million silicon atoms. However, foreign atoms can be deliberately introduced in controlled amounts into a semiconductor in order to change its electrical properties, this being termed *doping*. Phosphorus, arsenic or antimony atoms when added to silicon add easily-released electrons and so make more electrons available for conduction; such dopants are called *donors* and such semiconductors with more electrons available for conduction than holes are called *n-type semiconductors*. Boron, gallium, indium or aluminium atoms when added to silicon add holes into which electrons can move; such dopants are called *acceptors* and such semiconductors with an excess of holes are called *p-type semiconductors*.

Composition and structure of glass



It was mentioned above that Pliny describes how, centuries before his time, the Phoenicians had developed glass manufacture by melting together a mixture of sea-sand and soda. Common glass is still manufactured from roughly the same ingredients today. The chemical reaction upon which this process relies is of a simple 'acid-basic' type. Non-metallic oxides (many of which combine with water to form acids) are 'acidic' in nature whilst metallic oxides are generally strongly 'basic'. Acidic oxides usually react with basic oxides to form neutral 'salts'. Thus silicon dioxide (silica) SiO_2, generally in the form of sand, will combine with a number of metallic oxides when the two are heated strongly together. In addition to the sodium oxide Na_2O, derived from 'soda ash' (commercial sodium carbonate) when the latter is heated, lime CaO is also used in the manufacture of ordinary 'lime-soda' glass. These substances react together to give a mixture of sodium and calcium silicates – neutral salts – which will melt at temperatures much lower than those of silica or any of the metallic oxides used.

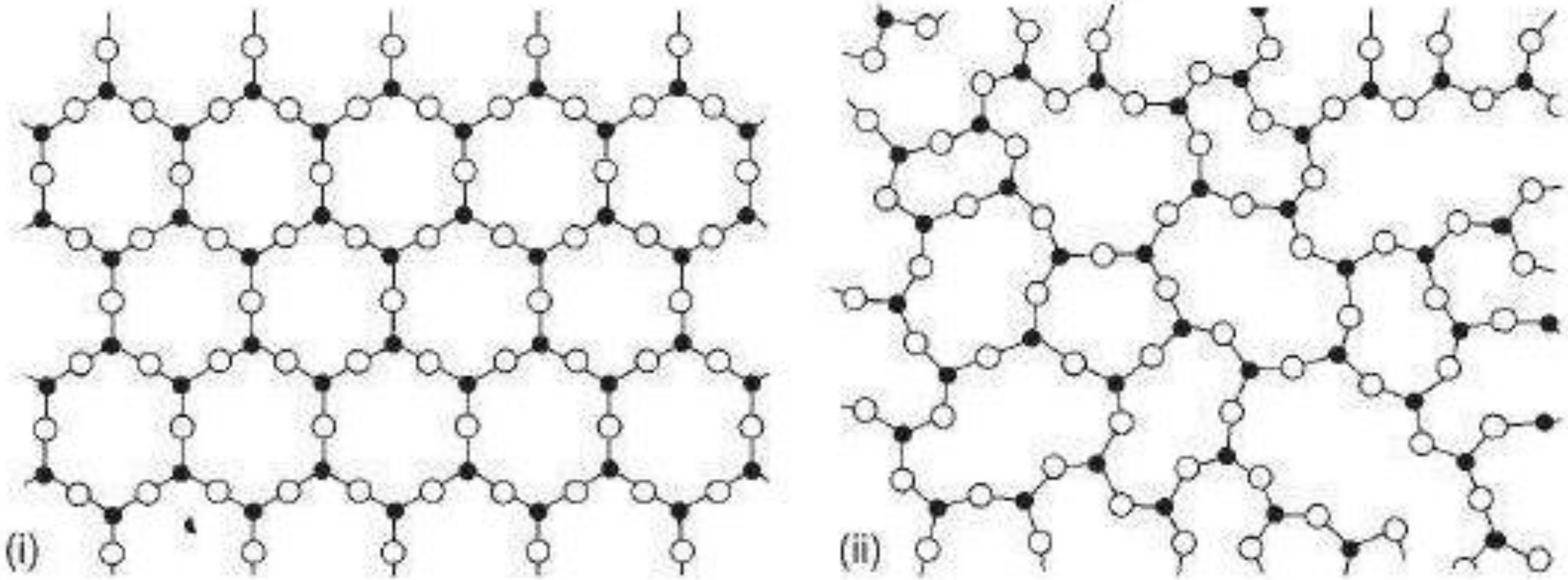


Figure 22.1 *This is a two-dimensional representation of the three-dimensional cage-like structure of silica in (i) crystalline silica (quartz) and (ii) silica glass. The fourth oxygen atom is 'vertically above' the silicon atom (Figure 21.1) and will be covalently bonded in turn to another silicon atom – and so on. In (i) there is a repetitive pattern throughout the orderly crystalline structure but in (ii) there is no repetitive pattern except inside the* $(SiO_4)_{-4}$ *units themselves – the structure is amorphous.*

Glass-transition temperature

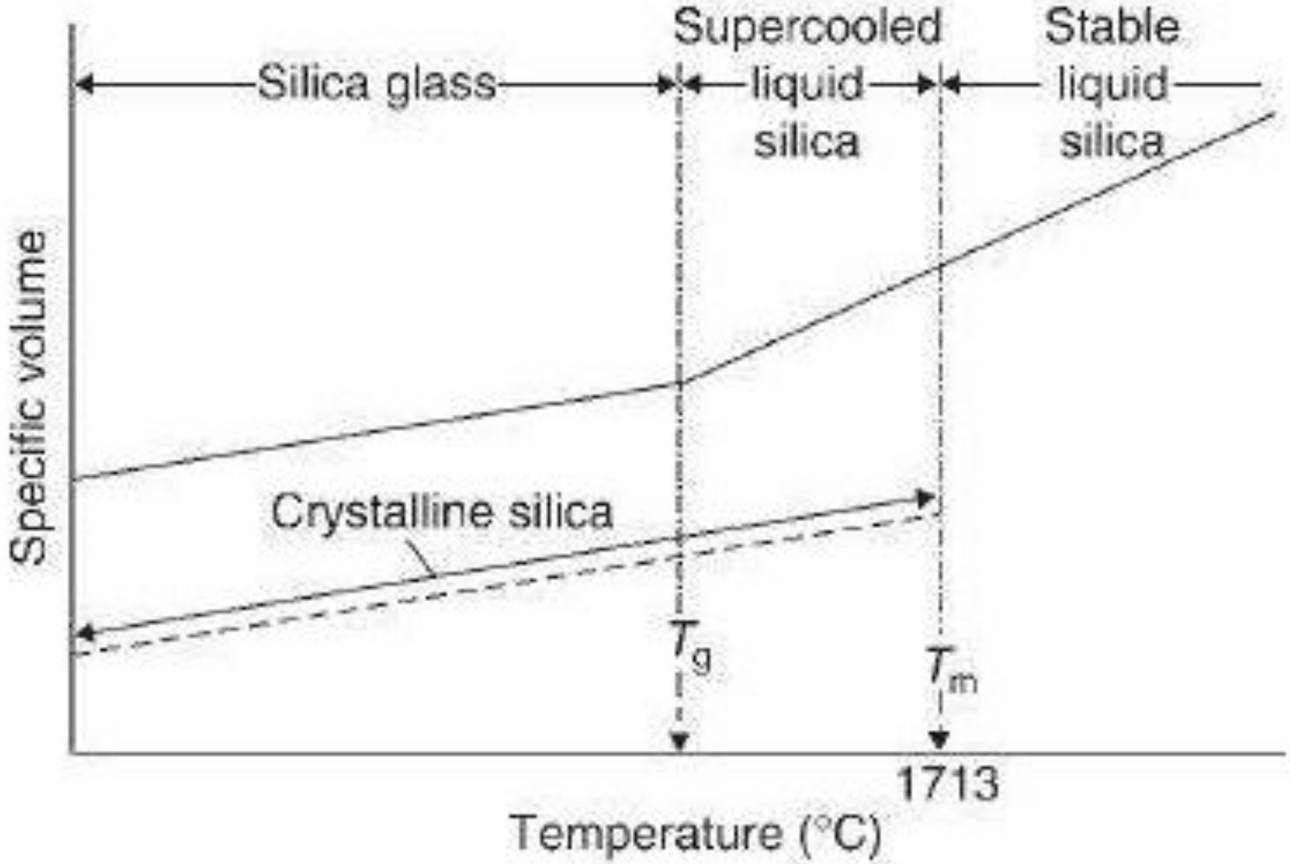
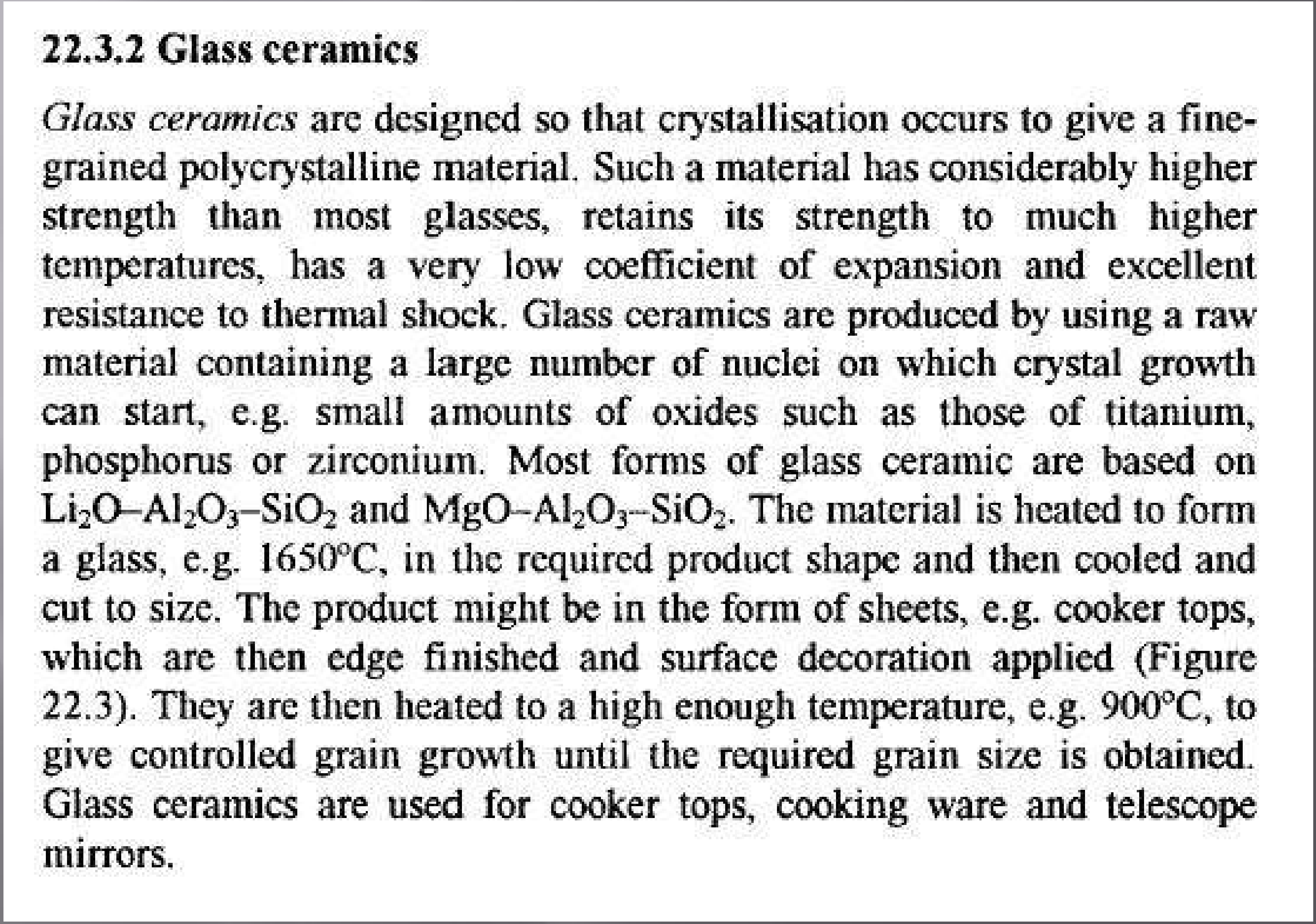


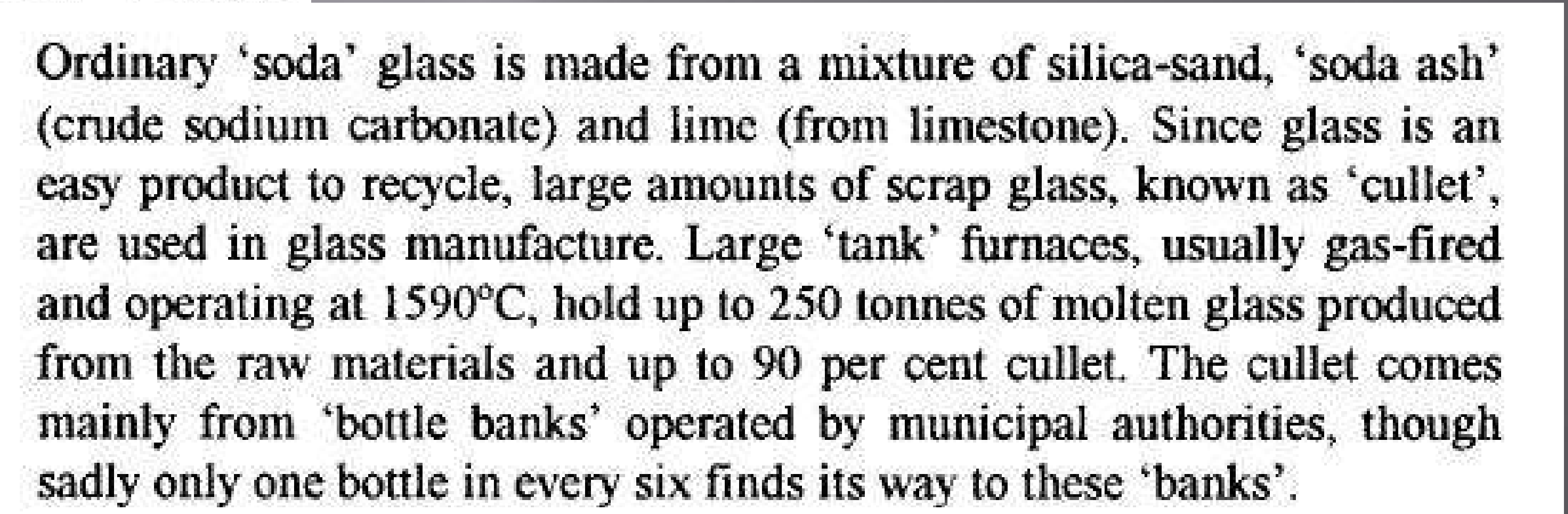
Figure 22.2 *The glass-transition temperature T_g of silica. The broken line indicates the crystallisation curve for SiO_2 which is cooled extremely slowly from above T_m.*



22.3.2 Glass ceramics

Glass ceramics are designed so that crystallisation occurs to give a fine-grained polycrystalline material. Such a material has considerably higher strength than most glasses, retains its strength to much higher temperatures, has a very low coefficient of expansion and excellent resistance to thermal shock. Glass ceramics are produced by using a raw material containing a large number of nuclei on which crystal growth can start, e.g. small amounts of oxides such as those of titanium, phosphorus or zirconium. Most forms of glass ceramic are based on $Li_2O–Al_2O_3–SiO_2$ and $MgO–Al_2O_3–SiO_2$. The material is heated to form a glass, e.g. 1650°C, in the required product shape and then cooled and cut to size. The product might be in the form of sheets, e.g. cooker tops, which are then edge finished and surface decoration applied (Figure 22.3). They are then heated to a high enough temperature, e.g. 900°C, to give controlled grain growth until the required grain size is obtained. Glass ceramics are used for cooker tops, cooking ware and telescope mirrors.

Glass manufacture



Ordinary 'soda' glass is made from a mixture of silica-sand, 'soda ash' (crude sodium carbonate) and lime (from limestone). Since glass is an easy product to recycle, large amounts of scrap glass, known as 'cullet', are used in glass manufacture. Large 'tank' furnaces, usually gas-fired and operating at 1590°C, hold up to 250 tonnes of molten glass produced from the raw materials and up to 90 per cent cullet. The cullet comes mainly from 'bottle banks' operated by municipal authorities, though sadly only one bottle in every six finds its way to these 'banks'.

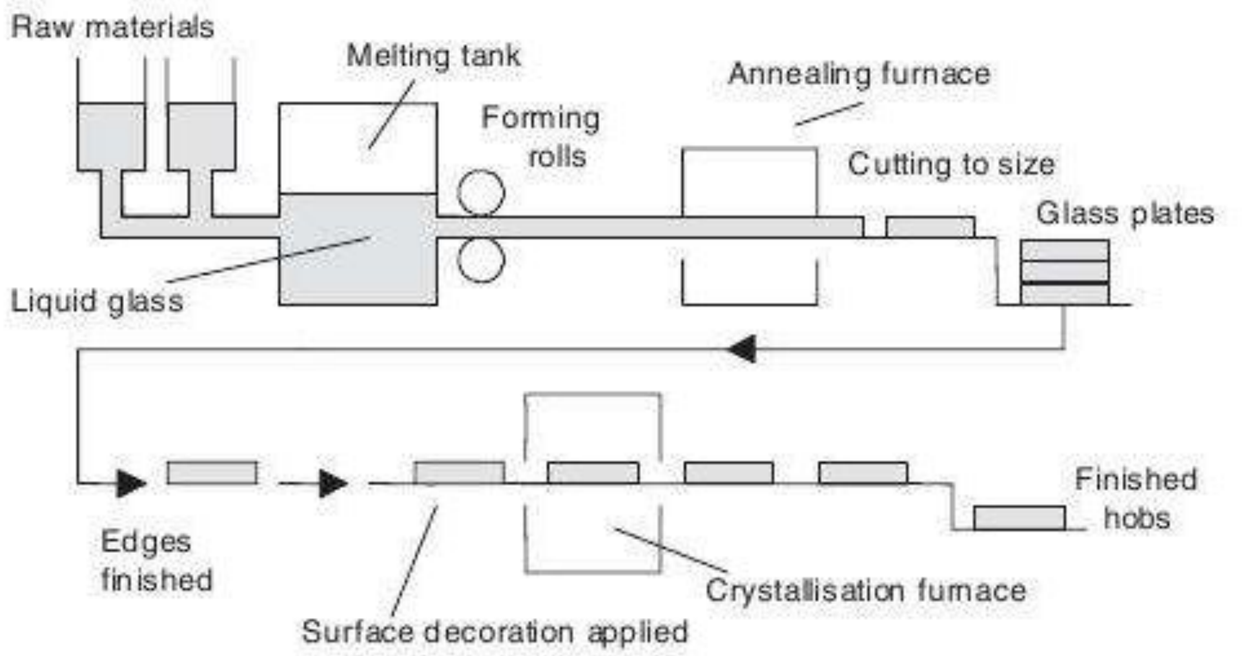
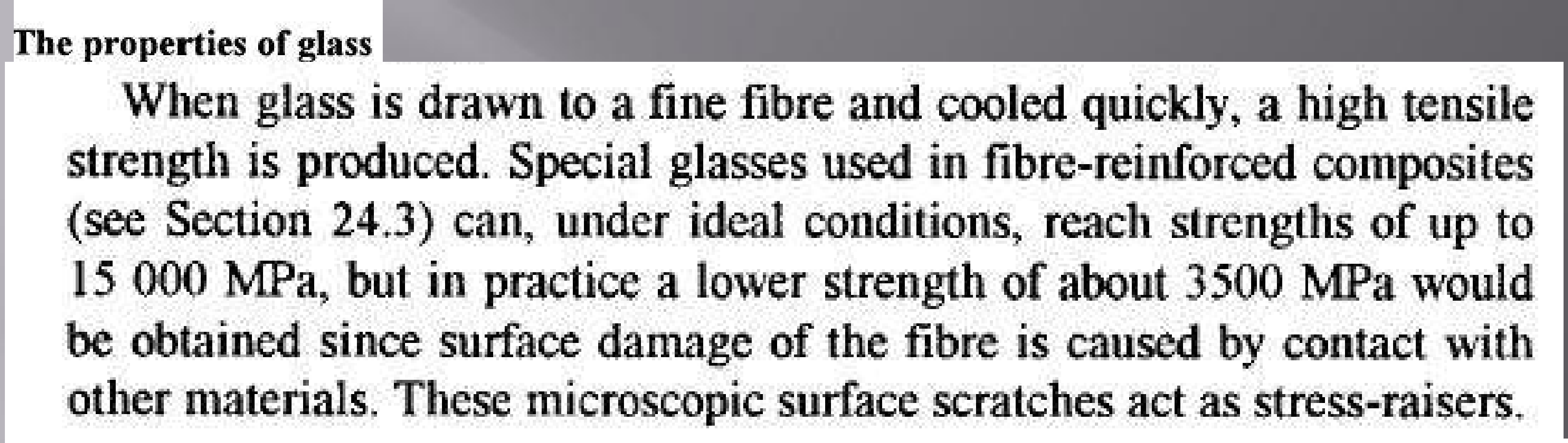


Figure 22.3 *The stages in the production of a ceramic glass cooker top.*



The properties of glass

When glass is drawn to a fine fibre and cooled quickly, a high tensile strength is produced. Special glasses used in fibre-reinforced composites (see Section 24.3) can, under ideal conditions, reach strengths of up to 15 000 MPa, but in practice a lower strength of about 3500 MPa would be obtained since surface damage of the fibre is caused by contact with other materials. These microscopic surface scratches act as stress-raisers.

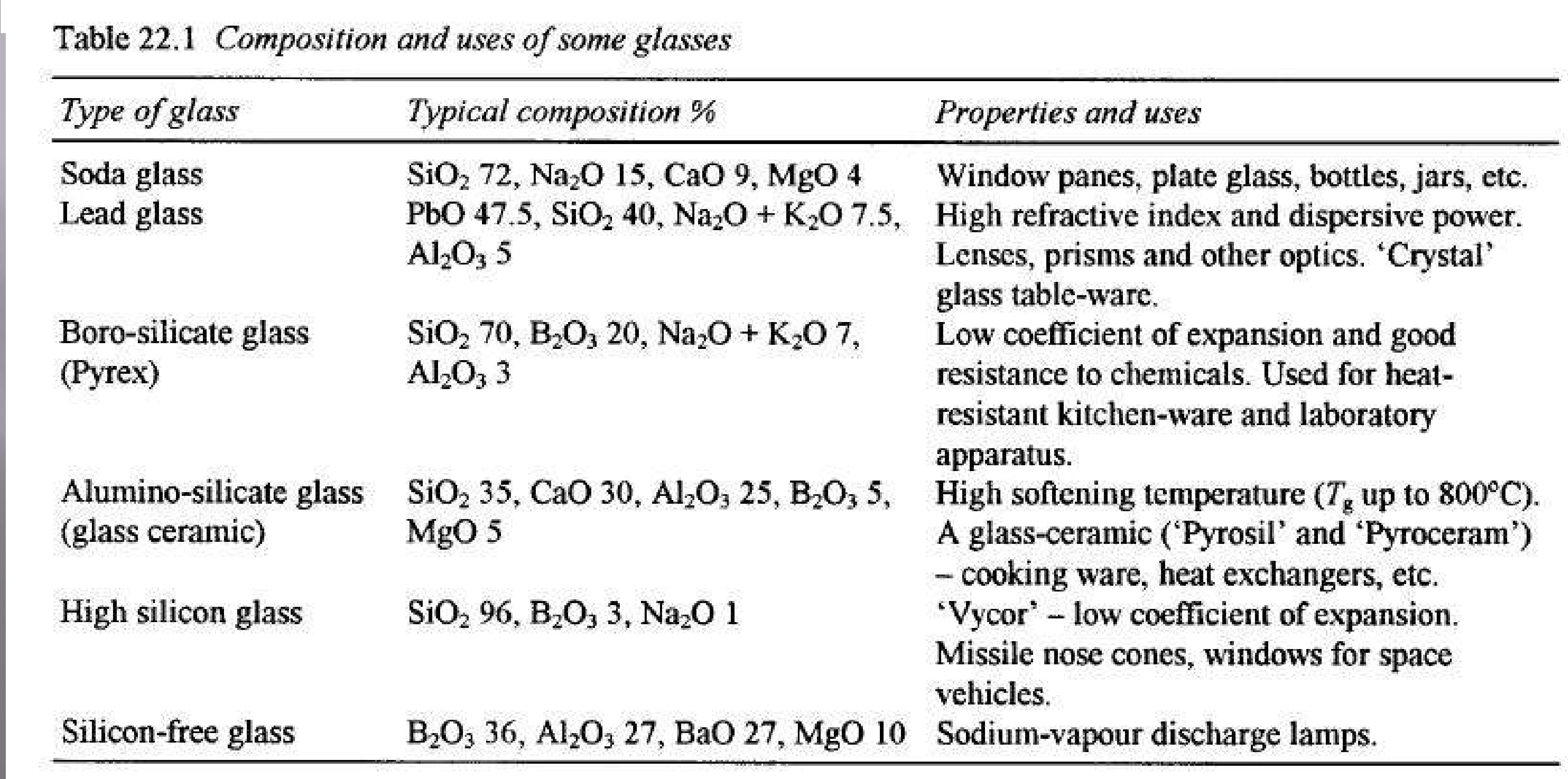
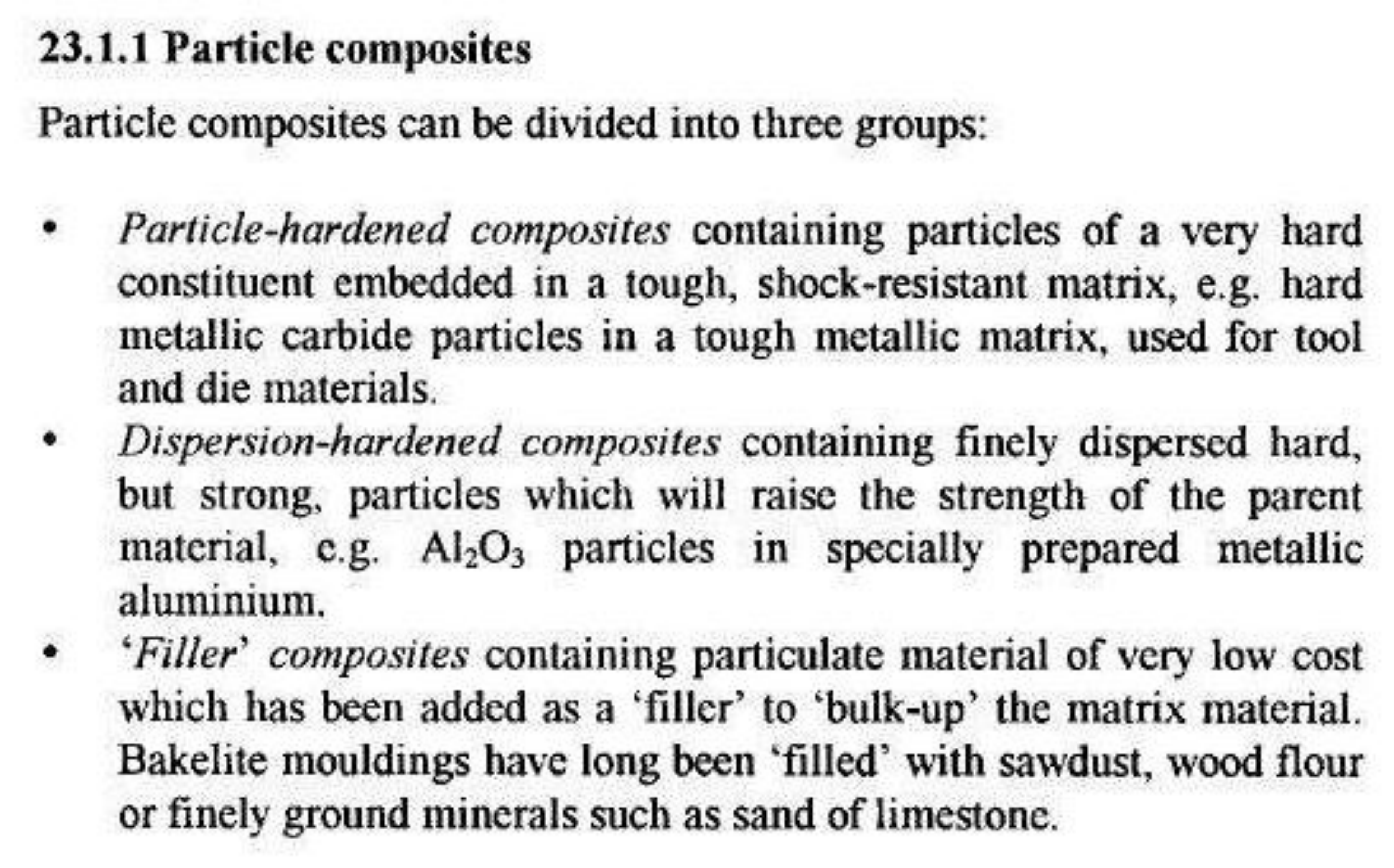


Table 22.1 *Composition and uses of some glasses*

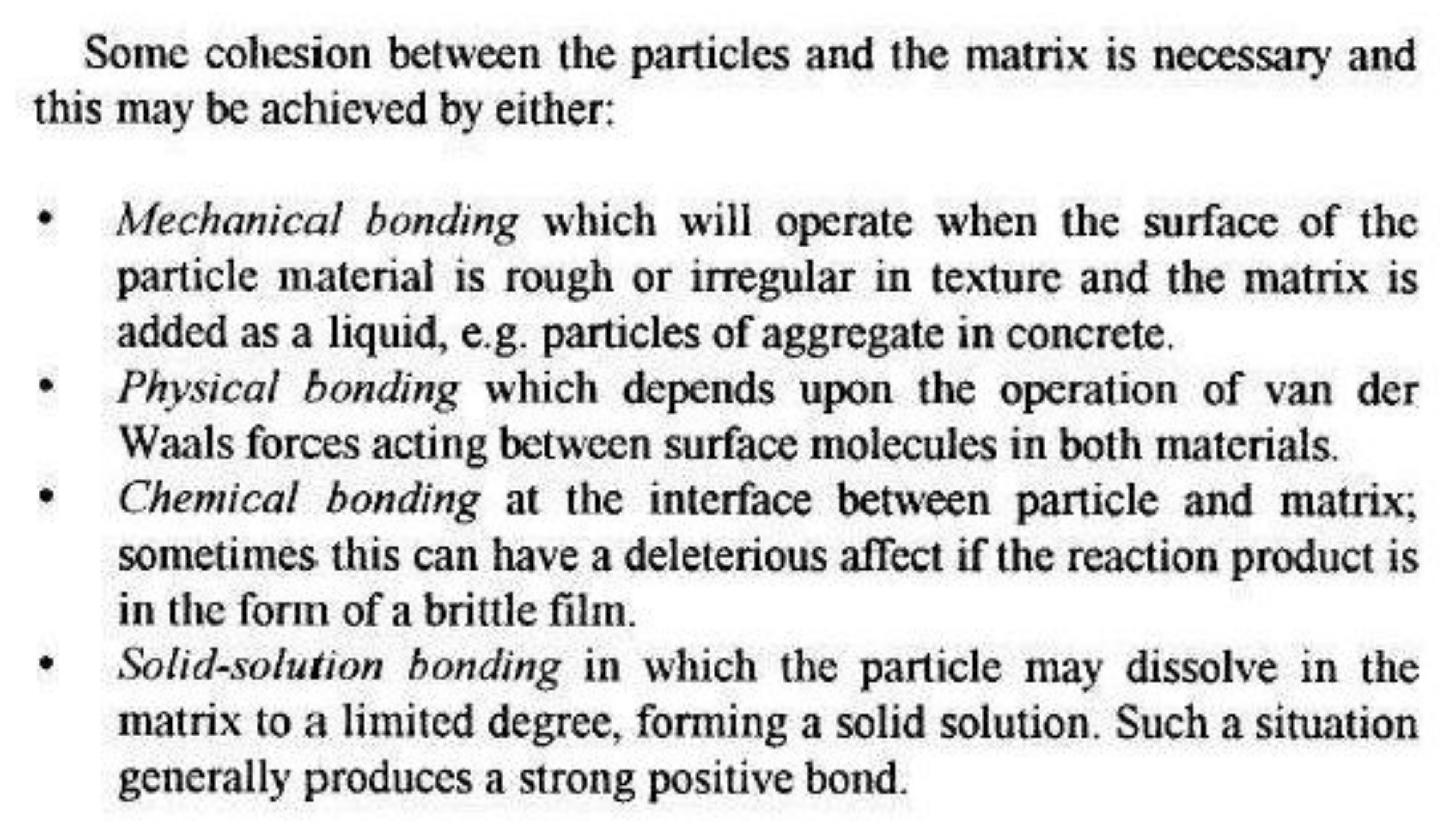
Type of glass	*Typical composition %*	*Properties and uses*
Soda glass	SiO_2 72, Na_2O 15, CaO 9, MgO 4	Window panes, plate glass, bottles, jars, etc.
Lead glass	PbO 47.5, SiO_2 40, Na_2O + K_2O 7.5, Al_2O_3 5	High refractive index and dispersive power. Lenses, prisms and other optics. 'Crystal' glass table-ware.
Boro-silicate glass (Pyrex)	SiO_2 70, B_2O_3 20, Na_2O + K_2O 7, Al_2O_3 3	Low coefficient of expansion and good resistance to chemicals. Used for heat-resistant kitchen-ware and laboratory apparatus.
Alumino-silicate glass (glass ceramic)	SiO_2 35, CaO 30, Al_2O_3 25, B_2O_3 5, MgO 5	High softening temperature (T_g up to 800°C). A glass-ceramic ('Pyrosil' and 'Pyroceram') – cooking ware, heat exchangers, etc.
High silicon glass	SiO_2 96, B_2O_3 3, Na_2O 1	'Vycor' – low coefficient of expansion. Missile nose cones, windows for space vehicles.
Silicon-free glass	B_2O_3 36, Al_2O_3 27, BaO 27, MgO 10	Sodium-vapour discharge lamps.



23.1.1 Particle composites

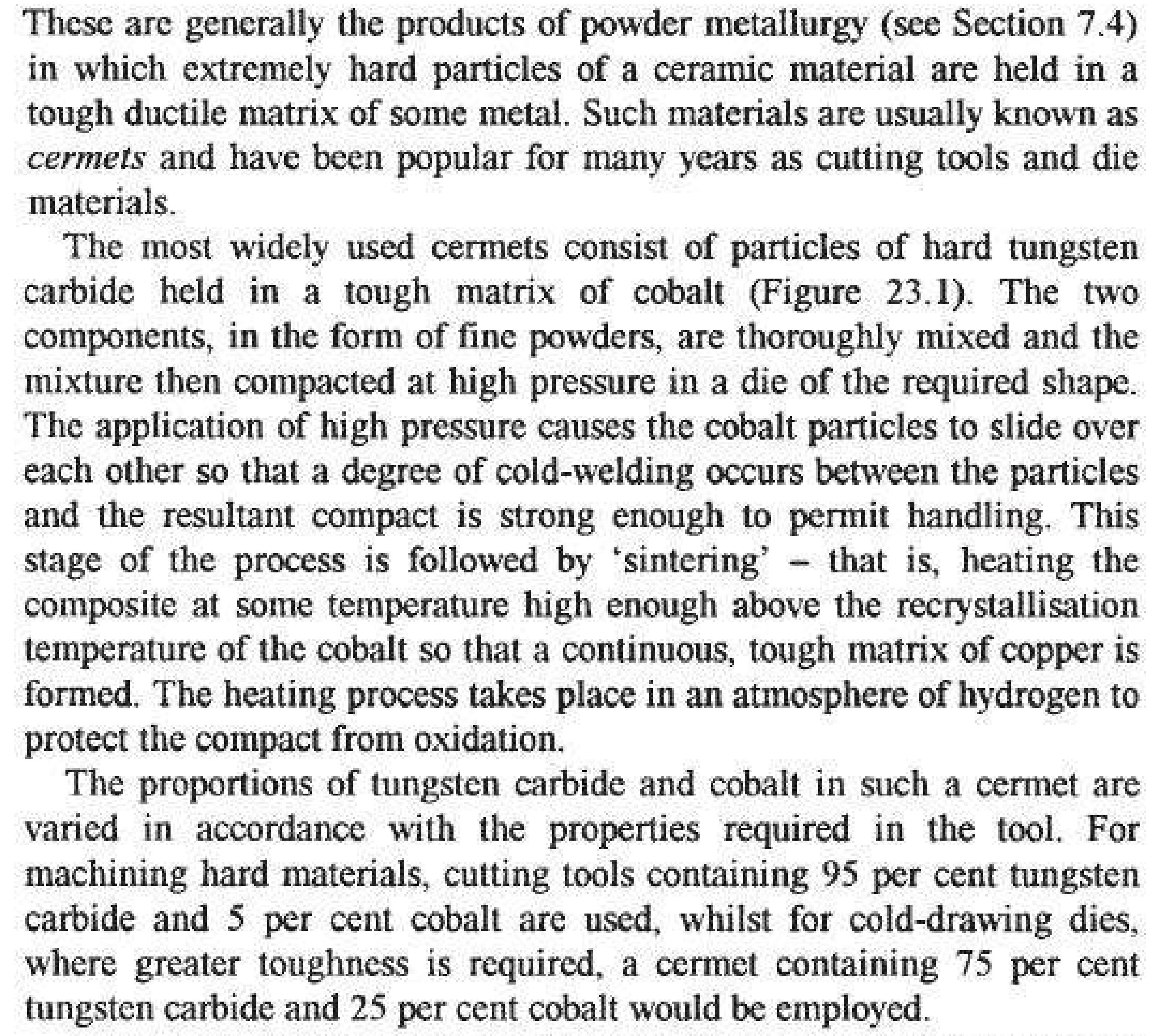
Particle composites can be divided into three groups:

- *Particle-hardened composites* containing particles of a very hard constituent embedded in a tough, shock-resistant matrix, e.g. hard metallic carbide particles in a tough metallic matrix, used for tool and die materials.
- *Dispersion-hardened composites* containing finely dispersed hard, but strong, particles which will raise the strength of the parent material, e.g. Al_2O_3 particles in specially prepared metallic aluminium.
- '*Filler*' *composites* containing particulate material of very low cost which has been added as a 'filler' to 'bulk-up' the matrix material. Bakelite mouldings have long been 'filled' with sawdust, wood flour or finely ground minerals such as sand of limestone.



Some cohesion between the particles and the matrix is necessary and this may be achieved by either:

- *Mechanical bonding* which will operate when the surface of the particle material is rough or irregular in texture and the matrix is added as a liquid, e.g. particles of aggregate in concrete.
- *Physical bonding* which depends upon the operation of van der Waals forces acting between surface molecules in both materials.
- *Chemical bonding* at the interface between particle and matrix; sometimes this can have a deleterious affect if the reaction product is in the form of a brittle film.
- *Solid-solution bonding* in which the particle may dissolve in the matrix to a limited degree, forming a solid solution. Such a situation generally produces a strong positive bond.



These are generally the products of powder metallurgy (see Section 7.4) in which extremely hard particles of a ceramic material are held in a tough ductile matrix of some metal. Such materials are usually known as *cermets* and have been popular for many years as cutting tools and die materials.

The most widely used cermets consist of particles of hard tungsten carbide held in a tough matrix of cobalt (Figure 23.1). The two components, in the form of fine powders, are thoroughly mixed and the mixture then compacted at high pressure in a die of the required shape. The application of high pressure causes the cobalt particles to slide over each other so that a degree of cold-welding occurs between the particles and the resultant compact is strong enough to permit handling. This stage of the process is followed by 'sintering' – that is, heating the composite at some temperature high enough above the recrystallisation temperature of the cobalt so that a continuous, tough matrix of copper is formed. The heating process takes place in an atmosphere of hydrogen to protect the compact from oxidation.

The proportions of tungsten carbide and cobalt in such a cermet are varied in accordance with the properties required in the tool. For machining hard materials, cutting tools containing 95 per cent tungsten carbide and 5 per cent cobalt are used, whilst for cold-drawing dies, where greater toughness is required, a cermet containing 75 per cent tungsten carbide and 25 per cent cobalt would be employed.

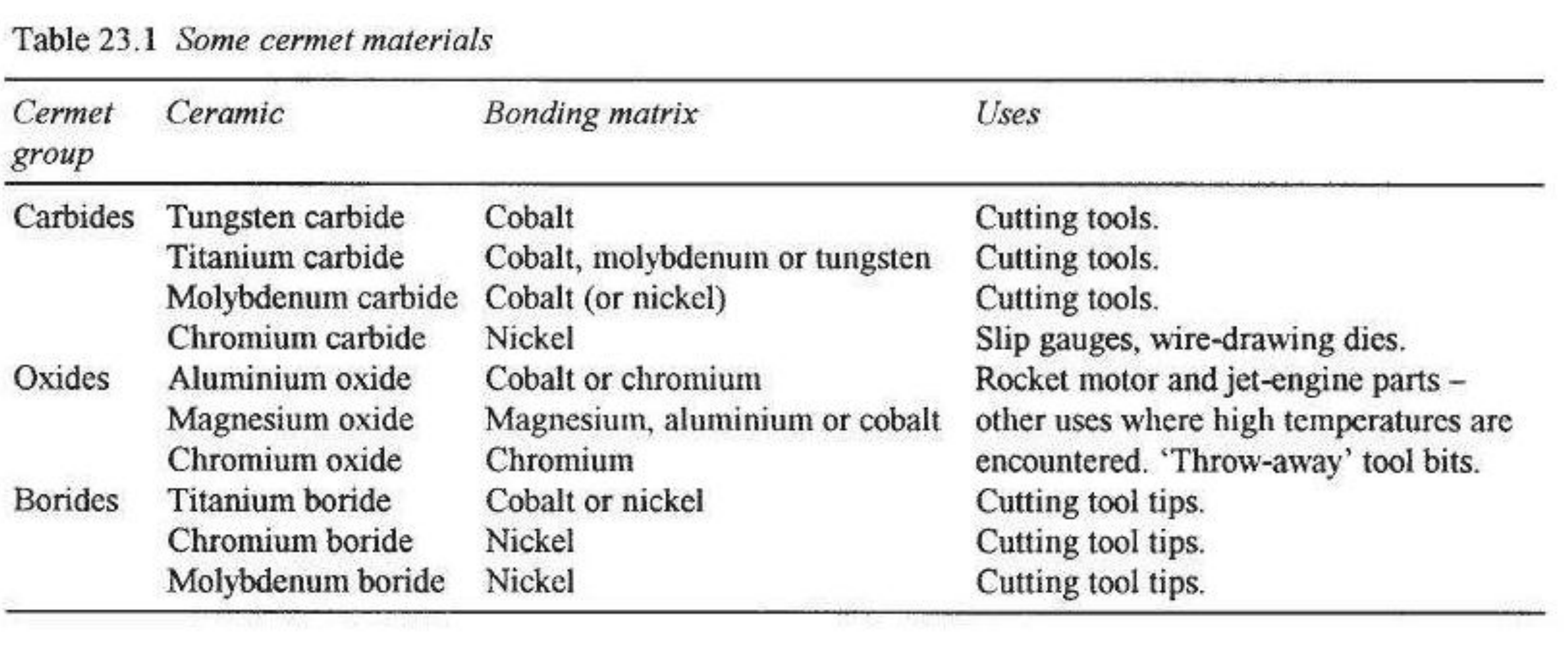


Table 23.1 *Some cermet materials*

Cermet group	*Ceramic*	*Bonding matrix*	*Uses*
Carbides	Tungsten carbide	Cobalt	Cutting tools.
	Titanium carbide	Cobalt, molybdenum or tungsten	Cutting tools.
	Molybdenum carbide	Cobalt (or nickel)	Cutting tools.
	Chromium carbide	Nickel	Slip gauges, wire-drawing dies.
Oxides	Aluminium oxide	Cobalt or chromium	Rocket motor and jet-engine parts – other uses where high temperatures are encountered. 'Throw-away' tool bits.
	Magnesium oxide	Magnesium, aluminium or cobalt	
	Chromium oxide	Chromium	
Borides	Titanium boride	Cobalt or nickel	Cutting tool tips.
	Chromium boride	Nickel	Cutting tool tips.
	Molybdenum boride	Nickel	Cutting tool tips.

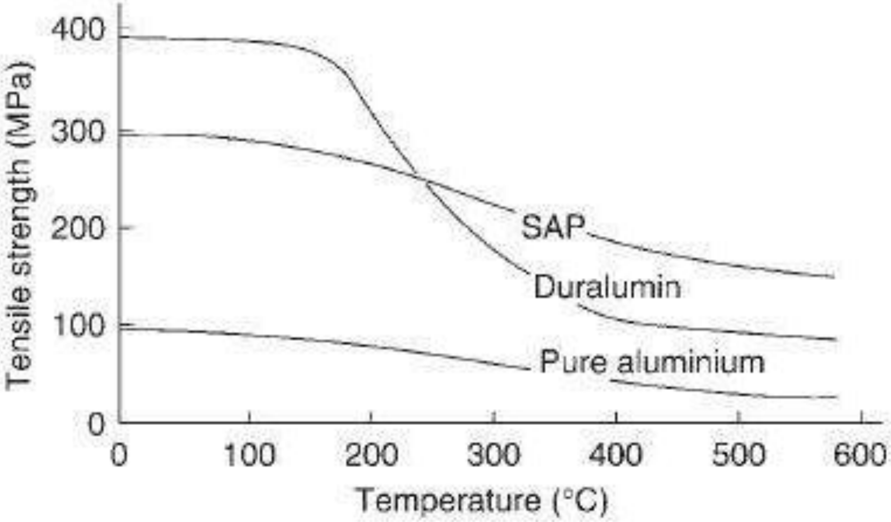
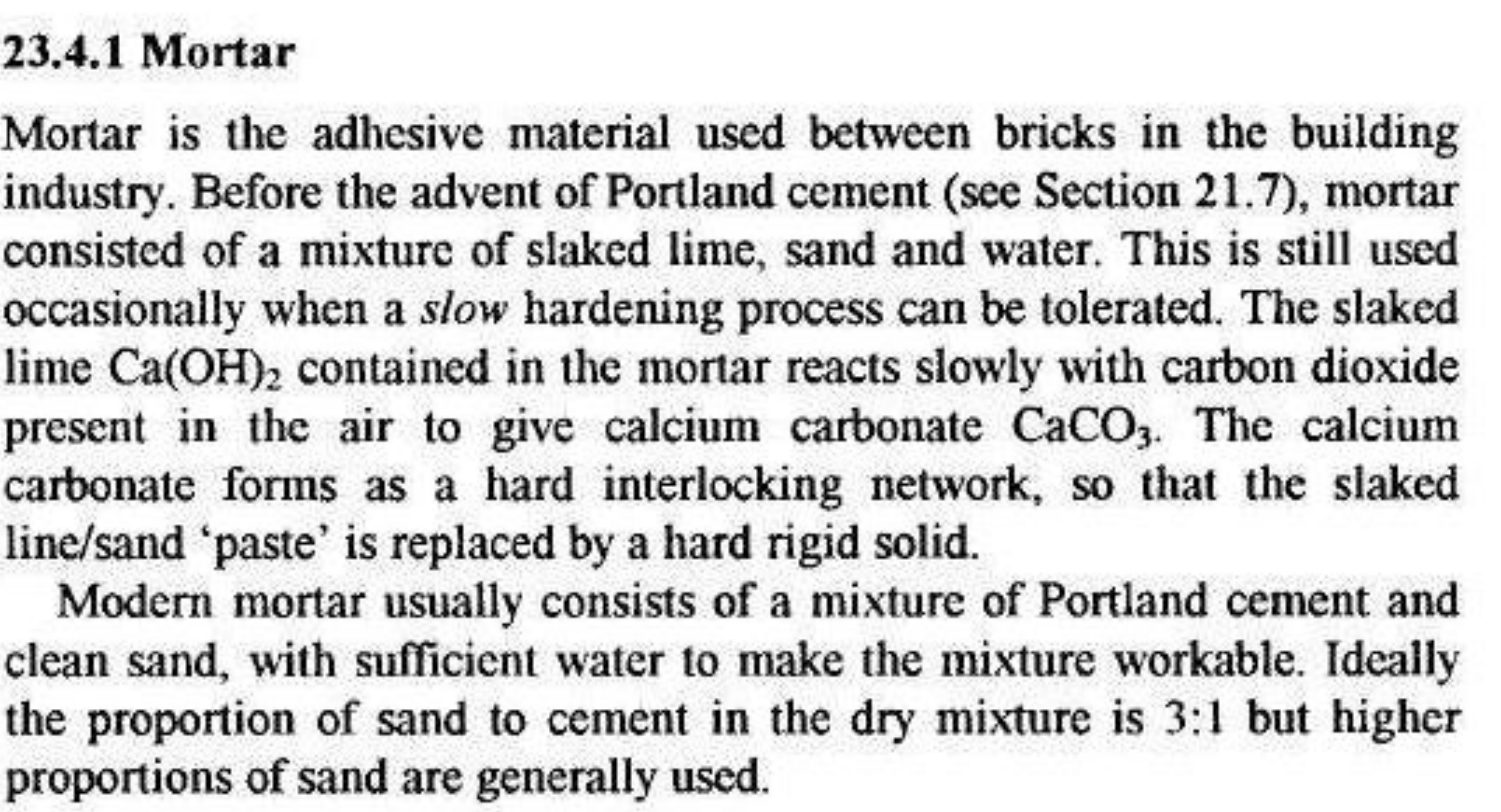


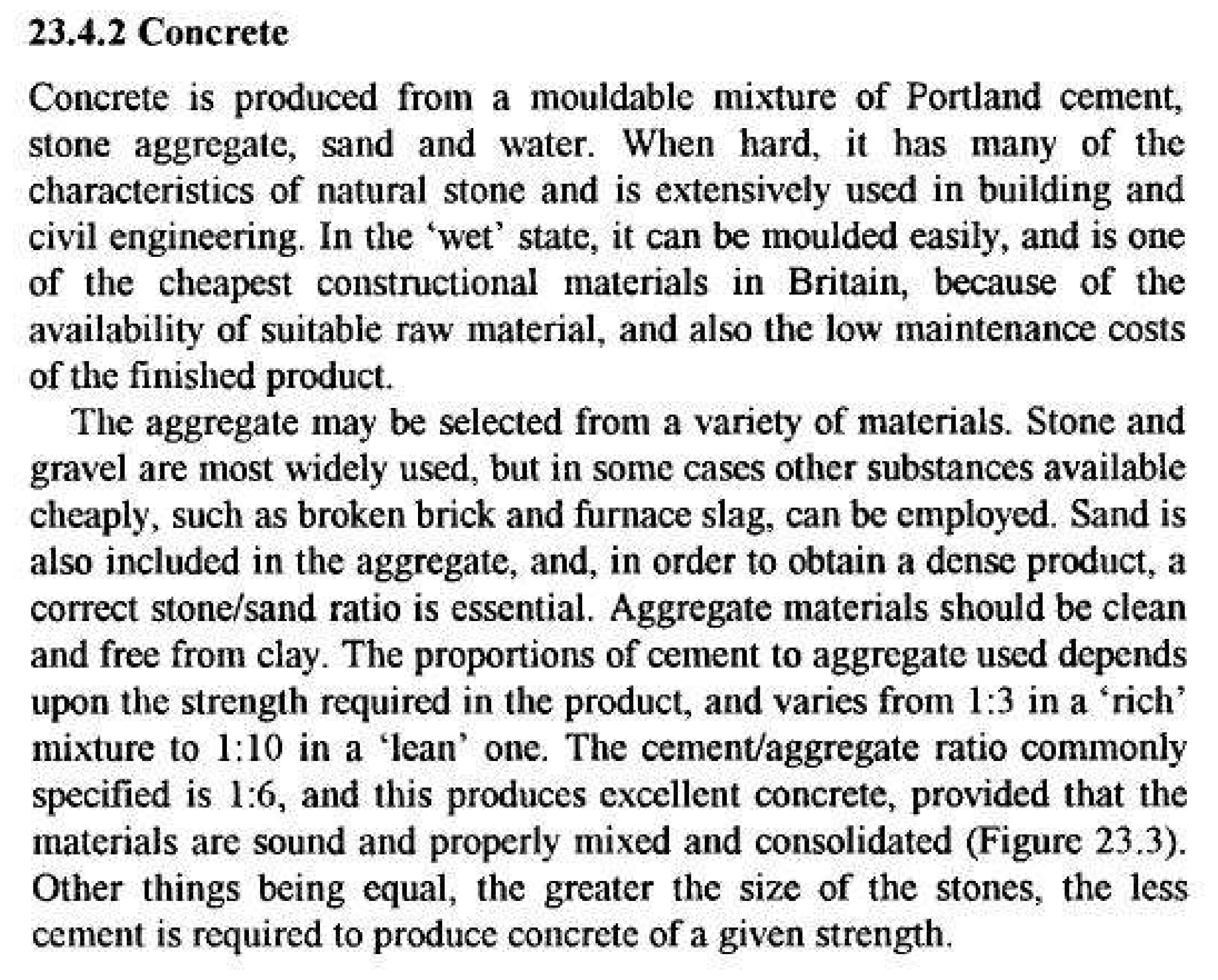
Figure 23.2 *The relationship between tensile strength and temperature for duralumin, SAP and pure aluminium.*



23.4.1 Mortar

Mortar is the adhesive material used between bricks in the building industry. Before the advent of Portland cement (see Section 21.7), mortar consisted of a mixture of slaked lime, sand and water. This is still used occasionally when a *slow* hardening process can be tolerated. The slaked lime $Ca(OH)_2$ contained in the mortar reacts slowly with carbon dioxide present in the air to give calcium carbonate $CaCO_3$. The calcium carbonate forms as a hard interlocking network, so that the slaked line/sand 'paste' is replaced by a hard rigid solid.

Modern mortar usually consists of a mixture of Portland cement and clean sand, with sufficient water to make the mixture workable. Ideally the proportion of sand to cement in the dry mixture is 3:1 but higher proportions of sand are generally used.



23.4.2 Concrete

Concrete is produced from a mouldable mixture of Portland cement, stone aggregate, sand and water. When hard, it has many of the characteristics of natural stone and is extensively used in building and civil engineering. In the 'wet' state, it can be moulded easily, and is one of the cheapest constructional materials in Britain, because of the availability of suitable raw material, and also the low maintenance costs of the finished product.

The aggregate may be selected from a variety of materials. Stone and gravel are most widely used, but in some cases other substances available cheaply, such as broken brick and furnace slag, can be employed. Sand is also included in the aggregate, and, in order to obtain a dense product, a correct stone/sand ratio is essential. Aggregate materials should be clean and free from clay. The proportions of cement to aggregate used depends upon the strength required in the product, and varies from 1:3 in a 'rich' mixture to 1:10 in a 'lean' one. The cement/aggregate ratio commonly specified is 1:6, and this produces excellent concrete, provided that the materials are sound and properly mixed and consolidated (Figure 23.3). Other things being equal, the greater the size of the stones, the less cement is required to produce concrete of a given strength.

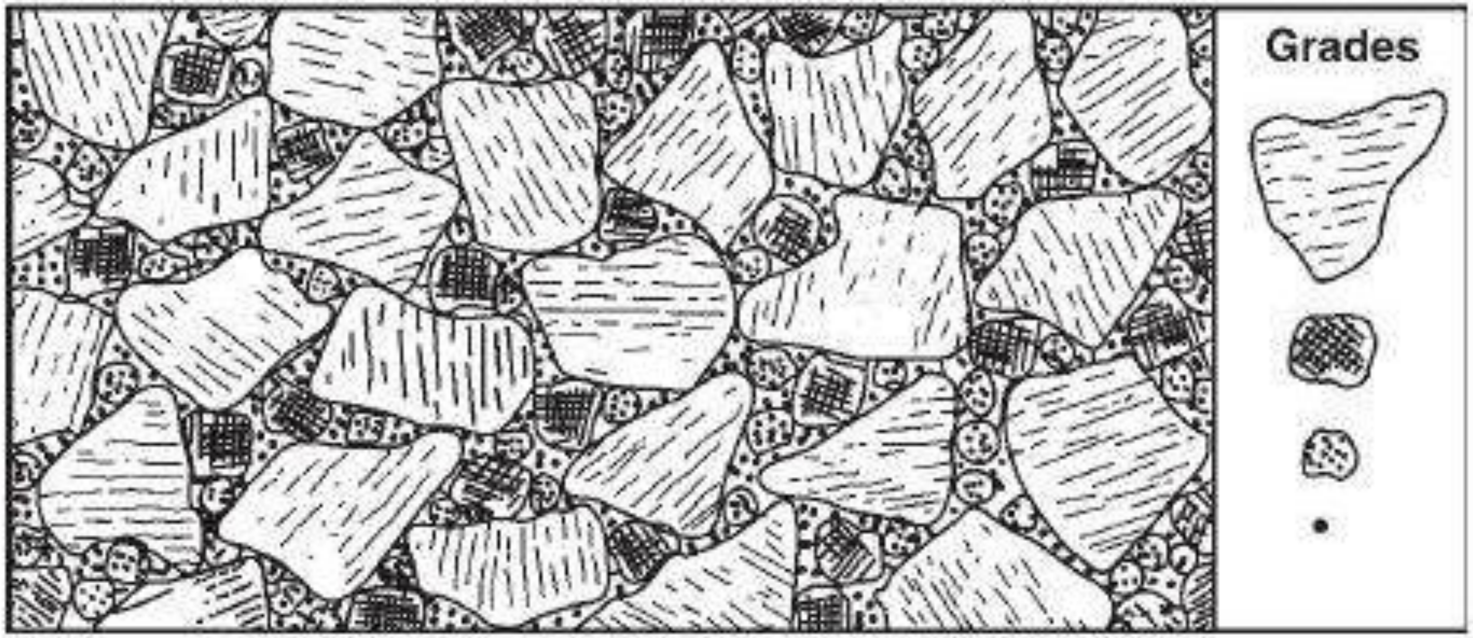


Figure 23.3 *A satisfactory concrete structure: the aggregate consists of different grades (or sizes) in the correct proportions so that the smaller particles fill the spaces between the larger ones, whilst particles of sand occupy the remaining gaps, and all are held together by a film of cement.*

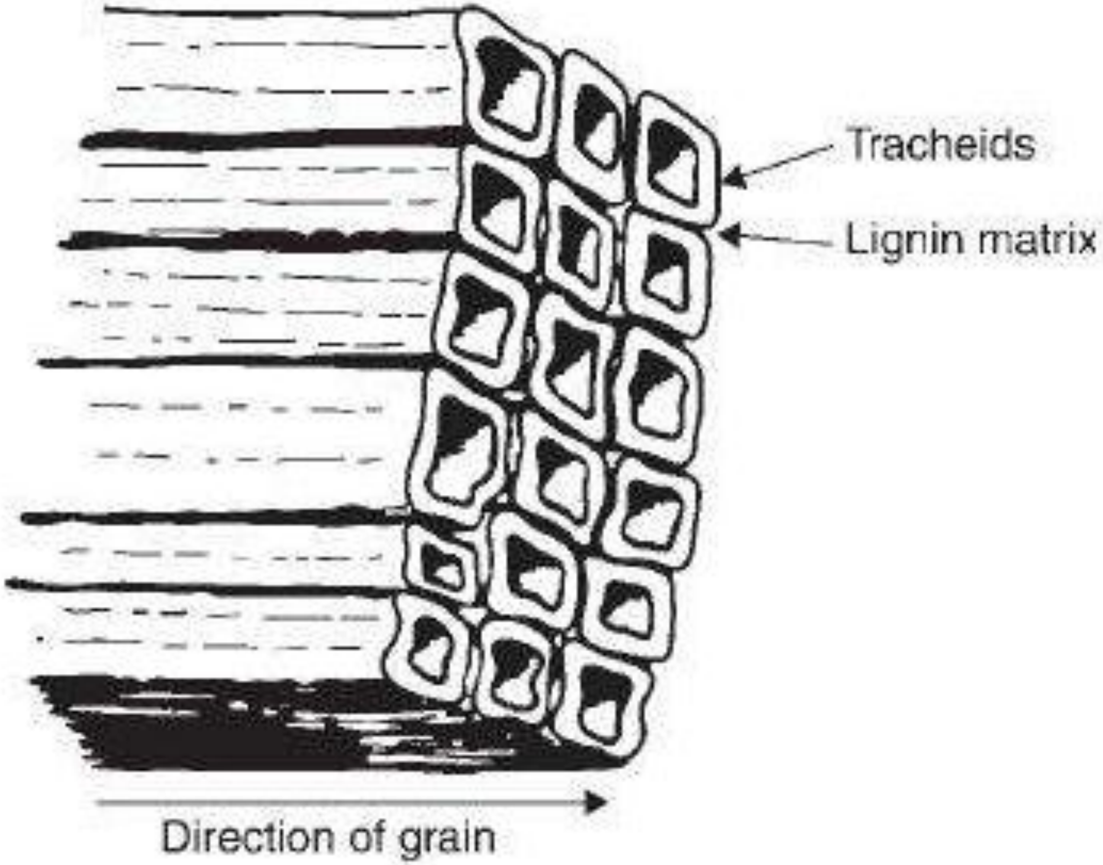
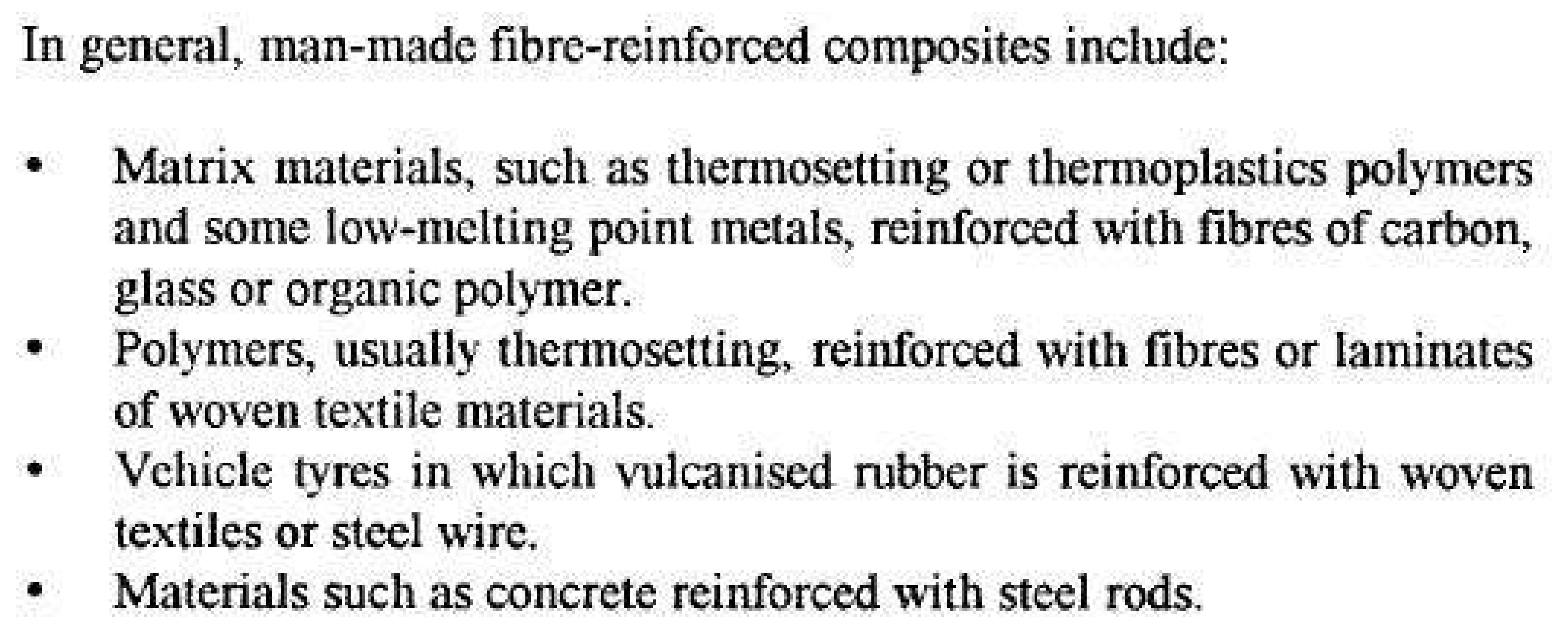
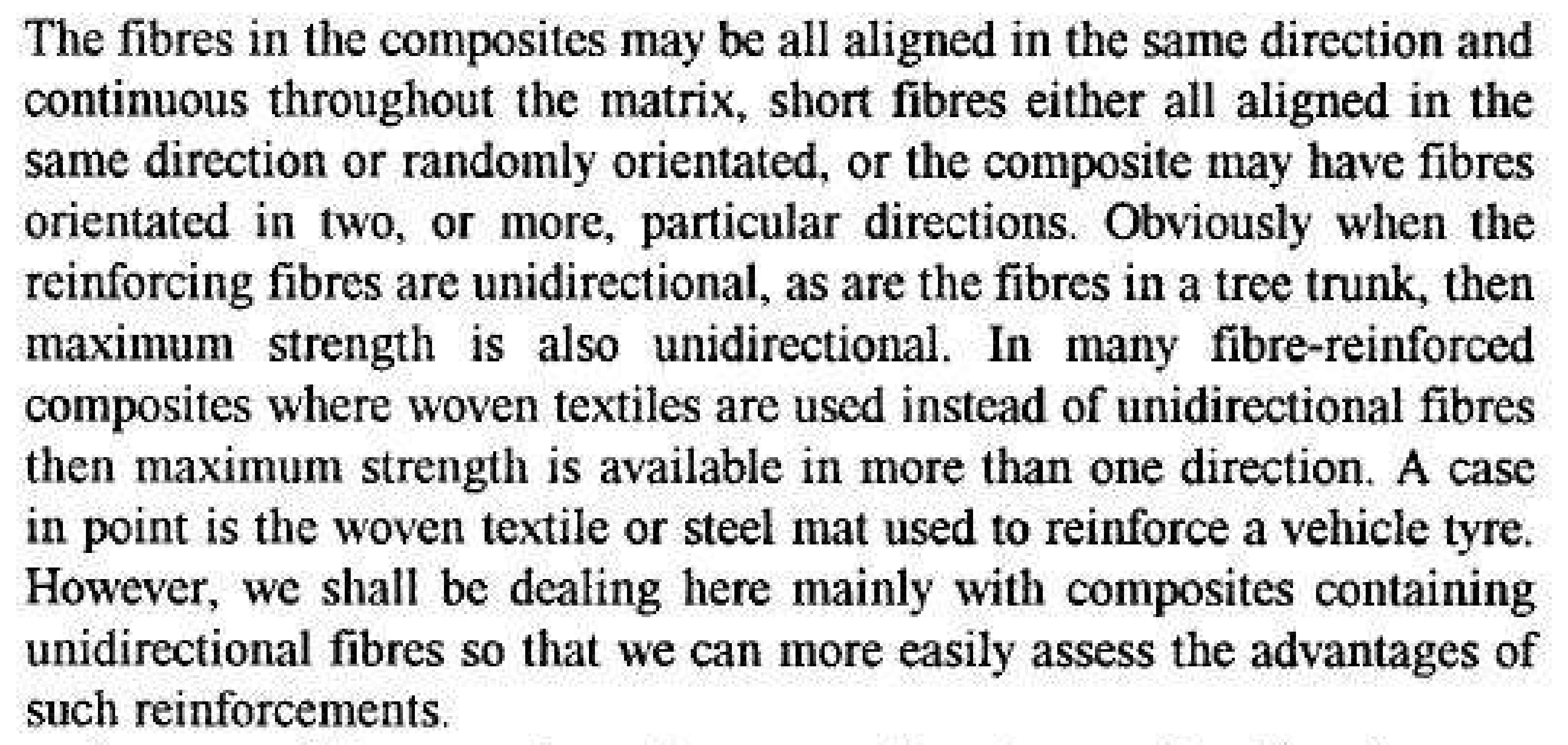


Figure 24.1 *The structure of wood – the cellulose fibres (tracheids) are cemented in a matrix of lignin resin.*

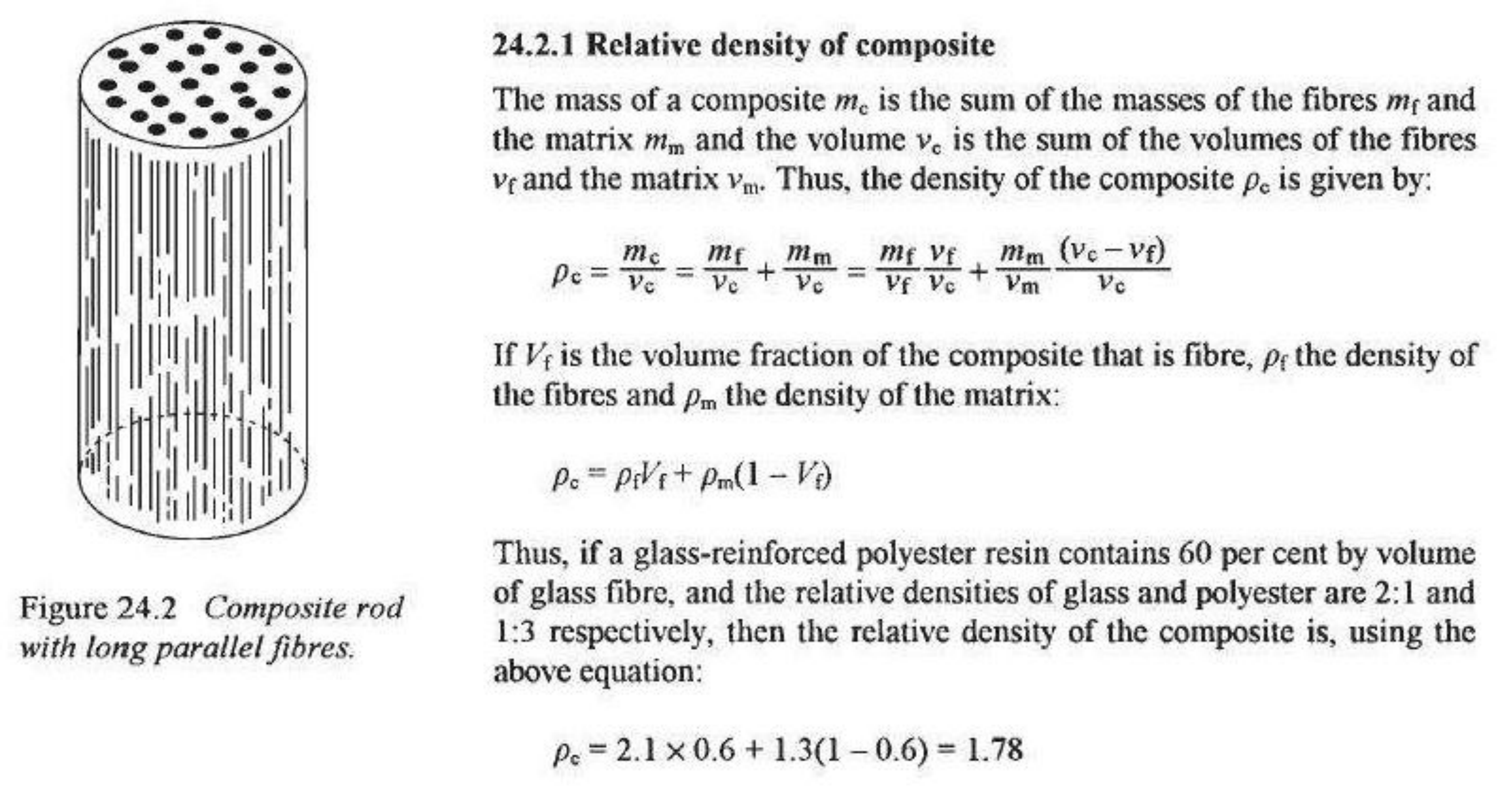


In general, man-made fibre-reinforced composites include:

- Matrix materials, such as thermosetting or thermoplastics polymers and some low-melting point metals, reinforced with fibres of carbon, glass or organic polymer.
- Polymers, usually thermosetting, reinforced with fibres or laminates of woven textile materials.
- Vehicle tyres in which vulcanised rubber is reinforced with woven textiles or steel wire.
- Materials such as concrete reinforced with steel rods.



The fibres in the composites may be all aligned in the same direction and continuous throughout the matrix, short fibres either all aligned in the same direction or randomly orientated, or the composite may have fibres orientated in two, or more, particular directions. Obviously when the reinforcing fibres are unidirectional, as are the fibres in a tree trunk, then maximum strength is also unidirectional. In many fibre-reinforced composites where woven textiles are used instead of unidirectional fibres then maximum strength is available in more than one direction. A case in point is the woven textile or steel mat used to reinforce a vehicle tyre. However, we shall be dealing here mainly with composites containing unidirectional fibres so that we can more easily assess the advantages of such reinforcements.



24.2.1 Relative density of composite

The mass of a composite m_c is the sum of the masses of the fibres m_f and the matrix m_m and the volume v_c is the sum of the volumes of the fibres v_f and the matrix v_m. Thus, the density of the composite ρ_c is given by:

$$\rho_c = \frac{m_c}{v_c} = \frac{m_f}{v_c} + \frac{m_m}{v_c} = \frac{m_f}{v_f}\frac{v_f}{v_c} + \frac{m_m}{v_m}\frac{(v_c - v_f)}{v_c}$$

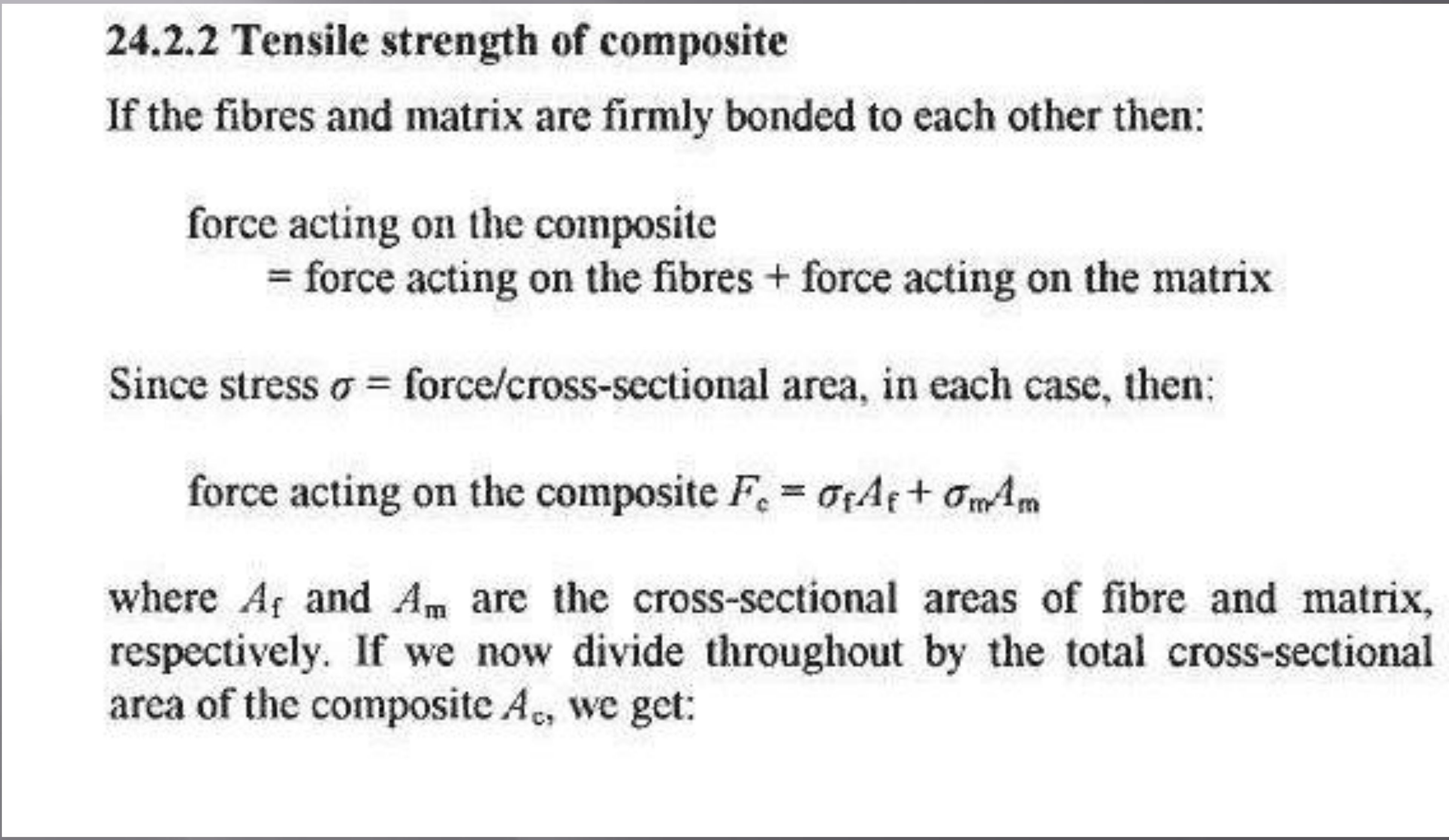
If V_f is the volume fraction of the composite that is fibre, ρ_f the density of the fibres and ρ_m the density of the matrix:

$$\rho_c = \rho_f V_f + \rho_m(1 - V_f)$$

Thus, if a glass-reinforced polyester resin contains 60 per cent by volume of glass fibre, and the relative densities of glass and polyester are 2:1 and 1:3 respectively, then the relative density of the composite is, using the above equation:

$$\rho_c = 2.1 \times 0.6 + 1.3(1 - 0.6) = 1.78$$

Figure 24.2 *Composite rod with long parallel fibres.*



24.2.2 Tensile strength of composite

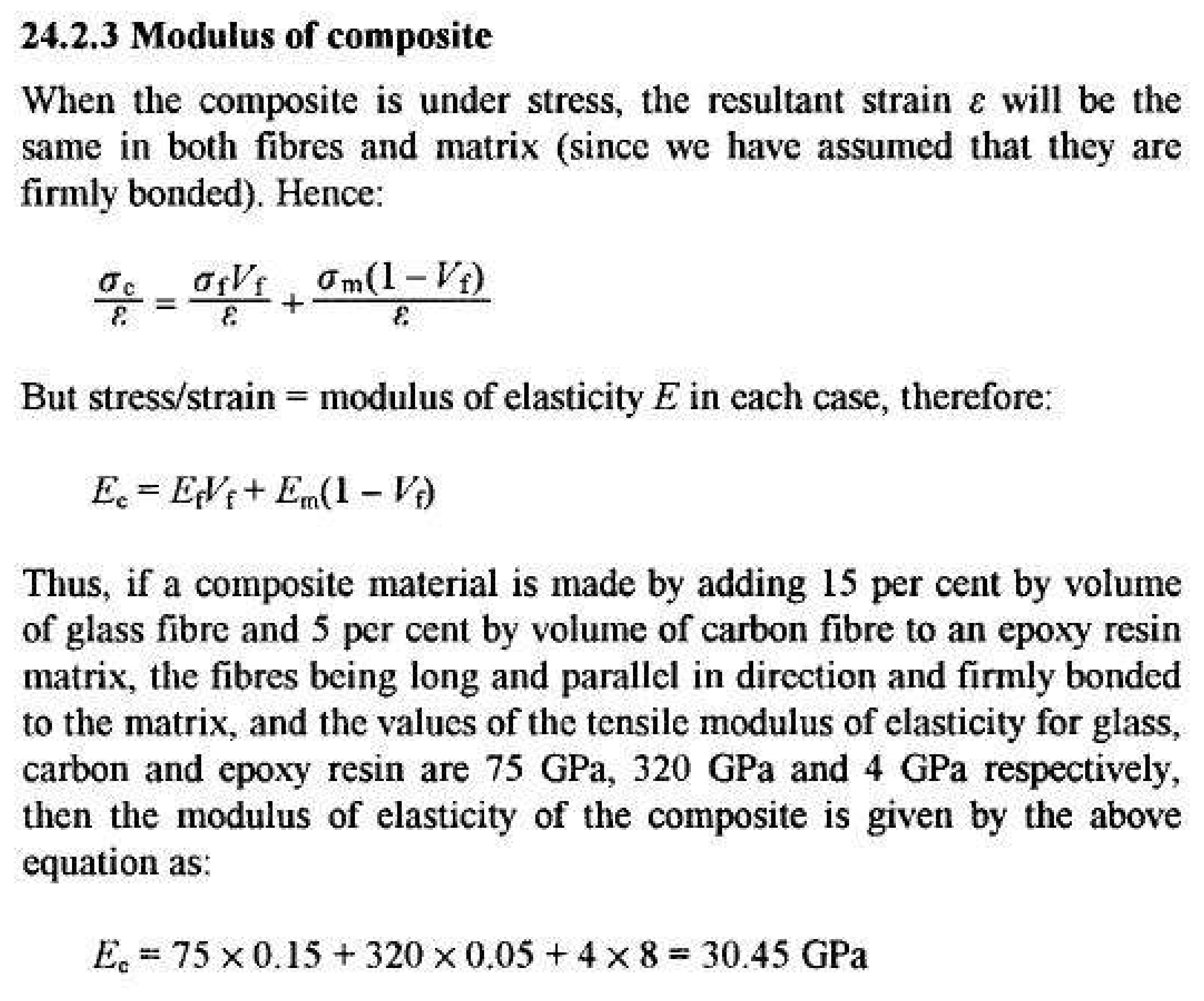
If the fibres and matrix are firmly bonded to each other then:

force acting on the composite
= force acting on the fibres + force acting on the matrix

Since stress σ = force/cross-sectional area, in each case, then:

force acting on the composite $F_c = \sigma_f A_f + \sigma_m A_m$

where A_f and A_m are the cross-sectional areas of fibre and matrix, respectively. If we now divide throughout by the total cross-sectional area of the composite A_c, we get:



24.2.3 Modulus of composite

When the composite is under stress, the resultant strain ε will be the same in both fibres and matrix (since we have assumed that they are firmly bonded). Hence:

$$\frac{\sigma_c}{\varepsilon} = \frac{\sigma_f V_f}{\varepsilon} + \frac{\sigma_m(1 - V_f)}{\varepsilon}$$

But stress/strain = modulus of elasticity E in each case, therefore:

$$E_c = E_f V_f + E_m(1 - V_f)$$

Thus, if a composite material is made by adding 15 per cent by volume of glass fibre and 5 per cent by volume of carbon fibre to an epoxy resin matrix, the fibres being long and parallel in direction and firmly bonded to the matrix, and the values of the tensile modulus of elasticity for glass, carbon and epoxy resin are 75 GPa, 320 GPa and 4 GPa respectively, then the modulus of elasticity of the composite is given by the above equation as:

$$E_c = 75 \times 0.15 + 320 \times 0.05 + 4 \times 8 = 30.45 \text{ GPa}$$

Fibres

Cold-setting resins strengthened by woven textile fibres, e.g. 'Tufnol', were developed many years ago for use in the electrical trades as tough panels with high electrical insulation properties, but glass fibre was the first man-made material to be used for reinforcement purposes to produce a strong lightweight material. Now a number of other man-made fibres, in particular carbon, boron, some ceramics and polymers, all possessing the necessary high strength, stiffness and low relative density, are in use. Research continues with the object of producing materials of increasingly high strength-to-weight ratio, i.e. high *specific strength*, for the aerospace industries and, since relative density is important, many fibres are made from compounds based on the elements boron, carbon, nitrogen, oxygen, aluminium and silicon – all elements with low atomic mass which often, though *not* inevitably, means that relative density is also low. Moreover, compounds based on these elements are likely to be covalently bonded – the strongest of chemical bonds – which is generally reflected in the mechanical strength of the compound.

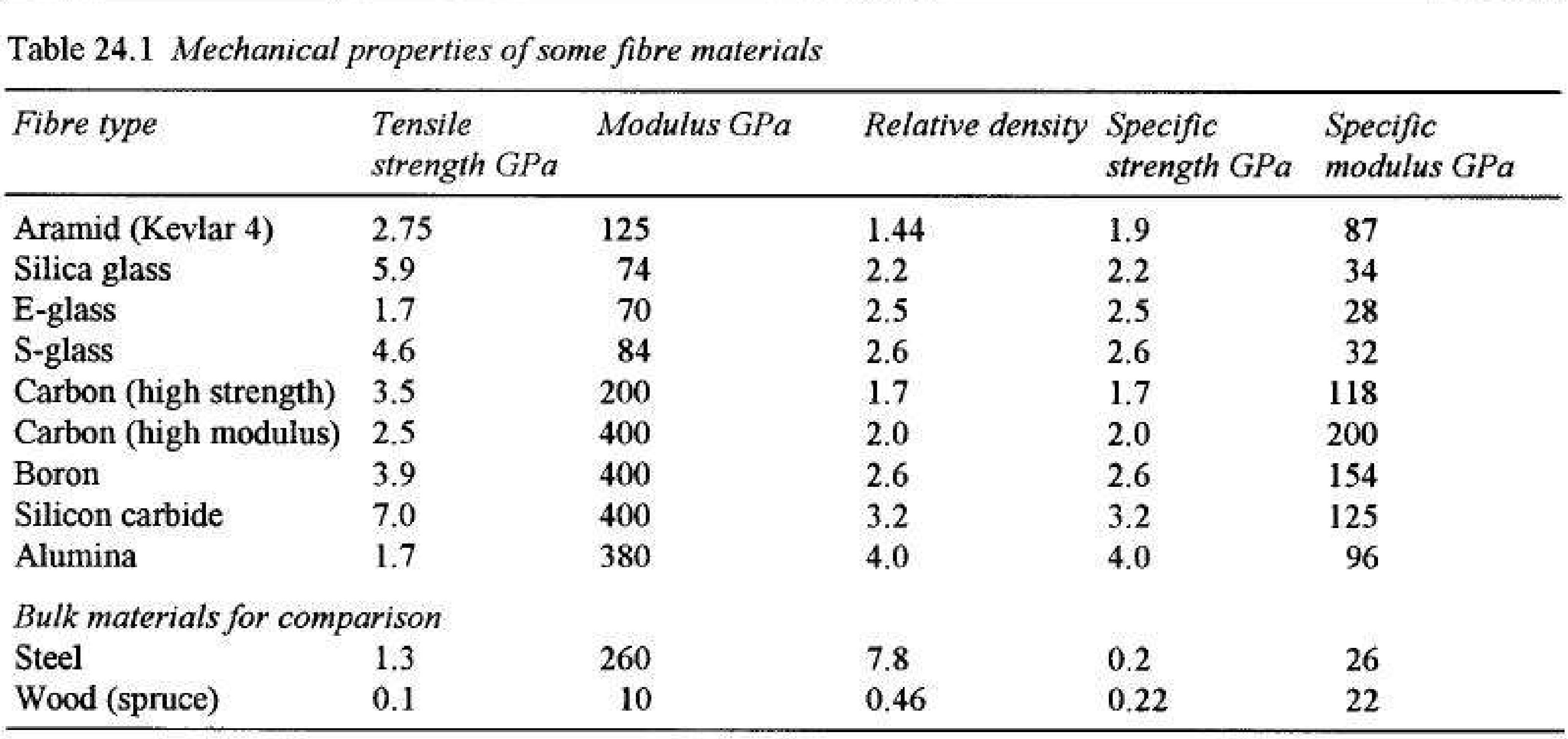
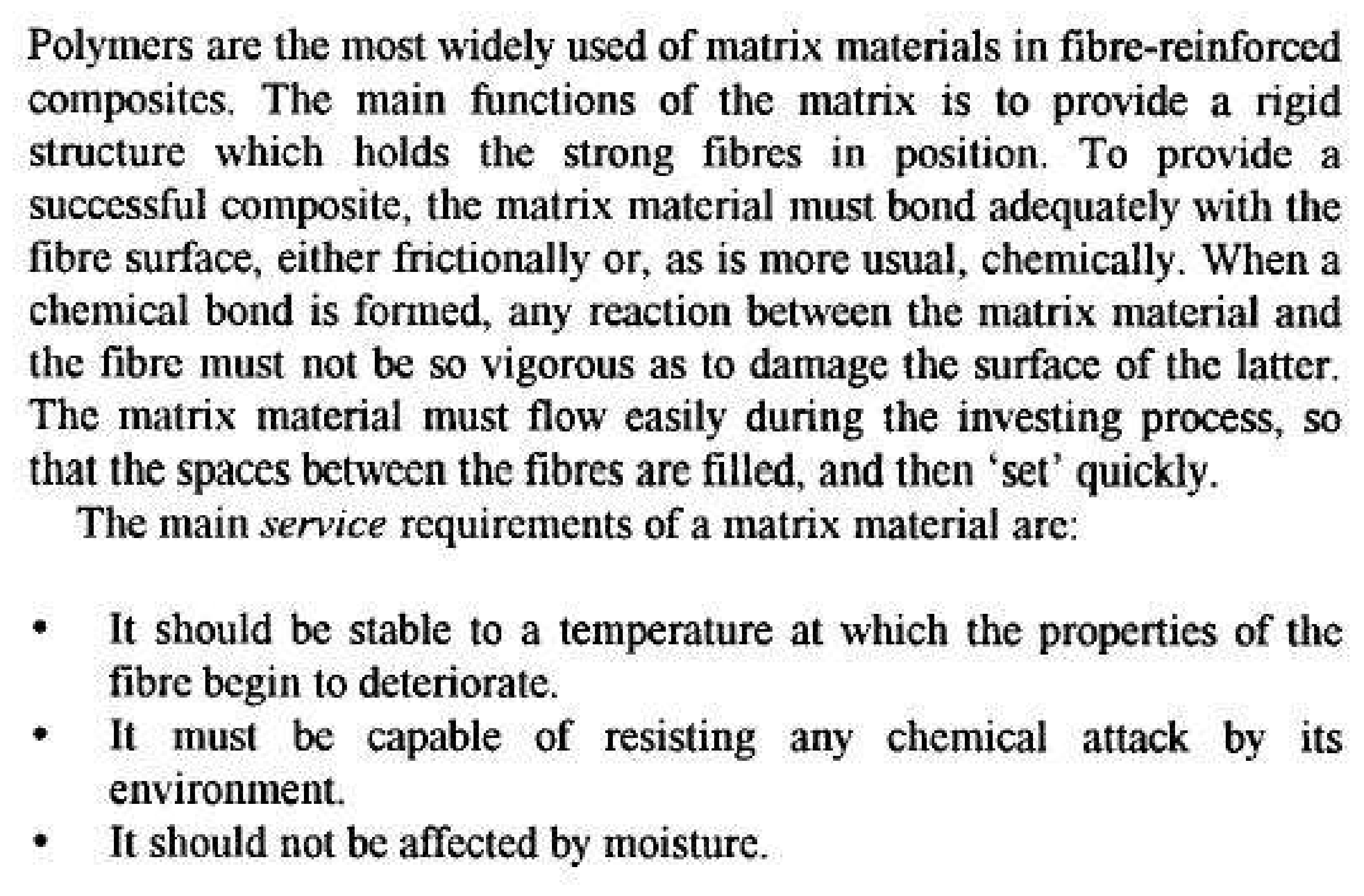


Table 24.1 *Mechanical properties of some fibre materials*

Fibre type	*Tensile strength GPa*	*Modulus GPa*	*Relative density*	*Specific strength GPa*	*Specific modulus GPa*
Aramid (Kevlar 4)	2.75	125	1.44	1.9	87
Silica glass	5.9	74	2.2	2.2	34
E-glass	1.7	70	2.5	2.5	28
S-glass	4.6	84	2.6	2.6	32
Carbon (high strength)	3.5	200	1.7	1.7	118
Carbon (high modulus)	2.5	400	2.0	2.0	200
Boron	3.9	400	2.6	2.6	154
Silicon carbide	7.0	400	3.2	3.2	125
Alumina	1.7	380	4.0	4.0	96
Bulk materials for comparison					
Steel	1.3	260	7.8	0.2	26
Wood (spruce)	0.1	10	0.46	0.22	22

Matrix materials



Polymers are the most widely used of matrix materials in fibre-reinforced composites. The main functions of the matrix is to provide a rigid structure which holds the strong fibres in position. To provide a successful composite, the matrix material must bond adequately with the fibre surface, either frictionally or, as is more usual, chemically. When a chemical bond is formed, any reaction between the matrix material and the fibre must not be so vigorous as to damage the surface of the latter. The matrix material must flow easily during the investing process, so that the spaces between the fibres are filled, and then 'set' quickly.

The main *service* requirements of a matrix material are:

- It should be stable to a temperature at which the properties of the fibre begin to deteriorate.
- It must be capable of resisting any chemical attack by its environment.
- It should not be affected by moisture.

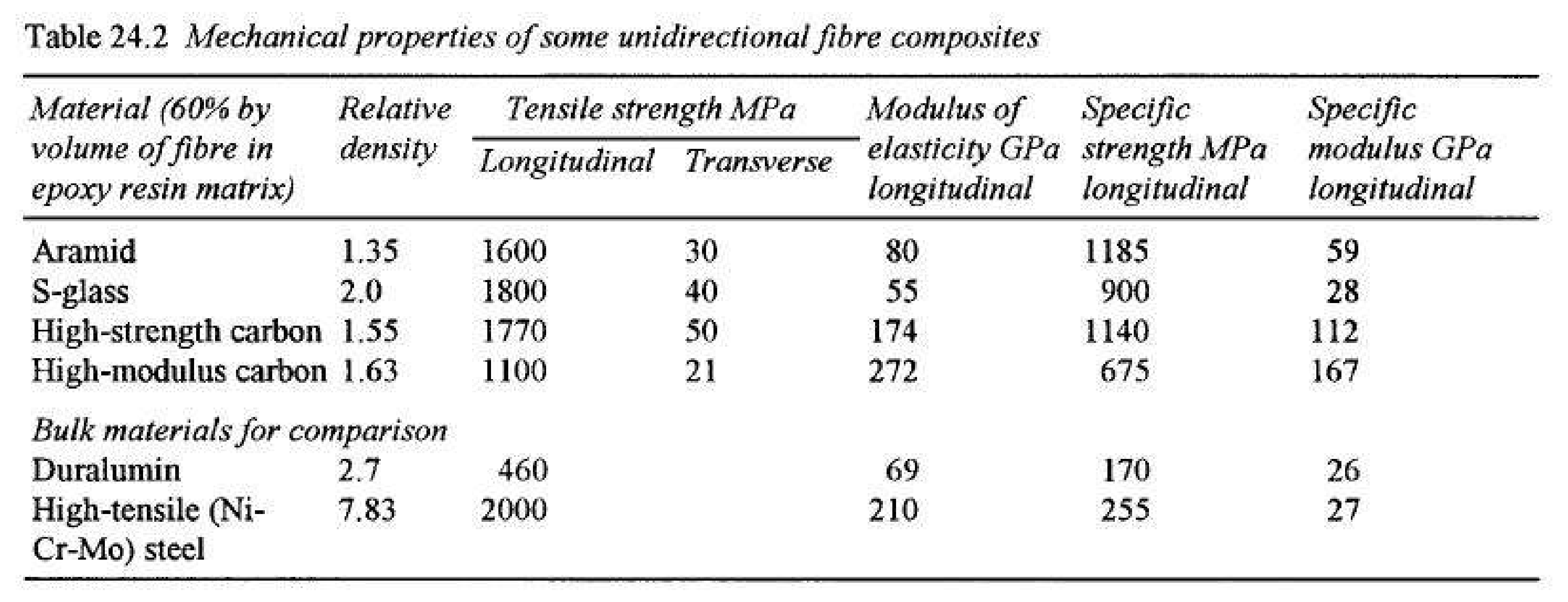
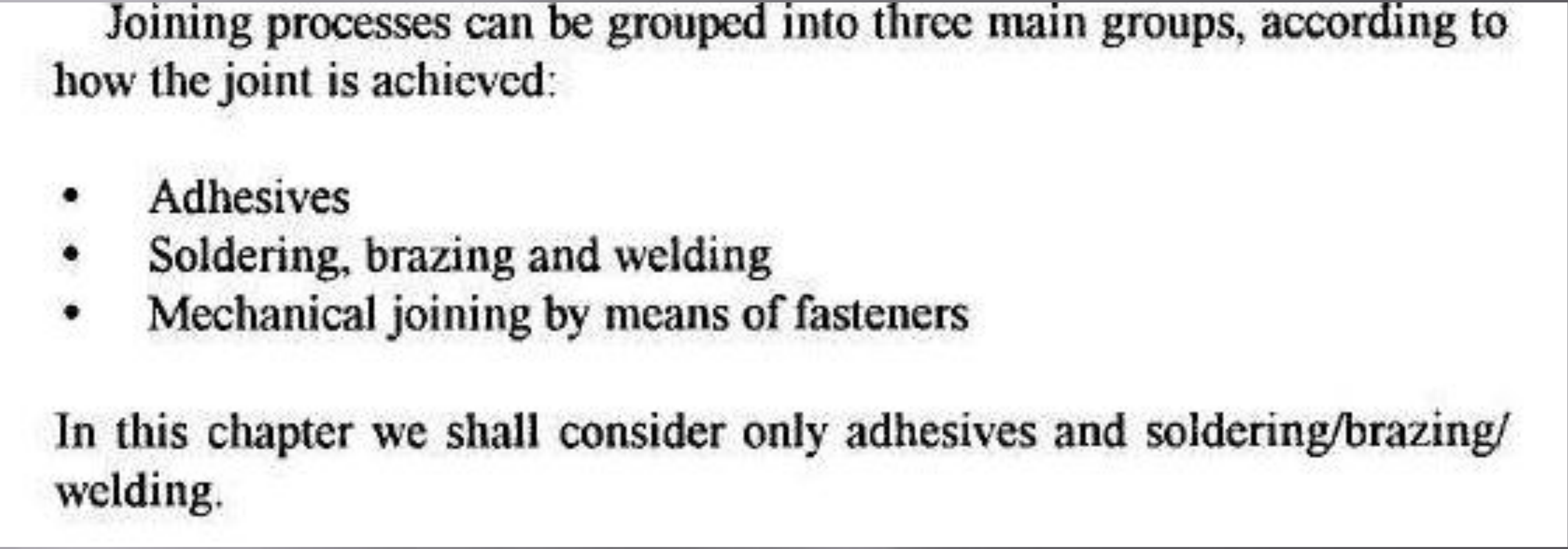


Table 24.2 *Mechanical properties of some unidirectional fibre composites*

Material (60% by volume of fibre in epoxy resin matrix)	*Relative density*	*Tensile strength MPa*		*Modulus of elasticity GPa longitudinal*	*Specific strength MPa longitudinal*	*Specific modulus GPa longitudinal*
		Longitudinal	*Transverse*			
Aramid	1.35	1600	30	80	1185	59
S-glass	2.0	1800	40	55	900	28
High-strength carbon	1.55	1770	50	174	1140	112
High-modulus carbon	1.63	1100	21	272	675	167
Bulk materials for comparison						
Duralumin	2.7	460		69	170	26
High-tensile (Ni-Cr-Mo) steel	7.83	2000		210	255	27



Joining processes can be grouped into three main groups, according to how the joint is achieved:

- Adhesives
- Soldering, brazing and welding
- Mechanical joining by means of fasteners

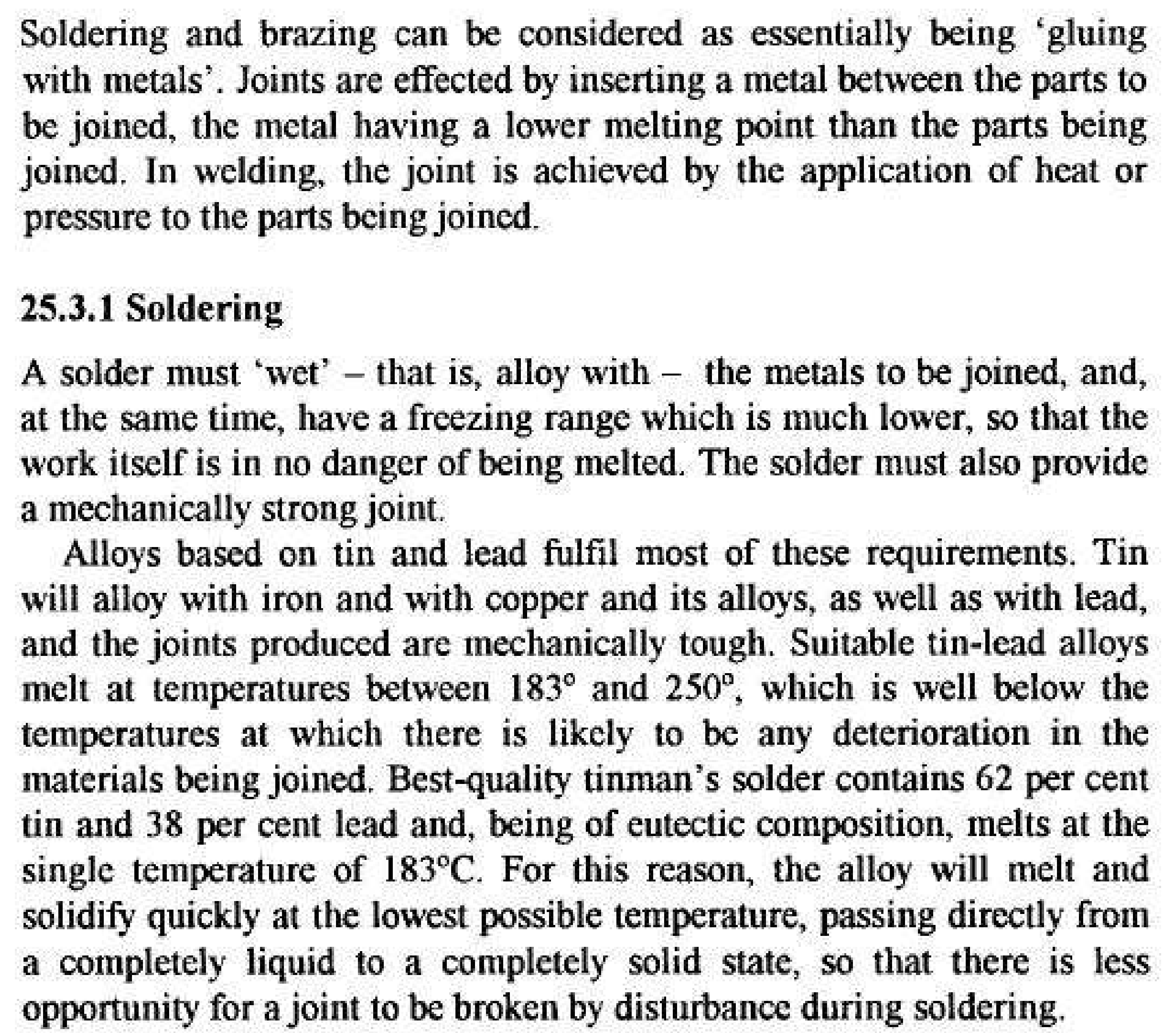
In this chapter we shall consider only adhesives and soldering/brazing/welding.

compression and shear better than tear or peel.

Table 25.1 *Adhesives*

Group	*Adhesive substance (or raw material)*	*Materials joined*
Animal glues	Animal hides or bones, fish, casein (from milk), blood albumen	Wood, paper, fabrics and leather.
Vegetable glues	Starch, dextrine	Paper and fabrics.
	Soya beans	Paper-sizing.
Natural resins	Bitumens (incl. asphalt)	Laying floor blocks, felt.
	Gum arabic	Paper and fabrics.
Inorganic cements	Sodium silicate	Foundry moulds.
	Portland cement, plaster of Paris	Building industries.
Elastomer materials	Natural rubber (latex/solvent)	Rubber, sealing strips.
	Synthetic rubbers (neoprene, nitrile)	Footwear industries, polythene, PVC.
Synthetic polymer materials	Polyvinyl acetate and vinyl copolymers	Wood, paper, fabrics, bookbinding.
	Cellulose derivatives (solvent release)	Glass, paper, balsa wood.
	Acrylics	Acrylics, polycarbonates.
	Anaerobic acrylics	Metals.
	Cyanoacrylates – cure in presence of moisture ('super glue')	Metals, rubbers, PVC, polycarbonates, polystyrene, polyimide
	Epoxy/amine and epoxy/polyamide	Metals, glass, ceramics, wood, reinforced plastics, very wide range of uses.
	Phenol, urea, melamine and resorcinol fomaldehydes	Weatherproof plywoods, fabrics and paper.
	Polyurethane – hot or cold-curing liquid	Polyurethane, PVC, polycarbonates, paper and fabrics.
	Polyimide – hot-curing film	Metals, glass, ceramics, polyimide.
	Silicones	Silicone rubbers, sealing seams and joints in other materials.

Soldering and brazing



Soldering and brazing can be considered as essentially being 'gluing with metals'. Joints are effected by inserting a metal between the parts to be joined, the metal having a lower melting point than the parts being joined. In welding, the joint is achieved by the application of heat or pressure to the parts being joined.

25.3.1 Soldering

A solder must 'wet' – that is, alloy with – the metals to be joined, and, at the same time, have a freezing range which is much lower, so that the work itself is in no danger of being melted. The solder must also provide a mechanically strong joint.

Alloys based on tin and lead fulfil most of these requirements. Tin will alloy with iron and with copper and its alloys, as well as with lead, and the joints produced are mechanically tough. Suitable tin-lead alloys melt at temperatures between 183° and 250°, which is well below the temperatures at which there is likely to be any deterioration in the materials being joined. Best-quality tinman's solder contains 62 per cent tin and 38 per cent lead and, being of eutectic composition, melts at the single temperature of 183°C. For this reason, the alloy will melt and solidify quickly at the lowest possible temperature, passing directly from a completely liquid to a completely solid state, so that there is less opportunity for a joint to be broken by disturbance during soldering.

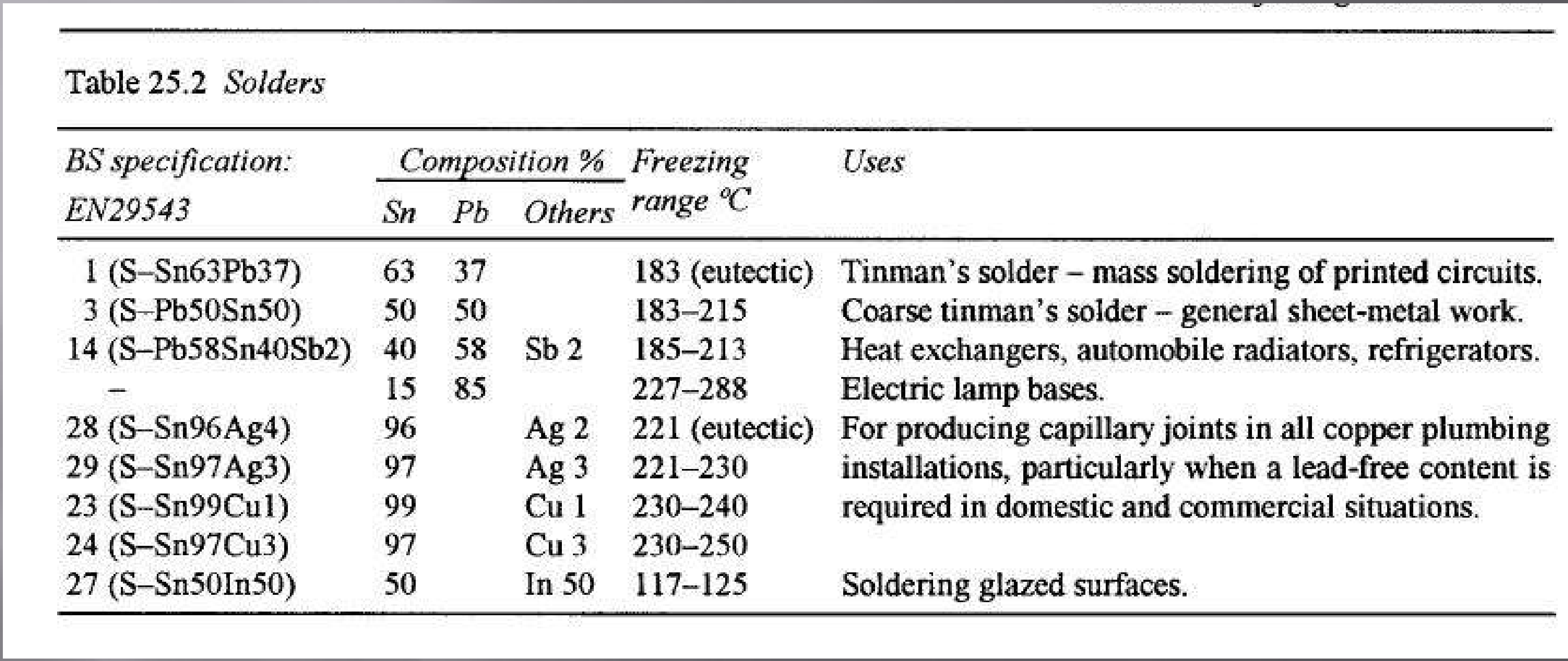
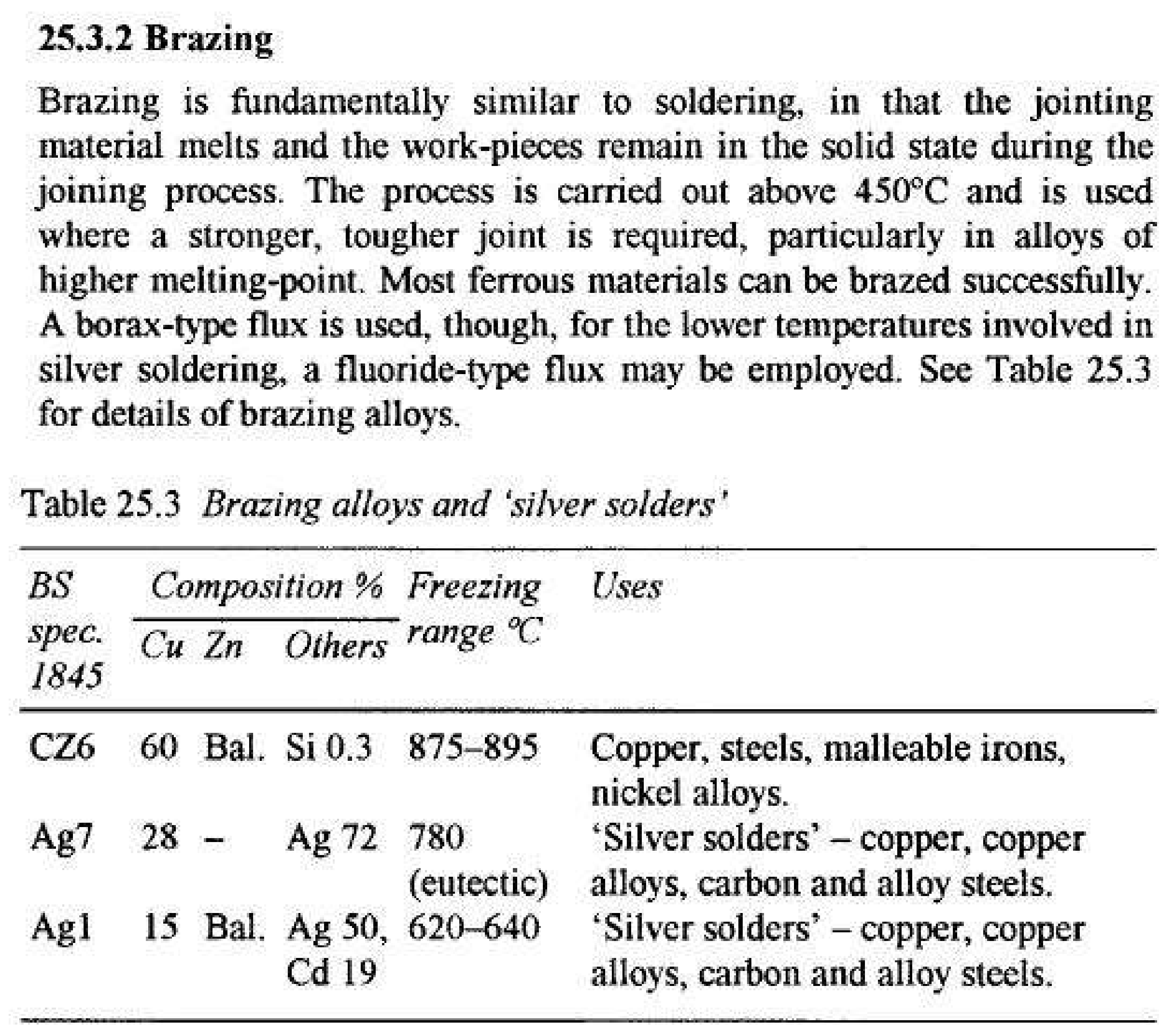


Table 25.2 *Solders*

BS specification: EN29543	*Composition %* *Sn*	*Pb*	*Others*	*Freezing range °C*	*Uses*
1 (S–Sn63Pb37)	63	37		183 (eutectic)	Tinman's solder – mass soldering of printed circuits.
3 (S–Pb50Sn50)	50	50		183–215	Coarse tinman's solder – general sheet-metal work.
14 (S–Pb58Sn40Sb2)	40	58	Sb 2	185–213	Heat exchangers, automobile radiators, refrigerators.
–	15	85		227–288	Electric lamp bases.
28 (S–Sn96Ag4)	96		Ag 2	221 (eutectic)	For producing capillary joints in all copper plumbing installations, particularly when a lead-free content is required in domestic and commercial situations.
29 (S–Sn97Ag3)	97		Ag 3	221–230	
23 (S–Sn99Cu1)	99		Cu 1	230–240	
24 (S–Sn97Cu3)	97		Cu 3	230–250	
27 (S–Sn50In50)	50		In 50	117–125	Soldering glazed surfaces.



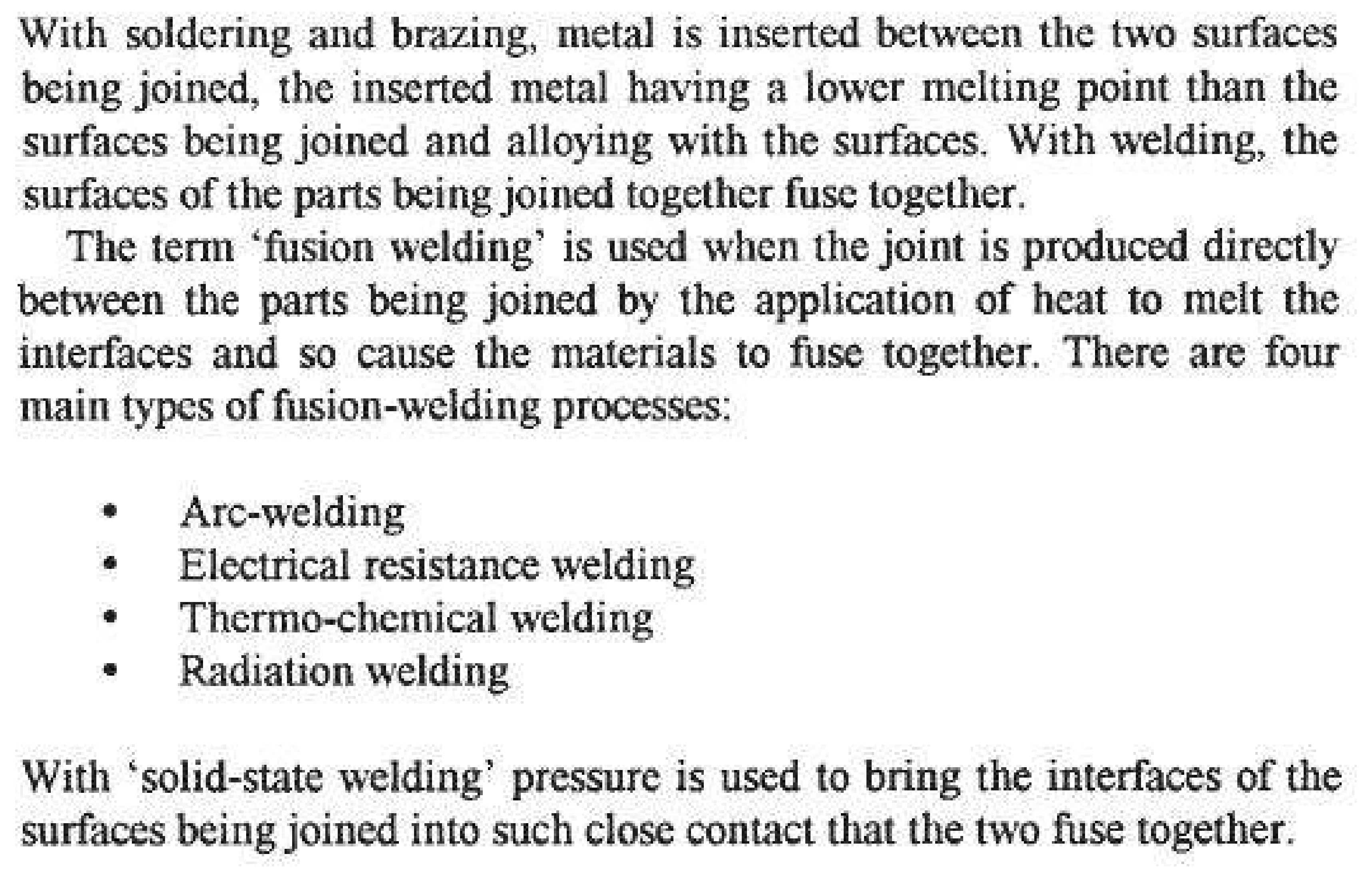
25.3.2 Brazing

Brazing is fundamentally similar to soldering, in that the jointing material melts and the work-pieces remain in the solid state during the joining process. The process is carried out above 450°C and is used where a stronger, tougher joint is required, particularly in alloys of higher melting-point. Most ferrous materials can be brazed successfully. A borax-type flux is used, though, for the lower temperatures involved in silver soldering, a fluoride-type flux may be employed. See Table 25.3 for details of brazing alloys.

Table 25.3 *Brazing alloys and 'silver solders'*

BS spec. 1845	*Composition %*			*Freezing range °C*	*Uses*
	Cu	*Zn*	*Others*		
CZ6	60	Bal.	Si 0.3	875–895	Copper, steels, malleable irons, nickel alloys.
Ag7	28	–	Ag 72	780 (eutectic)	'Silver solders' – copper, copper alloys, carbon and alloy steels.
Ag1	15	Bal.	Ag 50, Cd 19	620–640	'Silver solders' – copper, copper alloys, carbon and alloy steels.

Welding

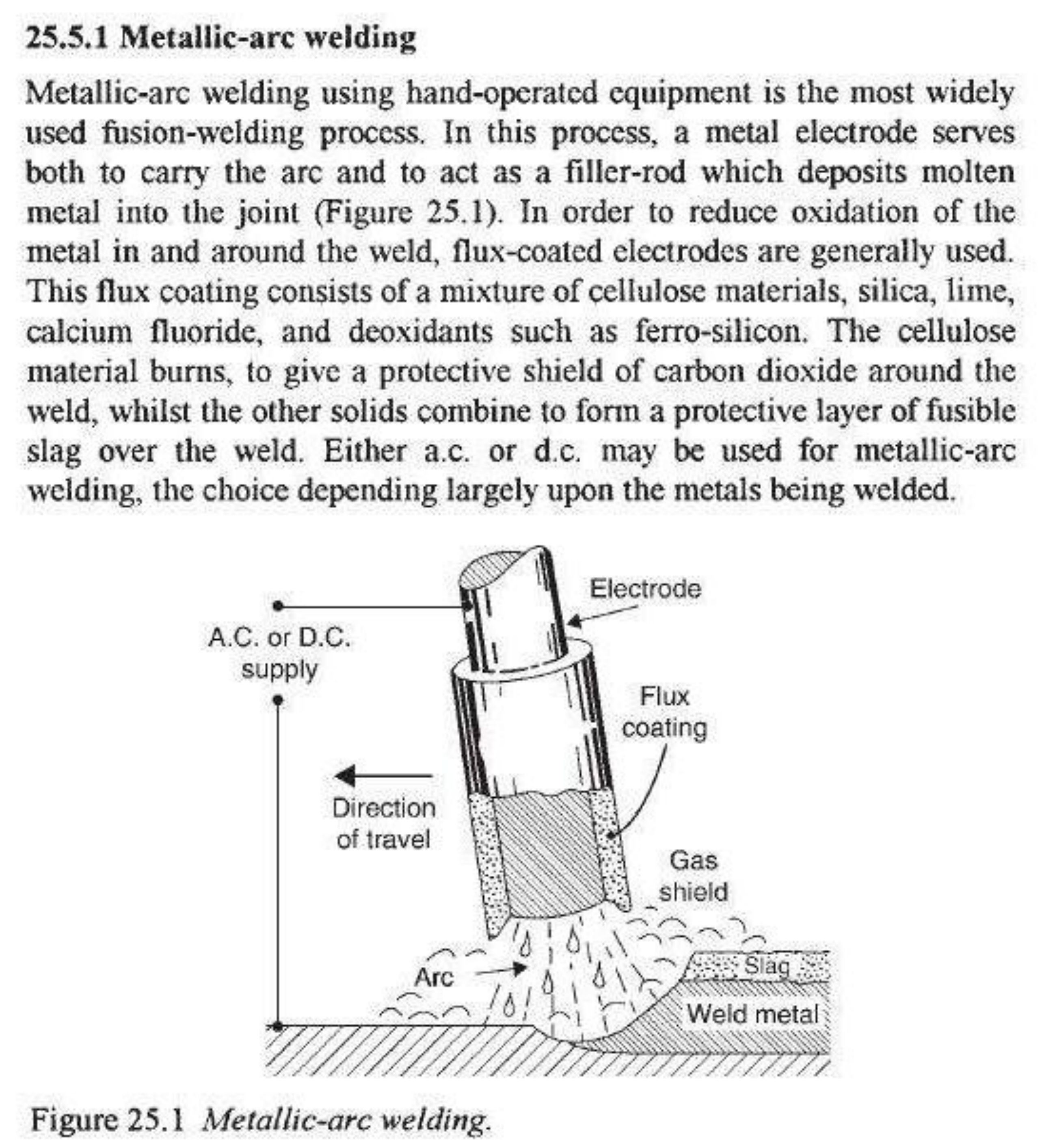


With soldering and brazing, metal is inserted between the two surfaces being joined, the inserted metal having a lower melting point than the surfaces being joined and alloying with the surfaces. With welding, the surfaces of the parts being joined together fuse together.

The term 'fusion welding' is used when the joint is produced directly between the parts being joined by the application of heat to melt the interfaces and so cause the materials to fuse together. There are four main types of fusion-welding processes:

- Arc-welding
- Electrical resistance welding
- Thermo-chemical welding
- Radiation welding

With 'solid-state welding' pressure is used to bring the interfaces of the surfaces being joined into such close contact that the two fuse together.



25.5.1 Metallic-arc welding

Metallic-arc welding using hand-operated equipment is the most widely used fusion-welding process. In this process, a metal electrode serves both to carry the arc and to act as a filler-rod which deposits molten metal into the joint (Figure 25.1). In order to reduce oxidation of the metal in and around the weld, flux-coated electrodes are generally used. This flux coating consists of a mixture of cellulose materials, silica, lime, calcium fluoride, and deoxidants such as ferro-silicon. The cellulose material burns, to give a protective shield of carbon dioxide around the weld, whilst the other solids combine to form a protective layer of fusible slag over the weld. Either a.c. or d.c. may be used for metallic-arc welding, the choice depending largely upon the metals being welded.

Figure 25.1 *Metallic-arc welding.*

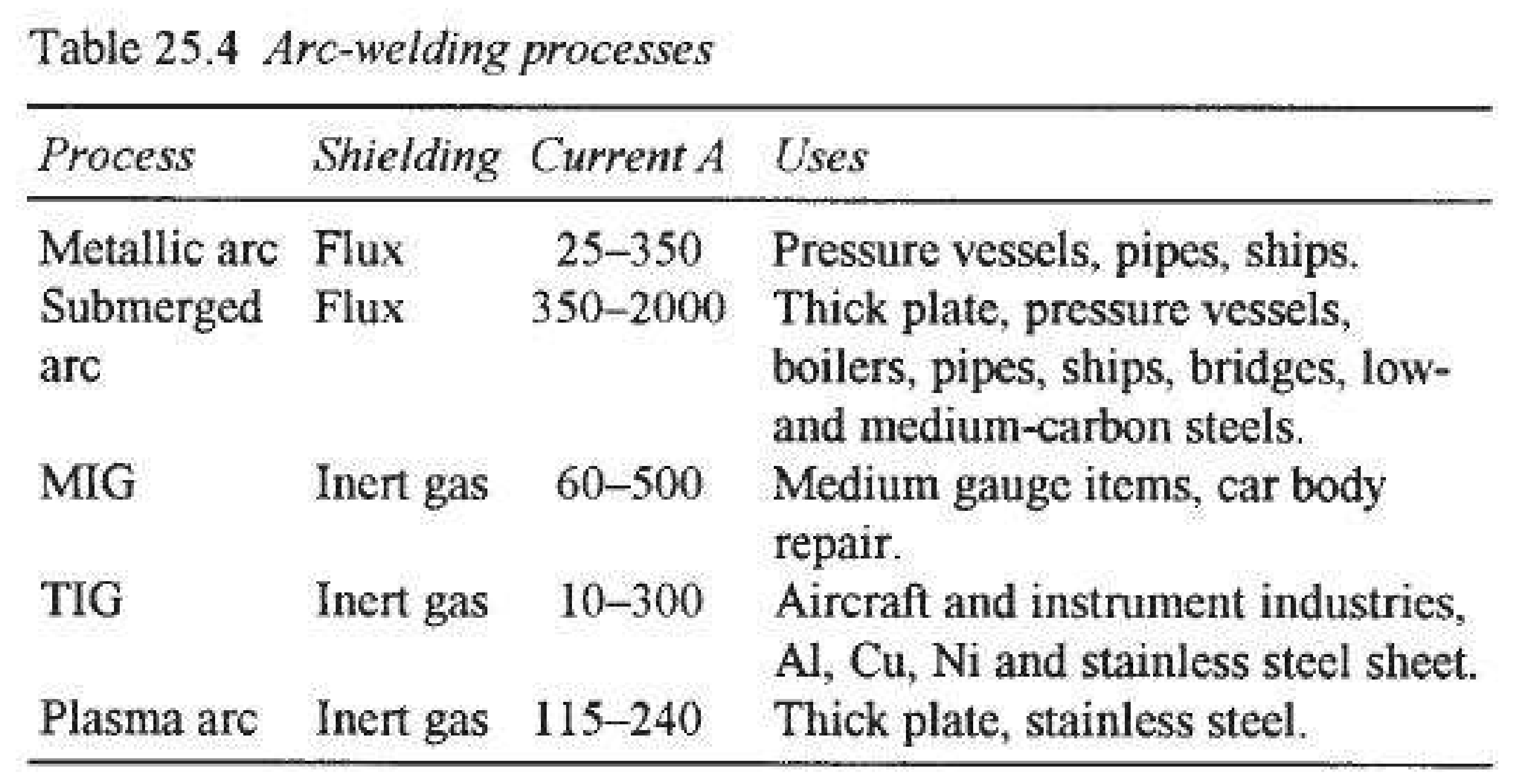
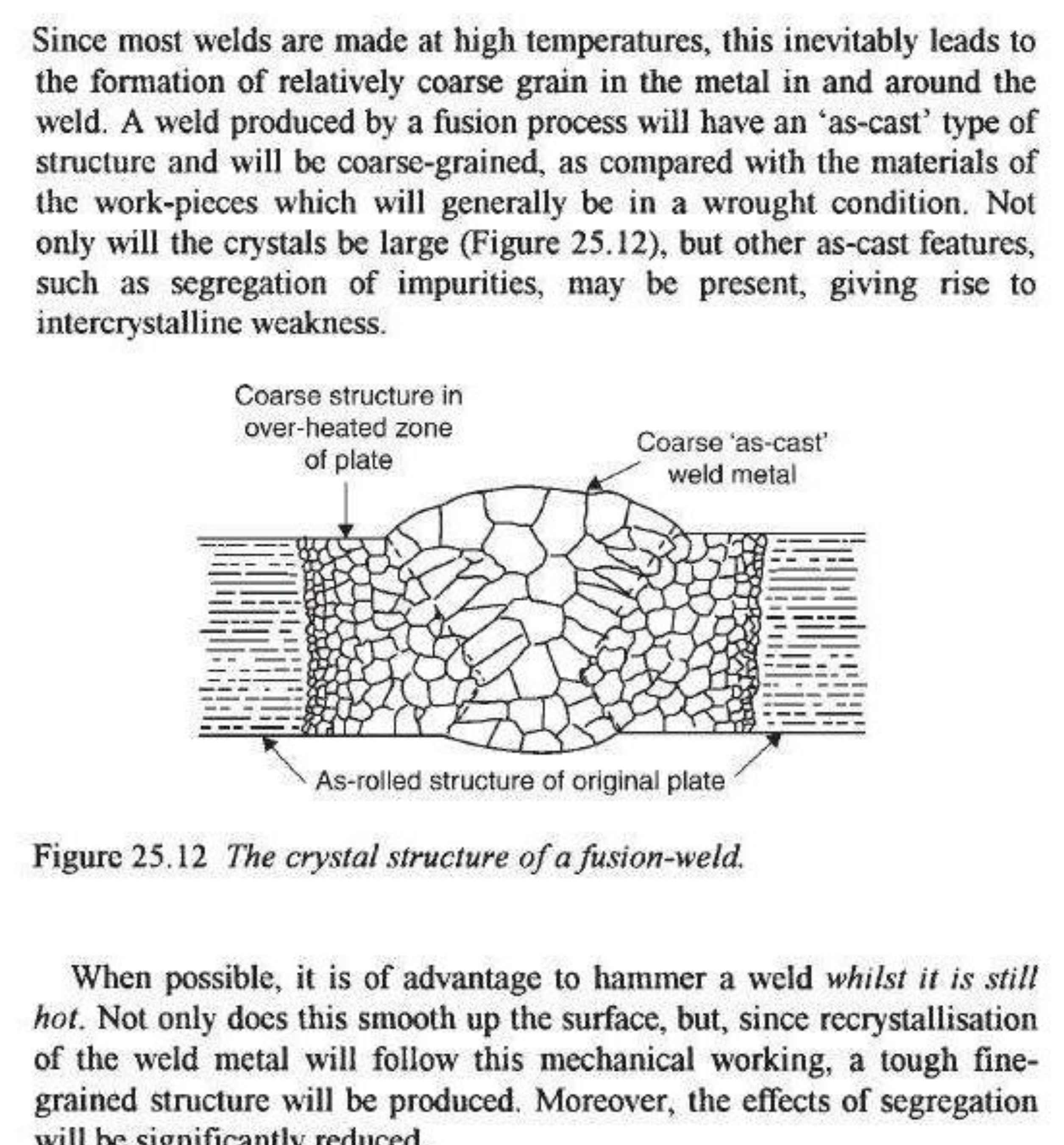


Table 25.4 *Arc-welding processes*

Process	*Shielding*	*Current A*	*Uses*
Metallic arc	Flux	25–350	Pressure vessels, pipes, ships.
Submerged arc	Flux	350–2000	Thick plate, pressure vessels, boilers, pipes, ships, bridges, low- and medium-carbon steels.
MIG	Inert gas	60–500	Medium gauge items, car body repair.
TIG	Inert gas	10–300	Aircraft and instrument industries, Al, Cu, Ni and stainless steel sheet.
Plasma arc	Inert gas	115–240	Thick plate, stainless steel.

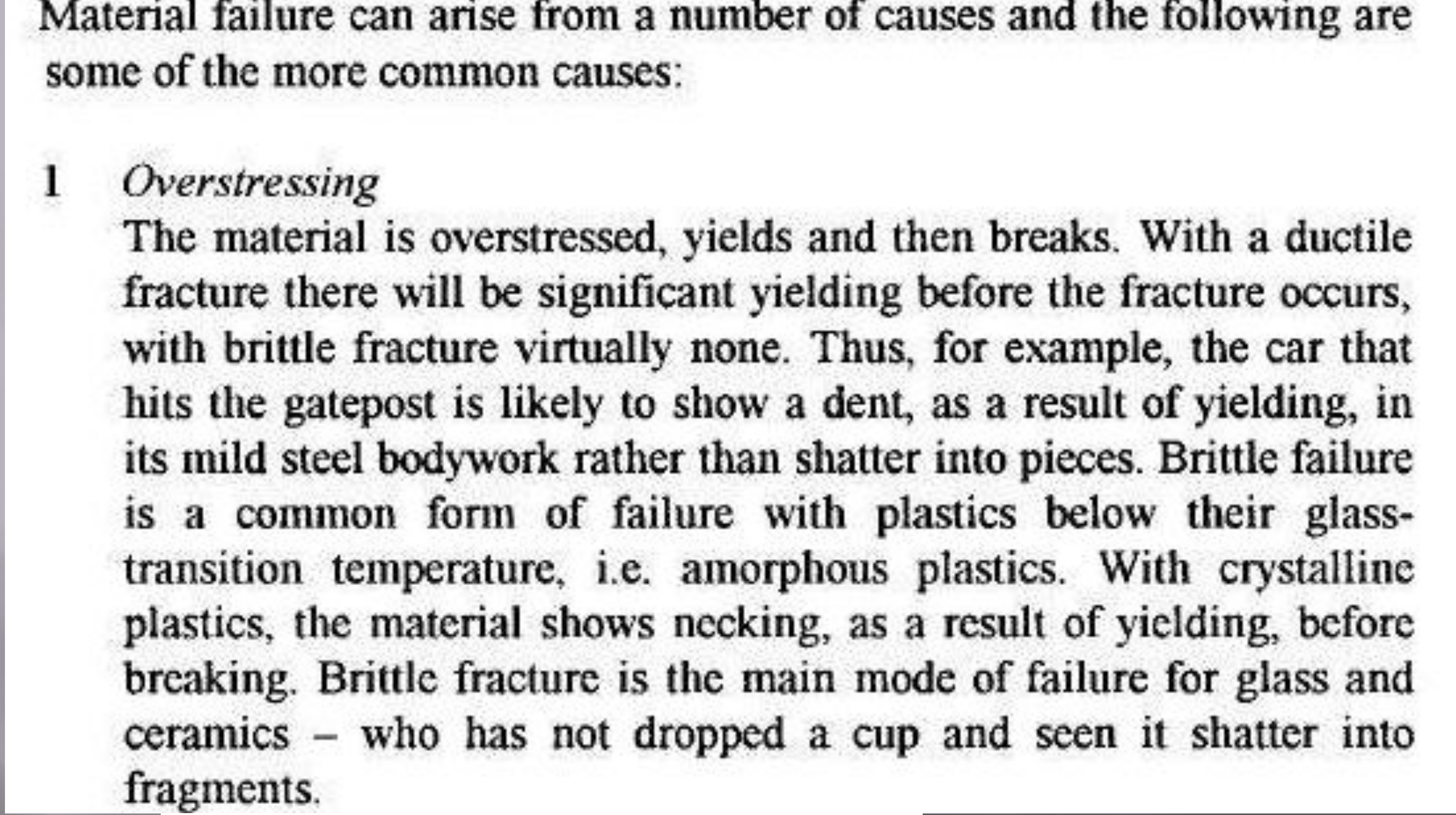
Structure of welds



Since most welds are made at high temperatures, this inevitably leads to the formation of relatively coarse grain in the metal in and around the weld. A weld produced by a fusion process will have an 'as-cast' type of structure and will be coarse-grained, as compared with the materials of the work-pieces which will generally be in a wrought condition. Not only will the crystals be large (Figure 25.12), but other as-cast features, such as segregation of impurities, may be present, giving rise to intercrystalline weakness.

Figure 25.12 *The crystal structure of a fusion-weld.*

When possible, it is of advantage to hammer a weld *whilst it is still hot*. Not only does this smooth up the surface, but, since recrystallisation of the weld metal will follow this mechanical working, a tough fine-grained structure will be produced. Moreover, the effects of segregation will be significantly reduced.

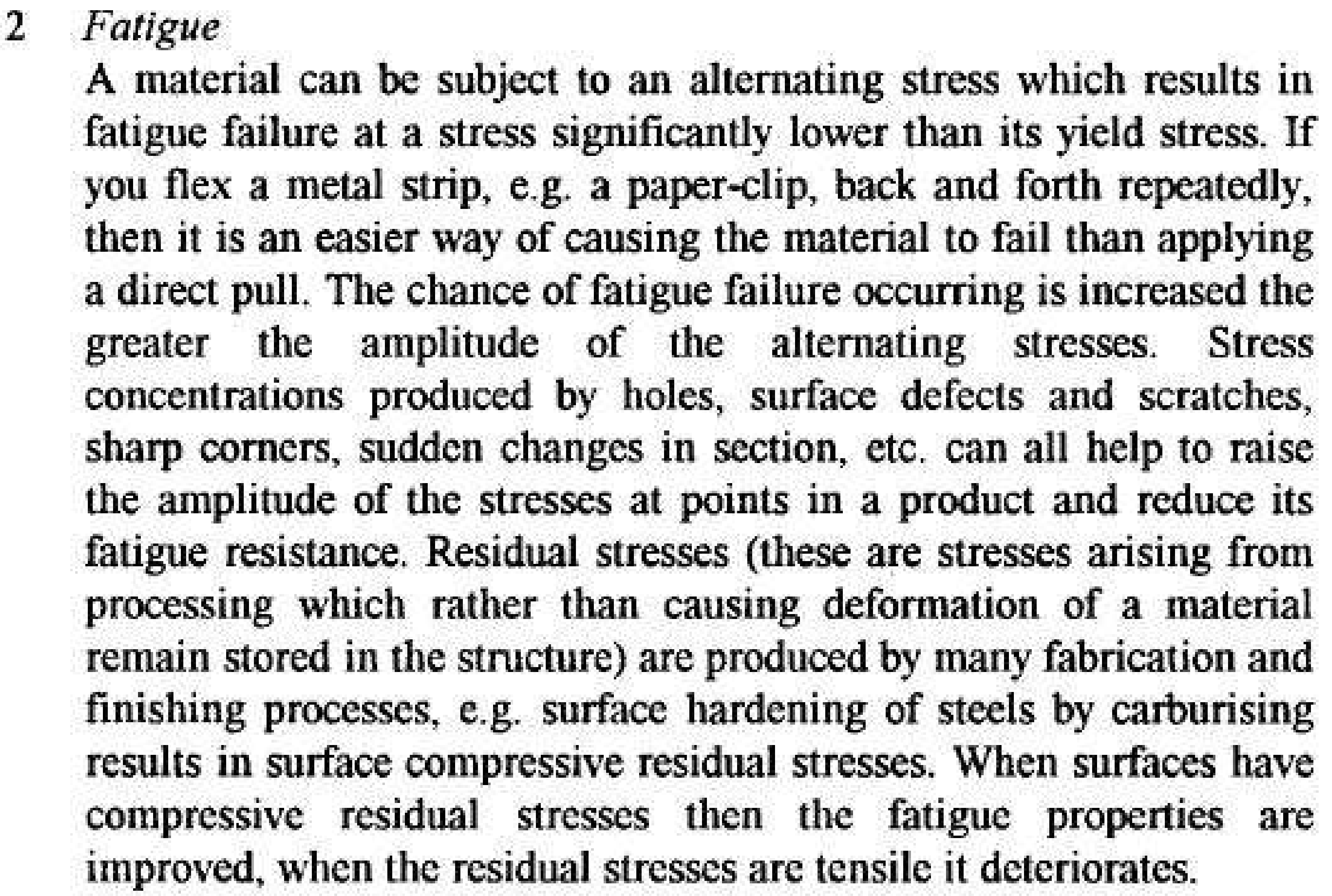


Material failure can arise from a number of causes and the following are some of the more common causes:

1 *Overstressing*

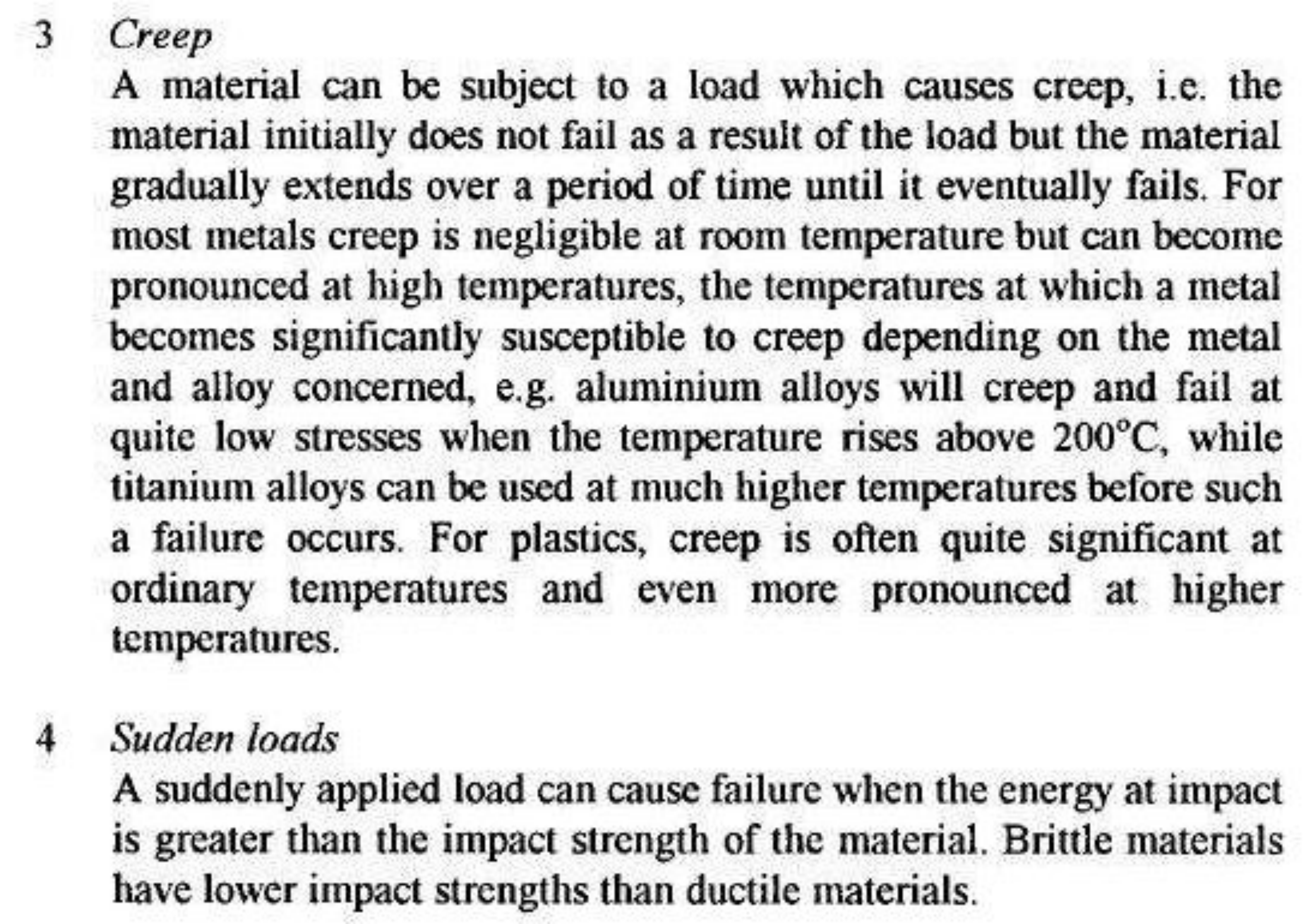
The material is overstressed, yields and then breaks. With a ductile fracture there will be significant yielding before the fracture occurs, with brittle fracture virtually none. Thus, for example, the car that hits the gatepost is likely to show a dent, as a result of yielding, in its mild steel bodywork rather than shatter into pieces. Brittle failure is a common form of failure with plastics below their glass-transition temperature, i.e. amorphous plastics. With crystalline plastics, the material shows necking, as a result of yielding, before breaking. Brittle fracture is the main mode of failure for glass and ceramics – who has not dropped a cup and seen it shatter into fragments.

$$\text{stress concentration factor} = \sqrt{\frac{L}{r}}$$



2 *Fatigue*

A material can be subject to an alternating stress which results in fatigue failure at a stress significantly lower than its yield stress. If you flex a metal strip, e.g. a paper-clip, back and forth repeatedly, then it is an easier way of causing the material to fail than applying a direct pull. The chance of fatigue failure occurring is increased the greater the amplitude of the alternating stresses. Stress concentrations produced by holes, surface defects and scratches, sharp corners, sudden changes in section, etc. can all help to raise the amplitude of the stresses at points in a product and reduce its fatigue resistance. Residual stresses (these are stresses arising from processing which rather than causing deformation of a material remain stored in the structure) are produced by many fabrication and finishing processes, e.g. surface hardening of steels by carburising results in surface compressive residual stresses. When surfaces have compressive residual stresses then the fatigue properties are improved, when the residual stresses are tensile it deteriorates.

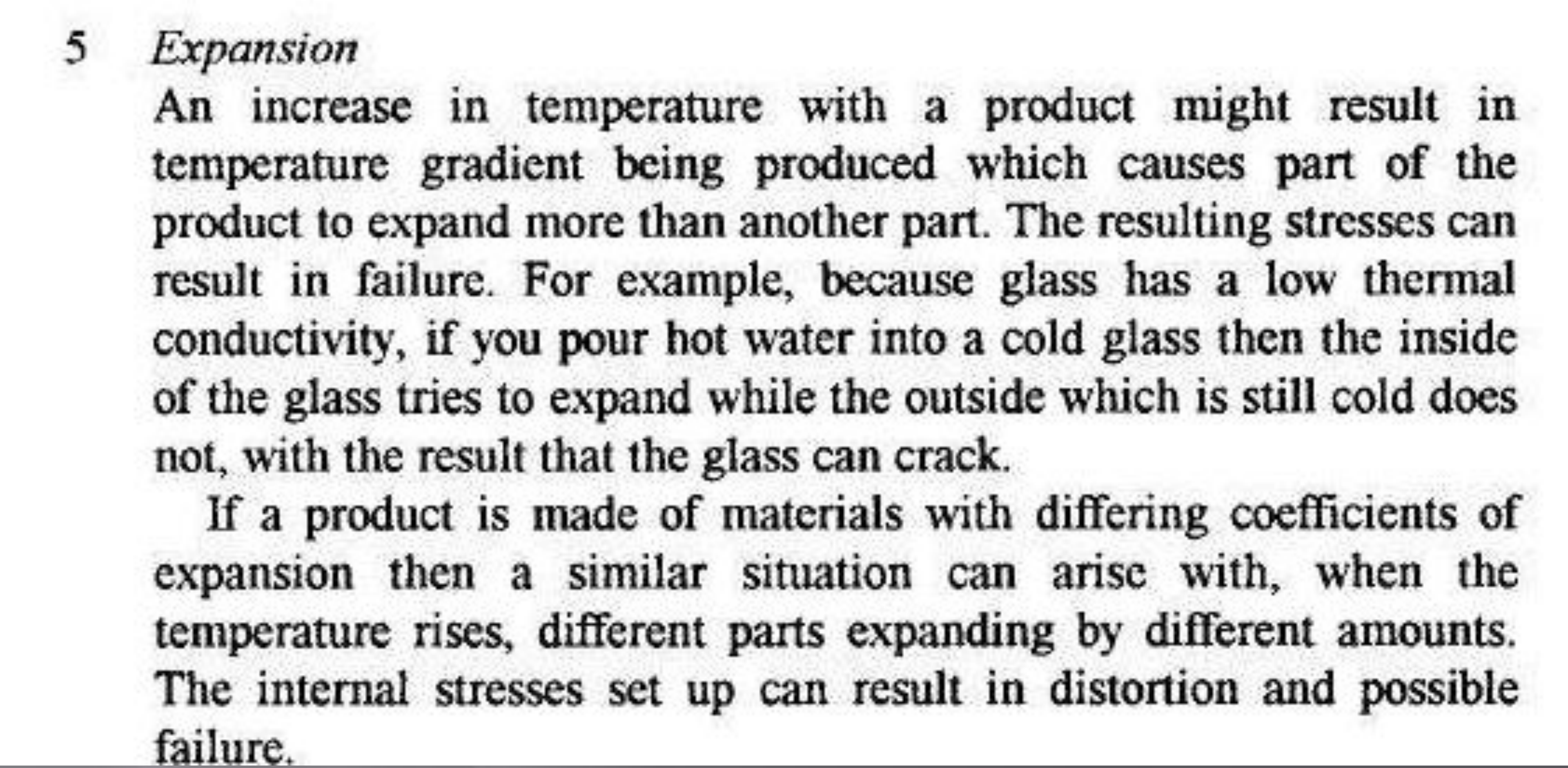


3 *Creep*

A material can be subject to a load which causes creep, i.e. the material initially does not fail as a result of the load but the material gradually extends over a period of time until it eventually fails. For most metals creep is negligible at room temperature but can become pronounced at high temperatures, the temperatures at which a metal becomes significantly susceptible to creep depending on the metal and alloy concerned, e.g. aluminium alloys will creep and fail at quite low stresses when the temperature rises above 200°C, while titanium alloys can be used at much higher temperatures before such a failure occurs. For plastics, creep is often quite significant at ordinary temperatures and even more pronounced at higher temperatures.

4 *Sudden loads*

A suddenly applied load can cause failure when the energy at impact is greater than the impact strength of the material. Brittle materials have lower impact strengths than ductile materials.



5 *Expansion*

An increase in temperature with a product might result in temperature gradient being produced which causes part of the product to expand more than another part. The resulting stresses can result in failure. For example, because glass has a low thermal conductivity, if you pour hot water into a cold glass then the inside of the glass tries to expand while the outside which is still cold does not, with the result that the glass can crack.

If a product is made of materials with differing coefficients of expansion then a similar situation can arise with, when the temperature rises, different parts expanding by different amounts. The internal stresses set up can result in distortion and possible failure.

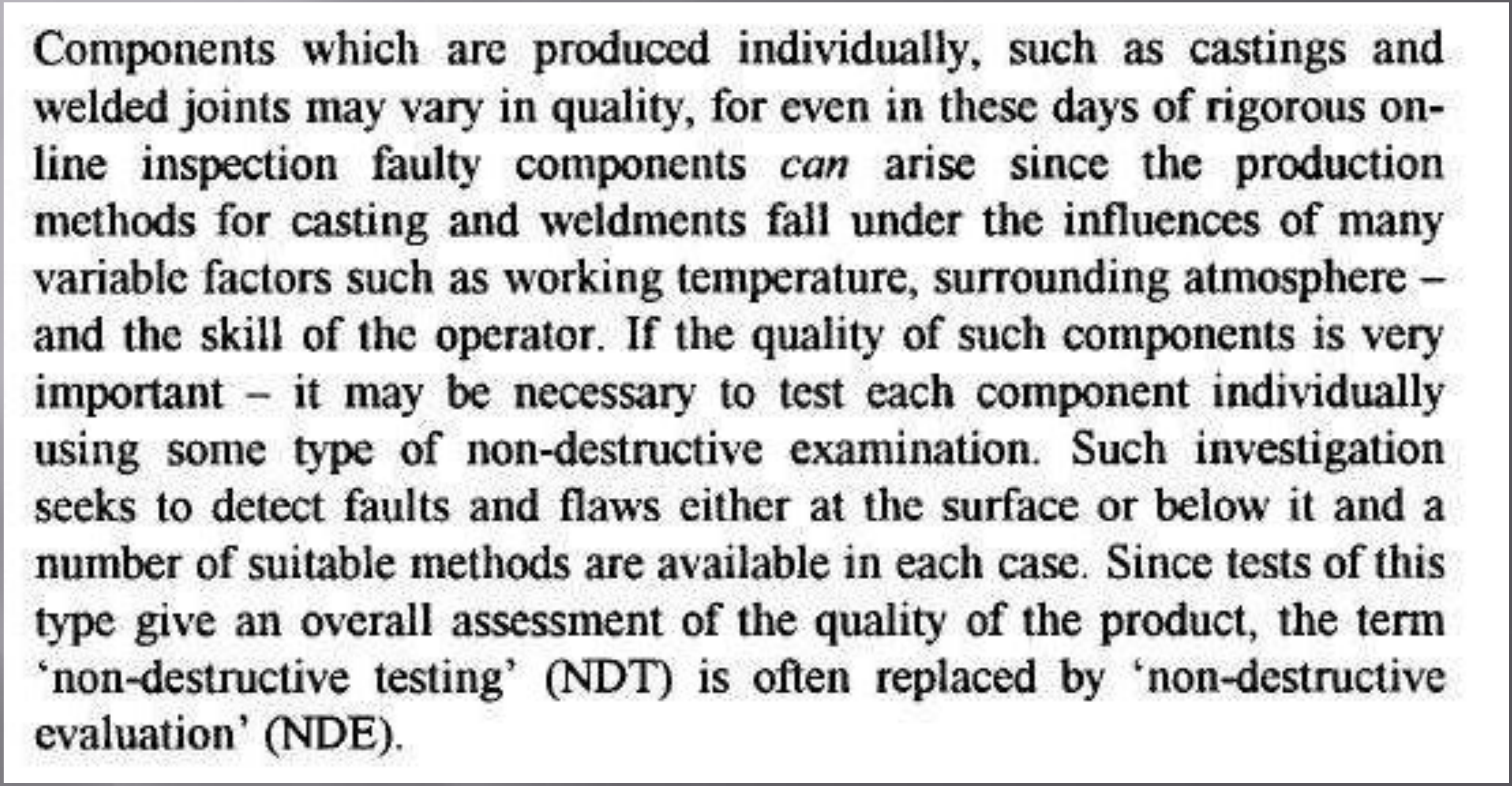
6 *Thermal cycling*

Thermal cycling is the term used for when the temperature of a product repeatedly fluctuates, so giving cycles of thermal expansion and contraction. If the material is constrained in some way then internal stresses will be set up and as a consequence the thermal cycling will result in alternating stresses being applied to the material which can result in fatigue failure.

7 *Degradation*

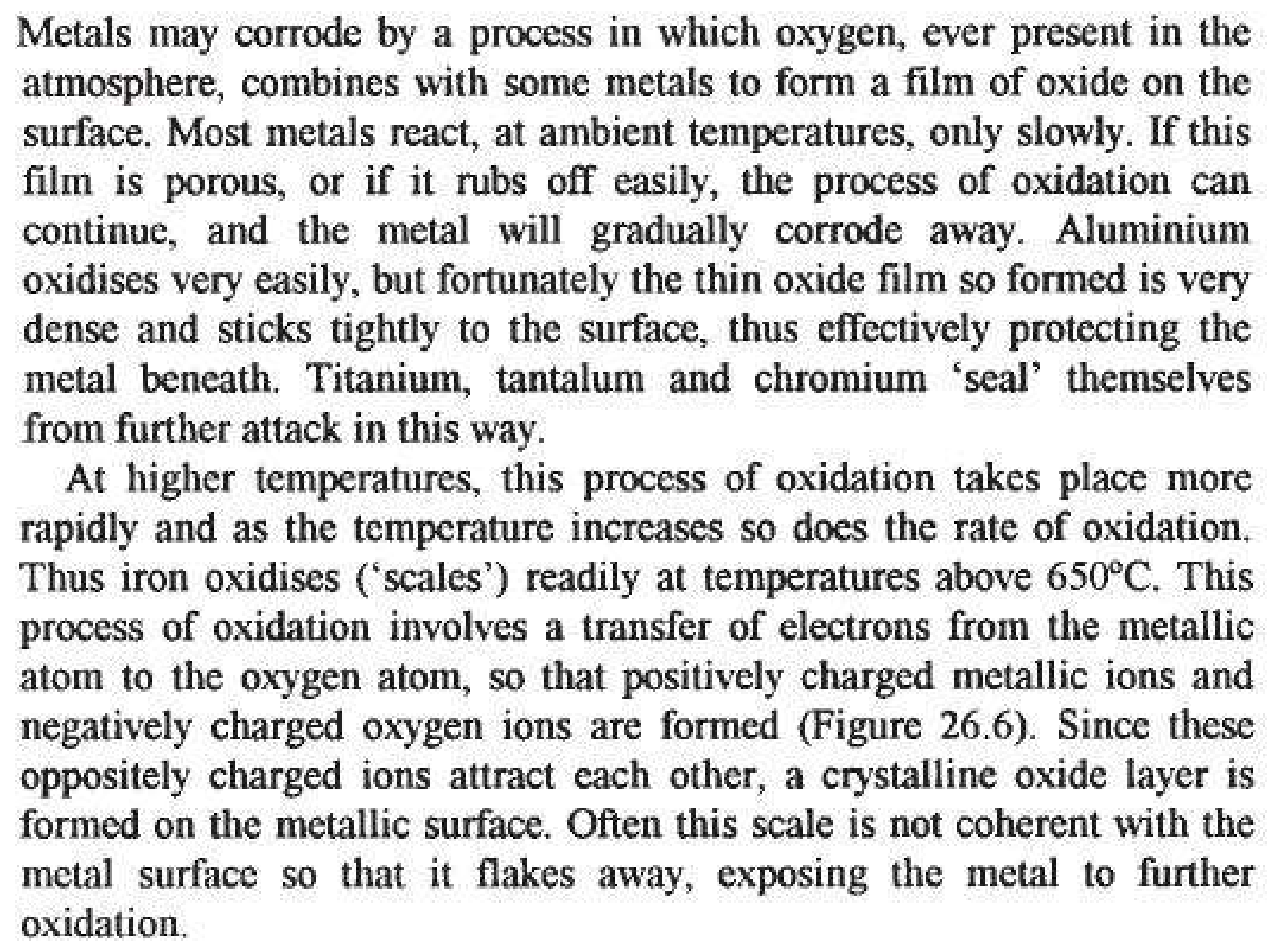
Sooner or later, all engineering materials decay in their surrounding environment. Much of this degradation is due to chemical reactions typified by the ‘rusting’ of steel and the corrosion of metals in general. The corrosion of steel is a problem which in some degree must be faced by all of us, and it is estimated that the annual cost of the fight against corrosion on a world-wide basis runs into some thousands of millions of pounds. Other engineering metals corrode when exposed to the atmosphere, though generally to a lesser extent than do iron and steel. Because of their high resistance to all forms of corrosion, plastics are replacing metals for many applications

Non-destructive testing



Components which are produced individually, such as castings and welded joints may vary in quality, for even in these days of rigorous on-line inspection faulty components *can* arise since the production methods for casting and weldments fall under the influences of many variable factors such as working temperature, surrounding atmosphere – and the skill of the operator. If the quality of such components is very important – it may be necessary to test each component individually using some type of non-destructive examination. Such investigation seeks to detect faults and flaws either at the surface or below it and a number of suitable methods are available in each case. Since tests of this type give an overall assessment of the quality of the product, the term 'non-destructive testing' (NDT) is often replaced by 'non-destructive evaluation' (NDE).

Degradation of metals by oxidation



Metals may corrode by a process in which oxygen, ever present in the atmosphere, combines with some metals to form a film of oxide on the surface. Most metals react, at ambient temperatures, only slowly. If this film is porous, or if it rubs off easily, the process of oxidation can continue, and the metal will gradually corrode away. Aluminium oxidises very easily, but fortunately the thin oxide film so formed is very dense and sticks tightly to the surface, thus effectively protecting the metal beneath. Titanium, tantalum and chromium 'seal' themselves from further attack in this way.

At higher temperatures, this process of oxidation takes place more rapidly and as the temperature increases so does the rate of oxidation. Thus iron oxidises ('scales') readily at temperatures above 650°C. This process of oxidation involves a transfer of electrons from the metallic atom to the oxygen atom, so that positively charged metallic ions and negatively charged oxygen ions are formed (Figure 26.6). Since these oppositely charged ions attract each other, a crystalline oxide layer is formed on the metallic surface. Often this scale is not coherent with the metal surface so that it flakes away, exposing the metal to further oxidation.

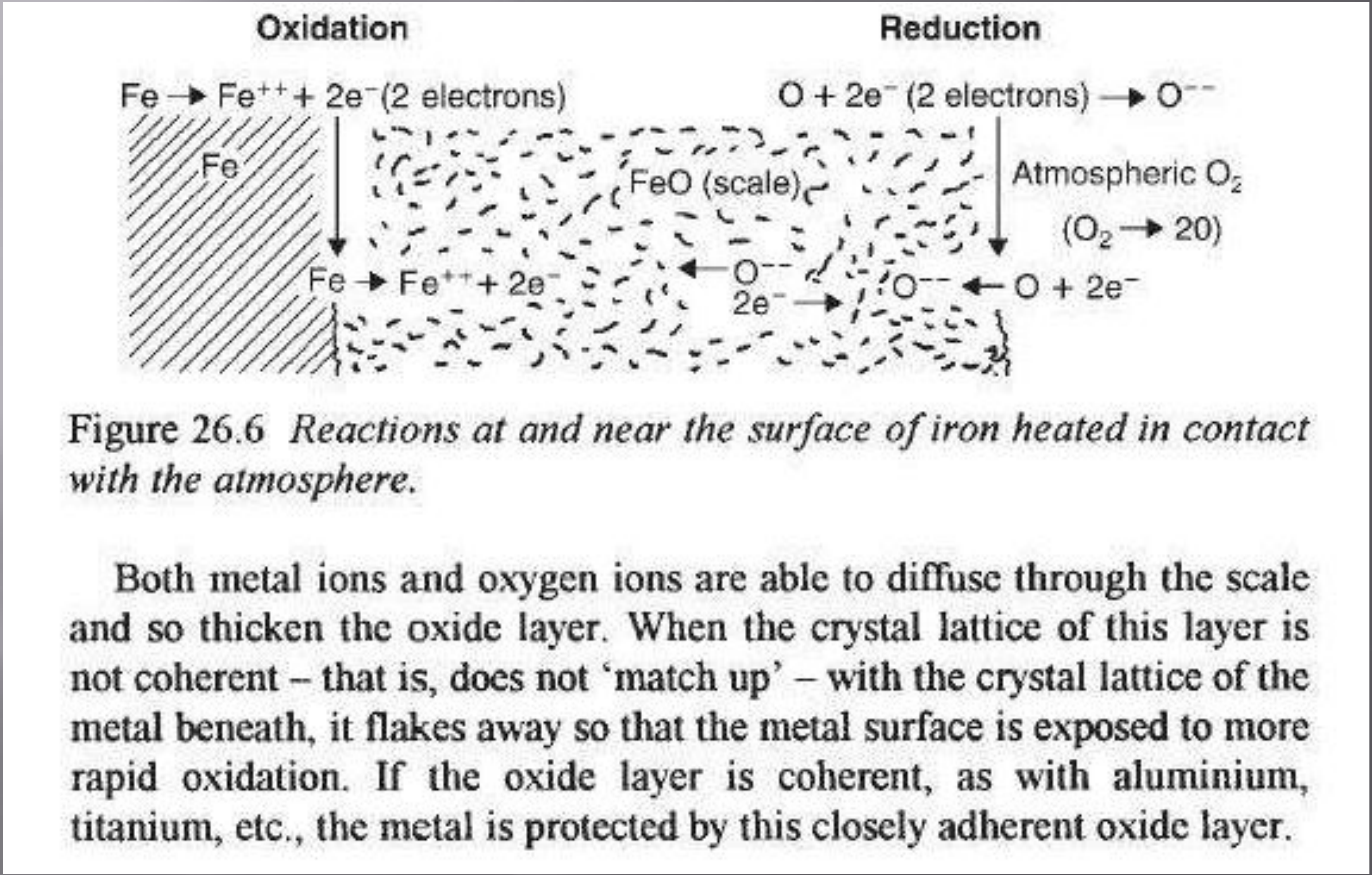


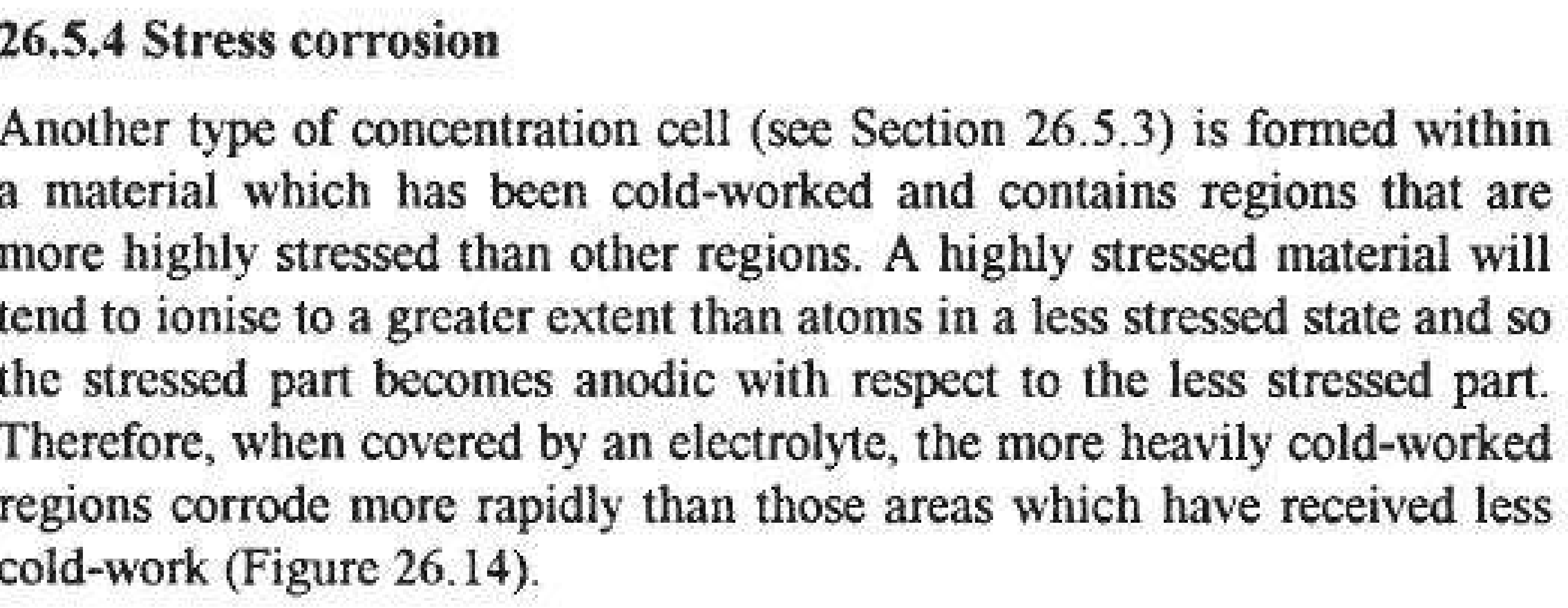
Figure 26.6 *Reactions at and near the surface of iron heated in contact with the atmosphere.*

Both metal ions and oxygen ions are able to diffuse through the scale and so thicken the oxide layer. When the crystal lattice of this layer is not coherent – that is, does not 'match up' – with the crystal lattice of the metal beneath, it flakes away so that the metal surface is exposed to more rapid oxidation. If the oxide layer is coherent, as with aluminium, titanium, etc., the metal is protected by this closely adherent oxide layer.

Table 26.1 *The Electrochemical (Galvanic) Series*

Metal ion	*Electrode potential V*
Gold Au^{+++}	+1.5
Silver Ag^{+}	+0.8
Copper Cu^{+}	+0.52
Copper Cu^{++}	+0.34
Hydrogen H^{+}	0.00
Iron Fe^{+++}	–0.05
Lead Pb^{+++}	–0.13
Tin Sn^{++}	–0.14
Nickel Ni^{++}	–0.25
Iron Fe^{++}	–0.44
Chromium Cr^{+++}	–0.74
Zinc Zn^{++}	–0.76
Aluminium Al^{+++}	–1.66
Magnesium Mg^{++}	–2.37
Lithium Li^{+}	–3.04

The potential are measured with respect to hydrogen which is the reference, + values indicating cathodic and – values anodic with respect to hydrogen. The term noble metals is used for those at the top of the table and base metals for those at the bottom.



26.5.4 Stress corrosion

Another type of concentration cell (see Section 26.5.3) is formed within a material which has been cold-worked and contains regions that are more highly stressed than other regions. A highly stressed material will tend to ionise to a greater extent than atoms in a less stressed state and so the stressed part becomes anodic with respect to the less stressed part. Therefore, when covered by an electrolyte, the more heavily cold-worked regions corrode more rapidly than those areas which have received less cold-work (Figure 26.14).

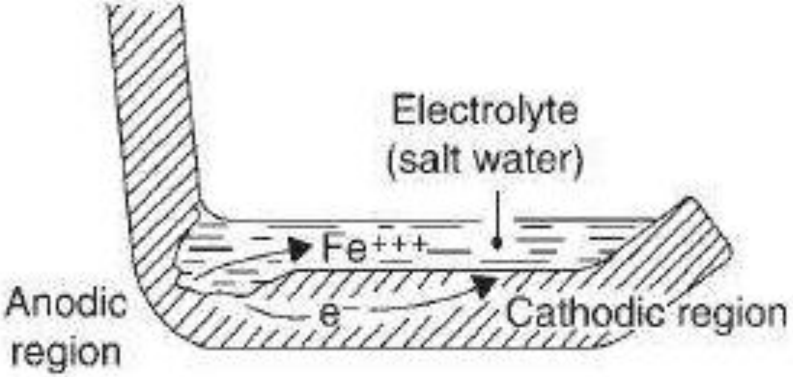
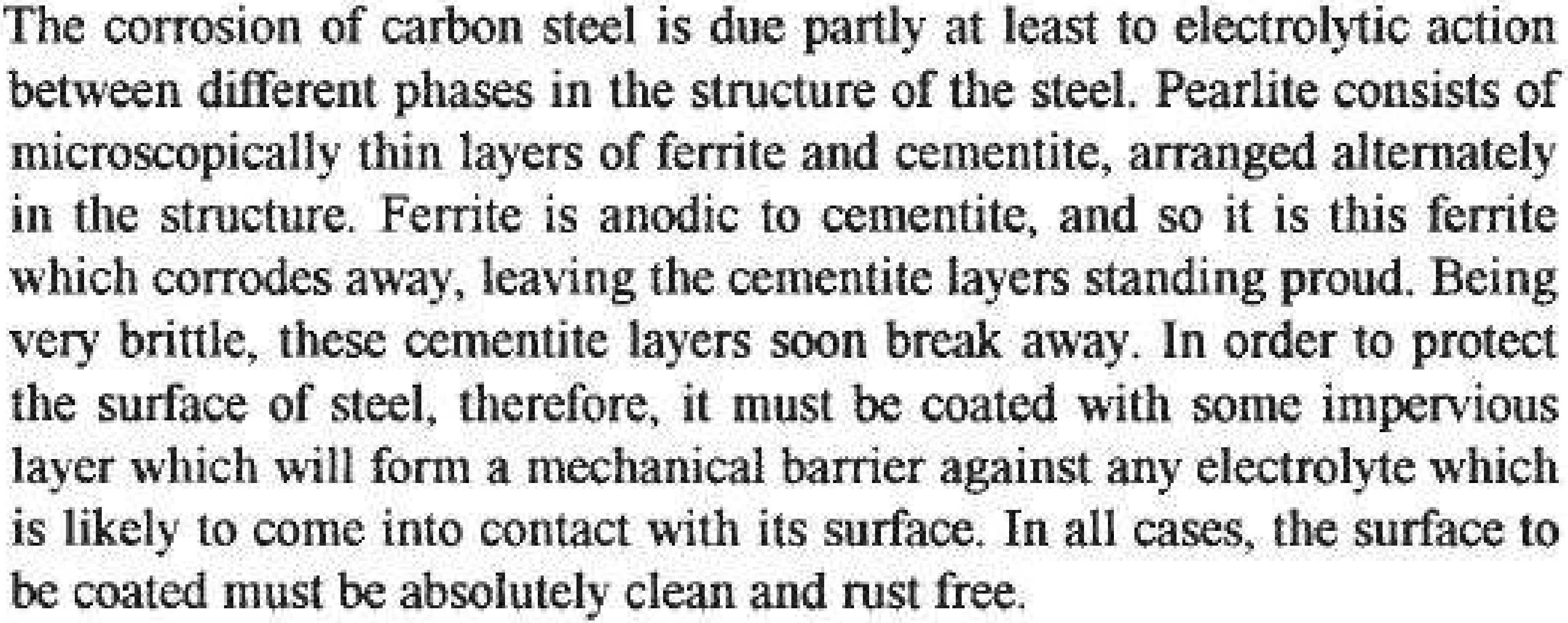


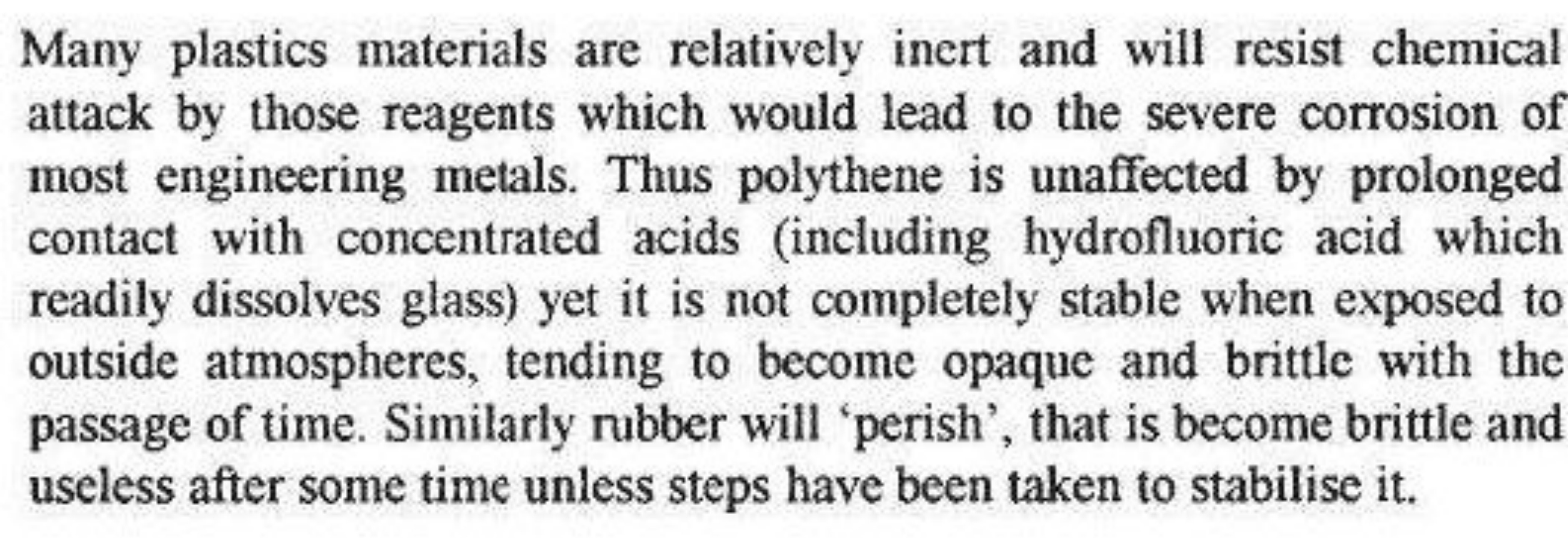
Figure 26.14 *Corrosion due to non-uniform cold work.*

The protection of metal surfaces

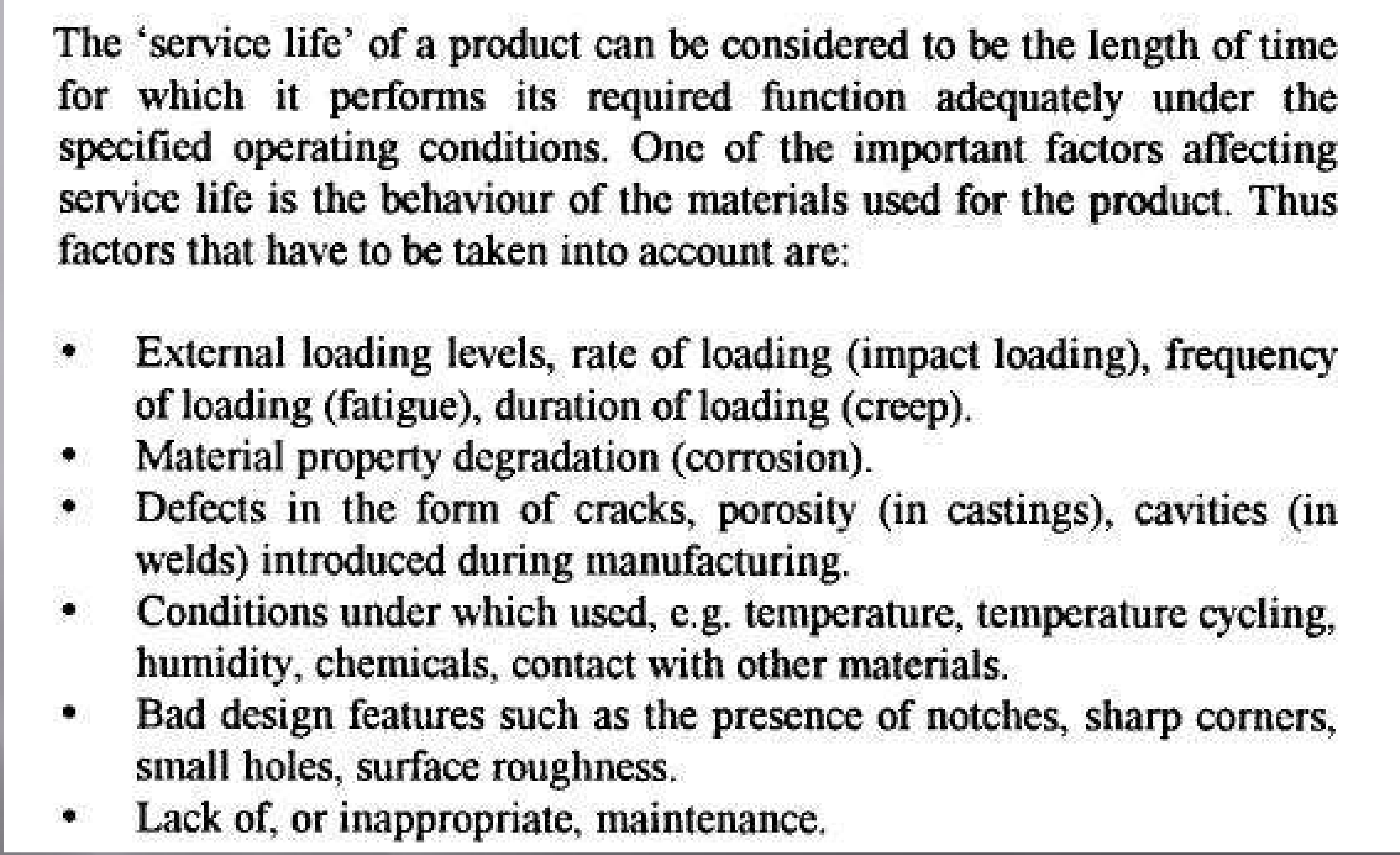


The corrosion of carbon steel is due partly at least to electrolytic action between different phases in the structure of the steel. Pearlite consists of microscopically thin layers of ferrite and cementite, arranged alternately in the structure. Ferrite is anodic to cementite, and so it is this ferrite which corrodes away, leaving the cementite layers standing proud. Being very brittle, these cementite layers soon break away. In order to protect the surface of steel, therefore, it must be coated with some impervious layer which will form a mechanical barrier against any electrolyte which is likely to come into contact with its surface. In all cases, the surface to be coated must be absolutely clean and rust free.

Stability of plastics

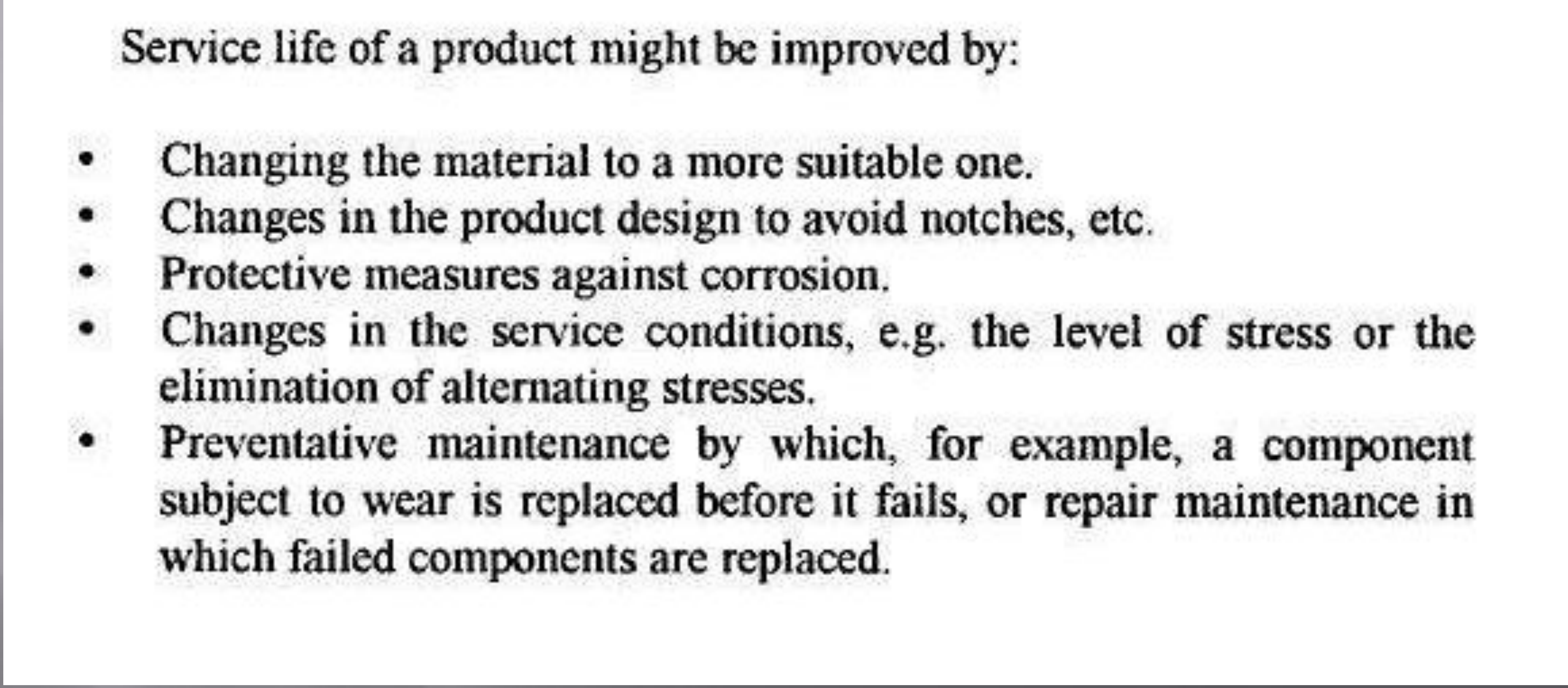


Many plastics materials are relatively inert and will resist chemical attack by those reagents which would lead to the severe corrosion of most engineering metals. Thus polythene is unaffected by prolonged contact with concentrated acids (including hydrofluoric acid which readily dissolves glass) yet it is not completely stable when exposed to outside atmospheres, tending to become opaque and brittle with the passage of time. Similarly rubber will ‘perish’, that is become brittle and useless after some time unless steps have been taken to stabilise it.



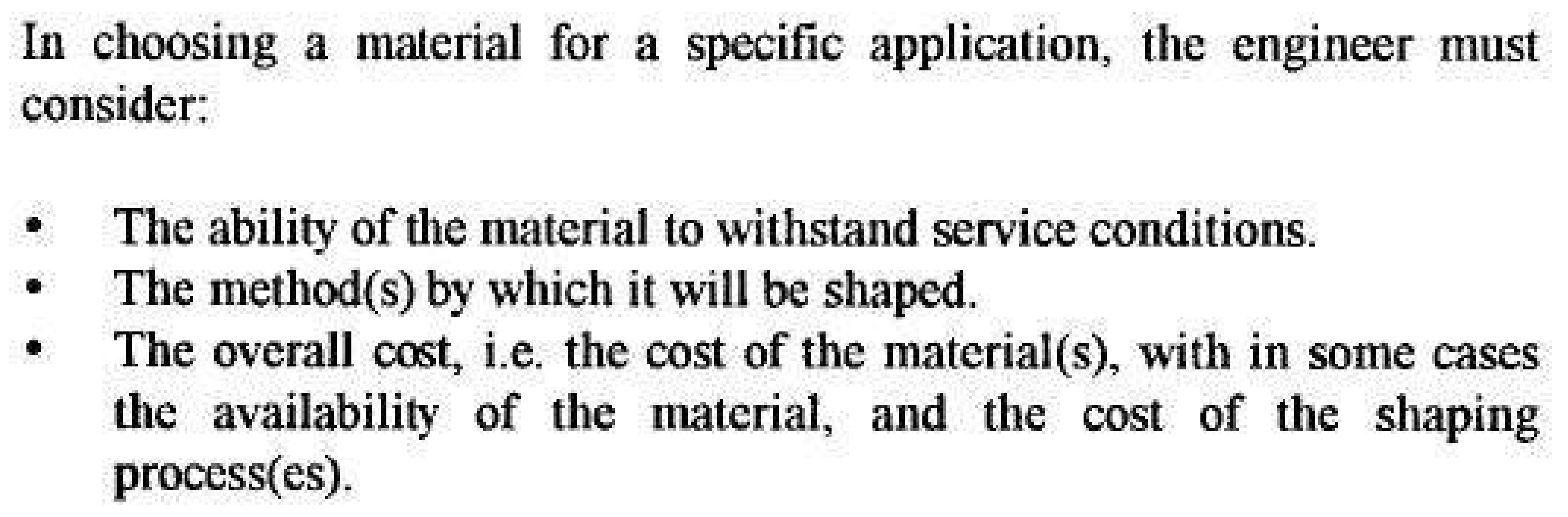
The 'service life' of a product can be considered to be the length of time for which it performs its required function adequately under the specified operating conditions. One of the important factors affecting service life is the behaviour of the materials used for the product. Thus factors that have to be taken into account are:

- External loading levels, rate of loading (impact loading), frequency of loading (fatigue), duration of loading (creep).
- Material property degradation (corrosion).
- Defects in the form of cracks, porosity (in castings), cavities (in welds) introduced during manufacturing.
- Conditions under which used, e.g. temperature, temperature cycling, humidity, chemicals, contact with other materials.
- Bad design features such as the presence of notches, sharp corners, small holes, surface roughness.
- Lack of, or inappropriate, maintenance.



Service life of a product might be improved by:

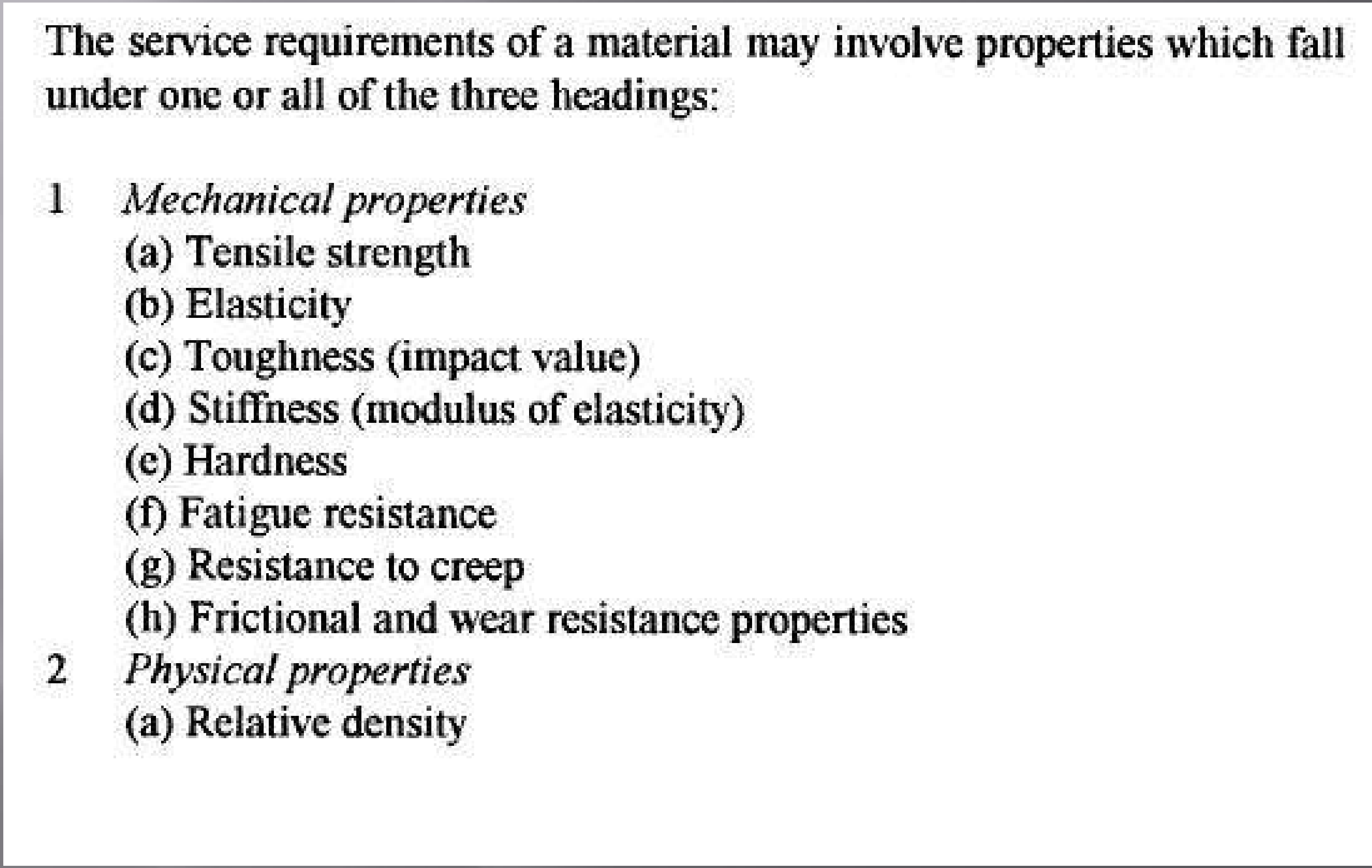
- Changing the material to a more suitable one.
- Changes in the product design to avoid notches, etc.
- Protective measures against corrosion.
- Changes in the service conditions, e.g. the level of stress or the elimination of alternating stresses.
- Preventative maintenance by which, for example, a component subject to wear is replaced before it fails, or repair maintenance in which failed components are replaced.



In choosing a material for a specific application, the engineer must consider:

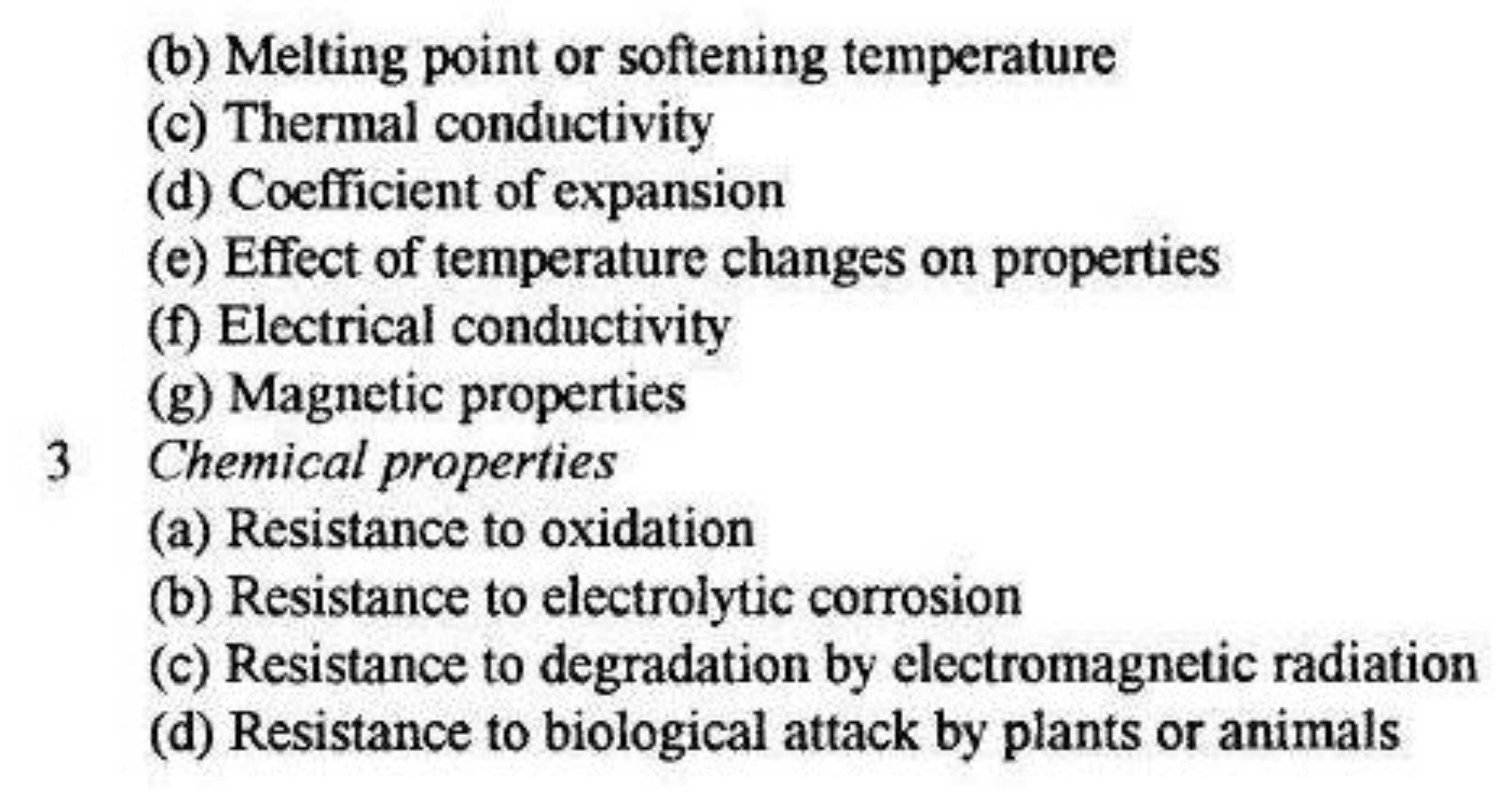
- The ability of the material to withstand service conditions.
- The method(s) by which it will be shaped.
- The overall cost, i.e. the cost of the material(s), with in some cases the availability of the material, and the cost of the shaping process(es).

Service requirements



The service requirements of a material may involve properties which fall under one or all of the three headings:

1 *Mechanical properties*
  (a) Tensile strength
  (b) Elasticity
  (c) Toughness (impact value)
  (d) Stiffness (modulus of elasticity)
  (e) Hardness
  (f) Fatigue resistance
  (g) Resistance to creep
  (h) Frictional and wear resistance properties
2 *Physical properties*
  (a) Relative density



(b) Melting point or softening temperature
(c) Thermal conductivity
(d) Coefficient of expansion
(e) Effect of temperature changes on properties
(f) Electrical conductivity
(g) Magnetic properties

3 *Chemical properties*

(a) Resistance to oxidation
(b) Resistance to electrolytic corrosion
(c) Resistance to degradation by electromagnetic radiation
(d) Resistance to biological attack by plants or animals

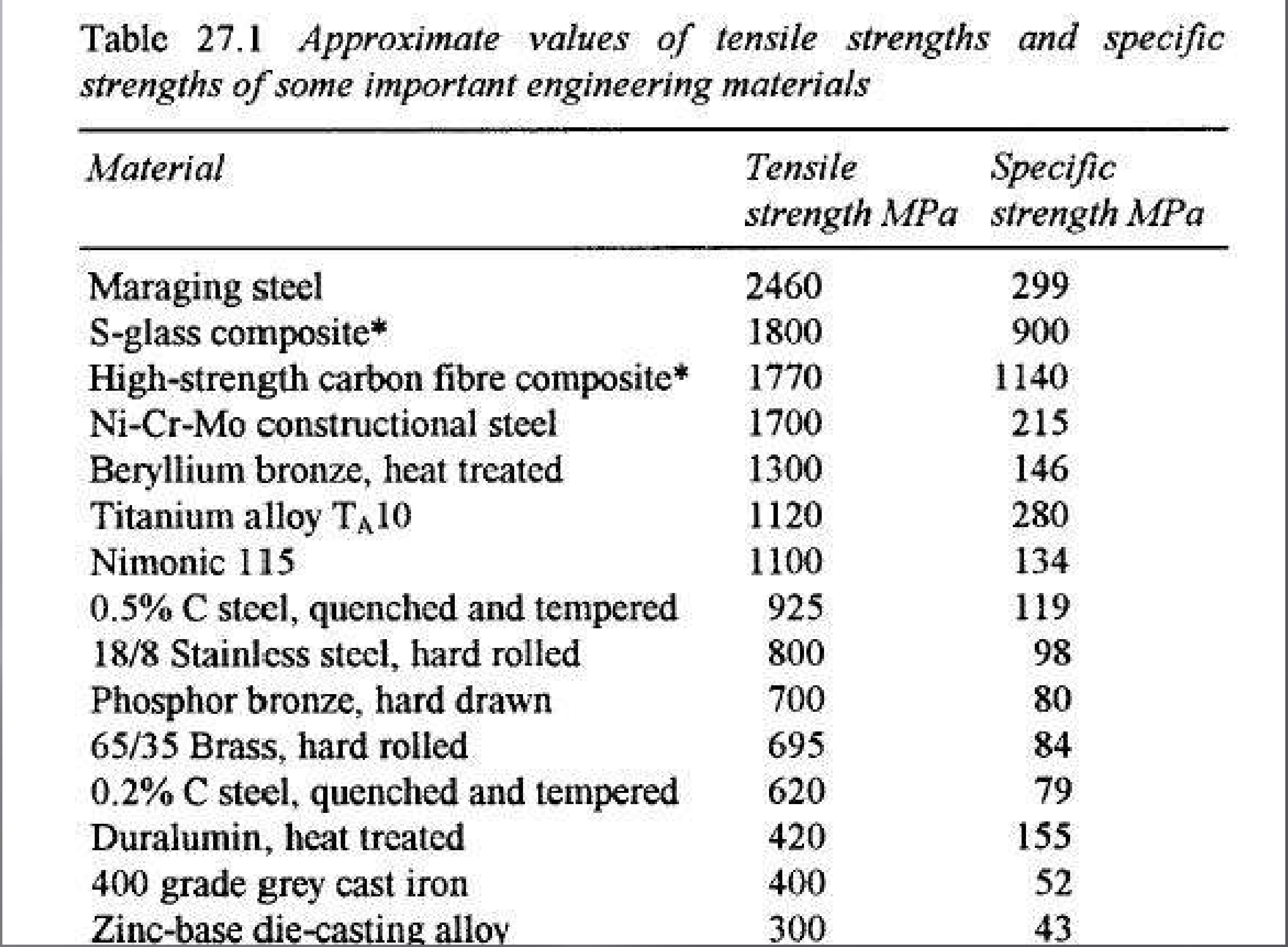
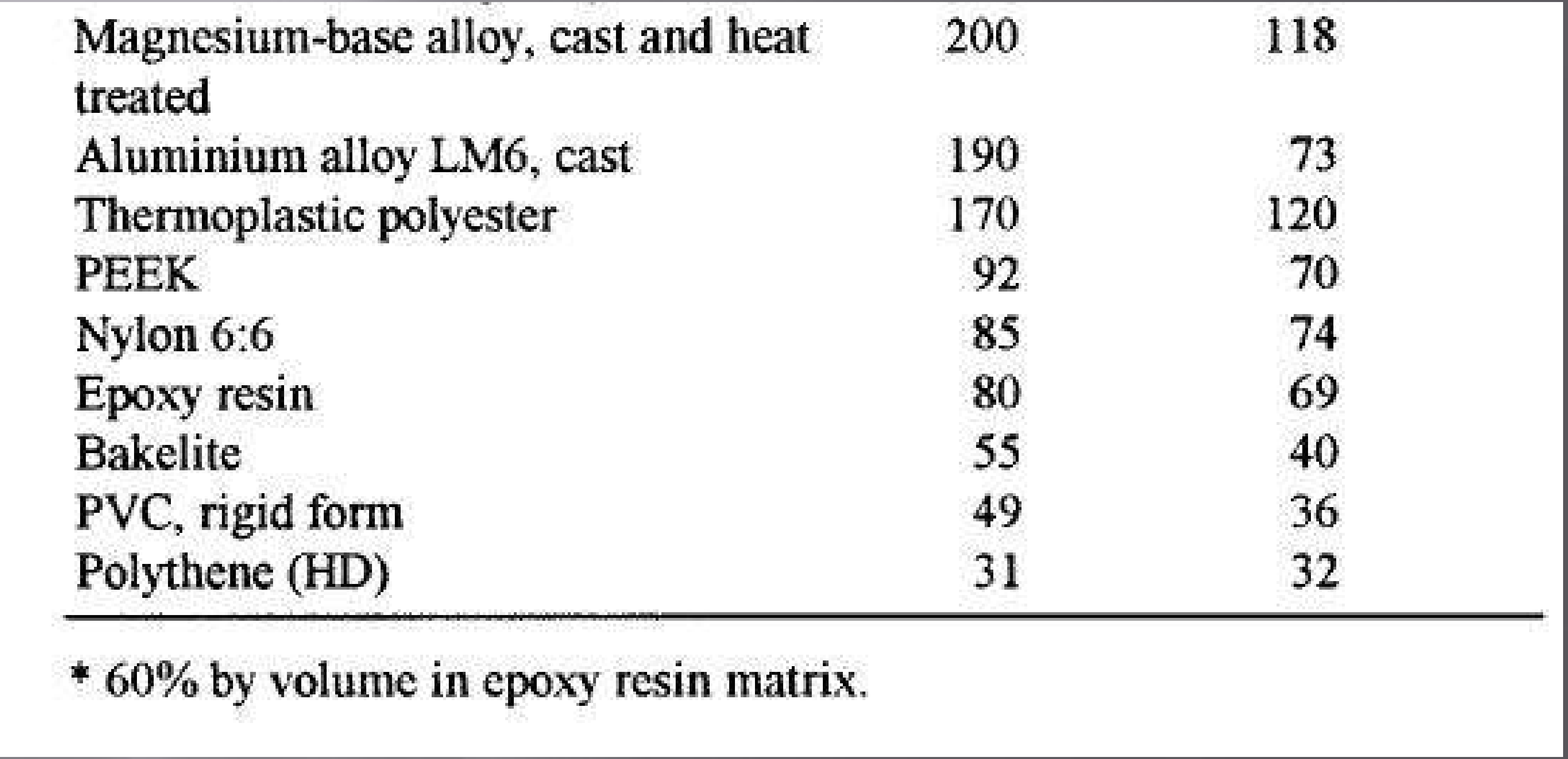


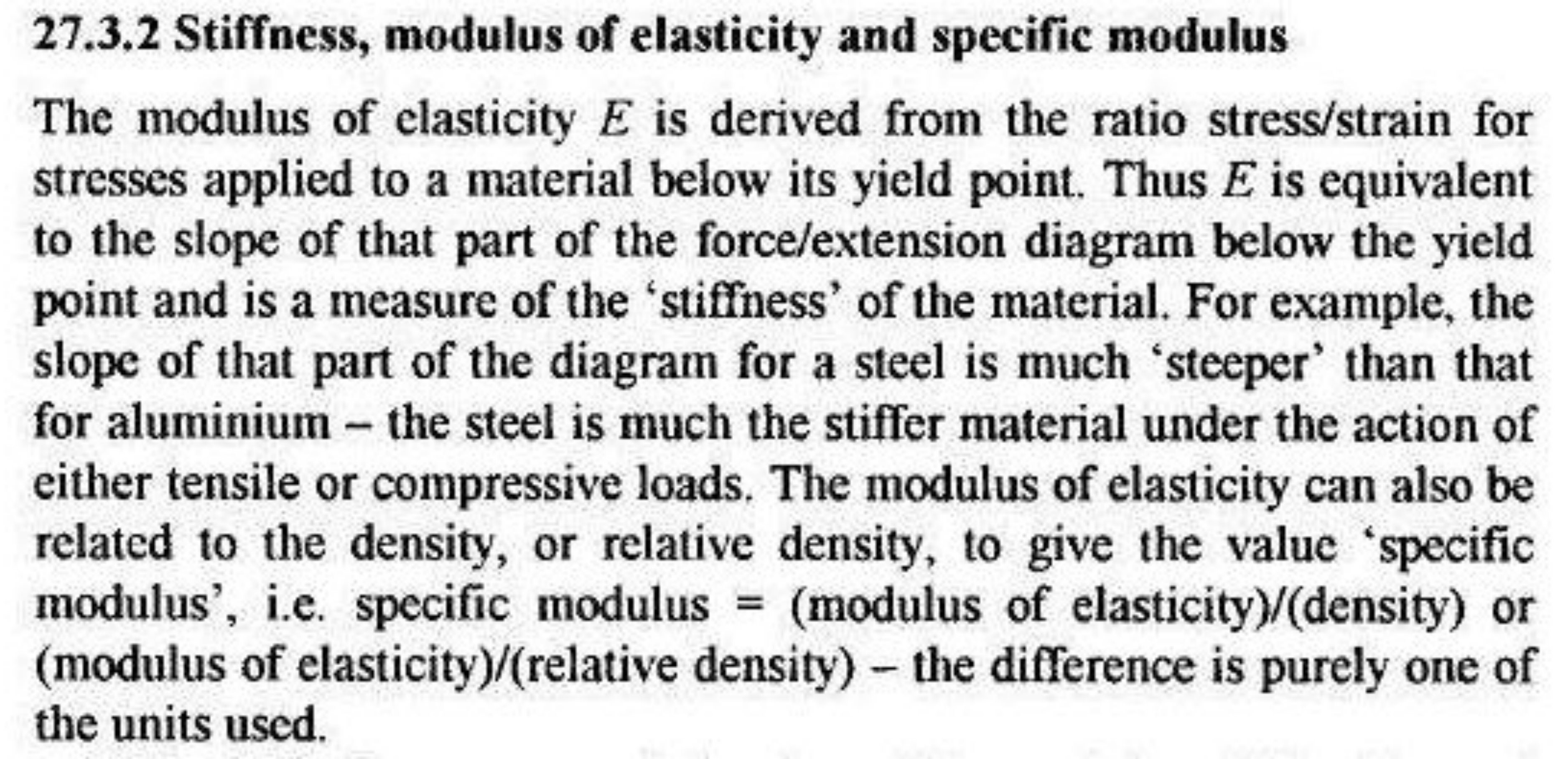
Table 27.1 *Approximate values of tensile strengths and specific strengths of some important engineering materials*

Material	*Tensile strength MPa*	*Specific strength MPa*
Maraging steel	2460	299
S-glass composite*	1800	900
High-strength carbon fibre composite*	1770	1140
Ni-Cr-Mo constructional steel	1700	215
Beryllium bronze, heat treated	1300	146
Titanium alloy T_A10	1120	280
Nimonic 115	1100	134
0.5% C steel, quenched and tempered	925	119
18/8 Stainless steel, hard rolled	800	98
Phosphor bronze, hard drawn	700	80
65/35 Brass, hard rolled	695	84
0.2% C steel, quenched and tempered	620	79
Duralumin, heat treated	420	155
400 grade grey cast iron	400	52
Zinc-base die-casting alloy	300	43



Magnesium-base alloy, cast and heat treated	200	118
Aluminium alloy LM6, cast	190	73
Thermoplastic polyester	170	120
PEEK	92	70
Nylon 6:6	85	74
Epoxy resin	80	69
Bakelite	55	40
PVC, rigid form	49	36
Polythene (HD)	31	32

* 60% by volume in epoxy resin matrix.



27.3.2 Stiffness, modulus of elasticity and specific modulus

The modulus of elasticity *E* is derived from the ratio stress/strain for stresses applied to a material below its yield point. Thus *E* is equivalent to the slope of that part of the force/extension diagram below the yield point and is a measure of the 'stiffness' of the material. For example, the slope of that part of the diagram for a steel is much 'steeper' than that for aluminium – the steel is much the stiffer material under the action of either tensile or compressive loads. The modulus of elasticity can also be related to the density, or relative density, to give the value 'specific modulus', i.e. specific modulus = (modulus of elasticity)/(density) or (modulus of elasticity)/(relative density) – the difference is purely one of the units used.

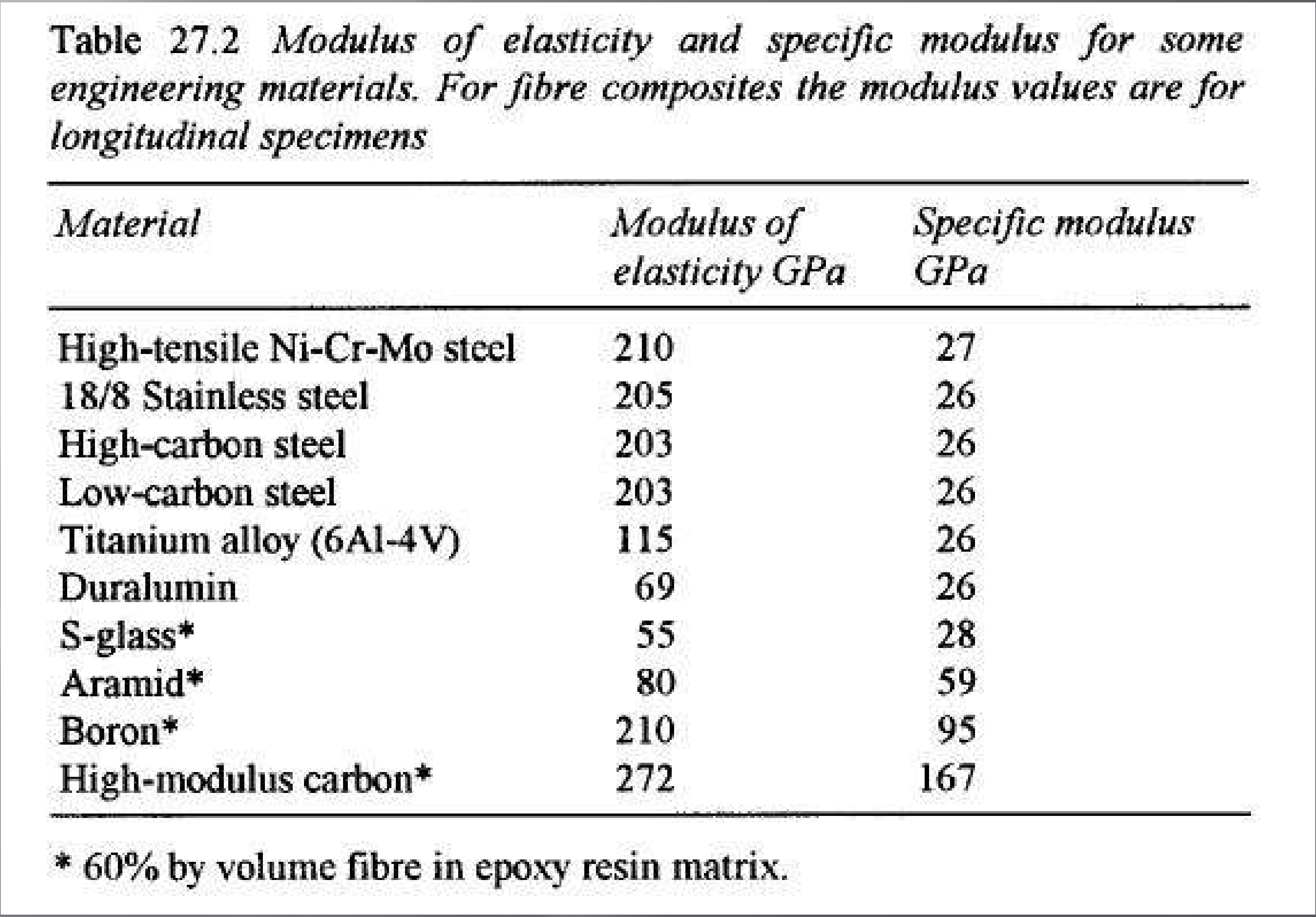


Table 27.2 *Modulus of elasticity and specific modulus for some engineering materials. For fibre composites the modulus values are for longitudinal specimens*

Material	*Modulus of elasticity GPa*	*Specific modulus GPa*
High-tensile Ni-Cr-Mo steel	210	27
18/8 Stainless steel	205	26
High-carbon steel	203	26
Low-carbon steel	203	26
Titanium alloy (6Al-4V)	115	26
Duralumin	69	26
S-glass*	55	28
Aramid*	80	59
Boron*	210	95
High-modulus carbon*	272	167

* 60% by volume fibre in epoxy resin matrix.

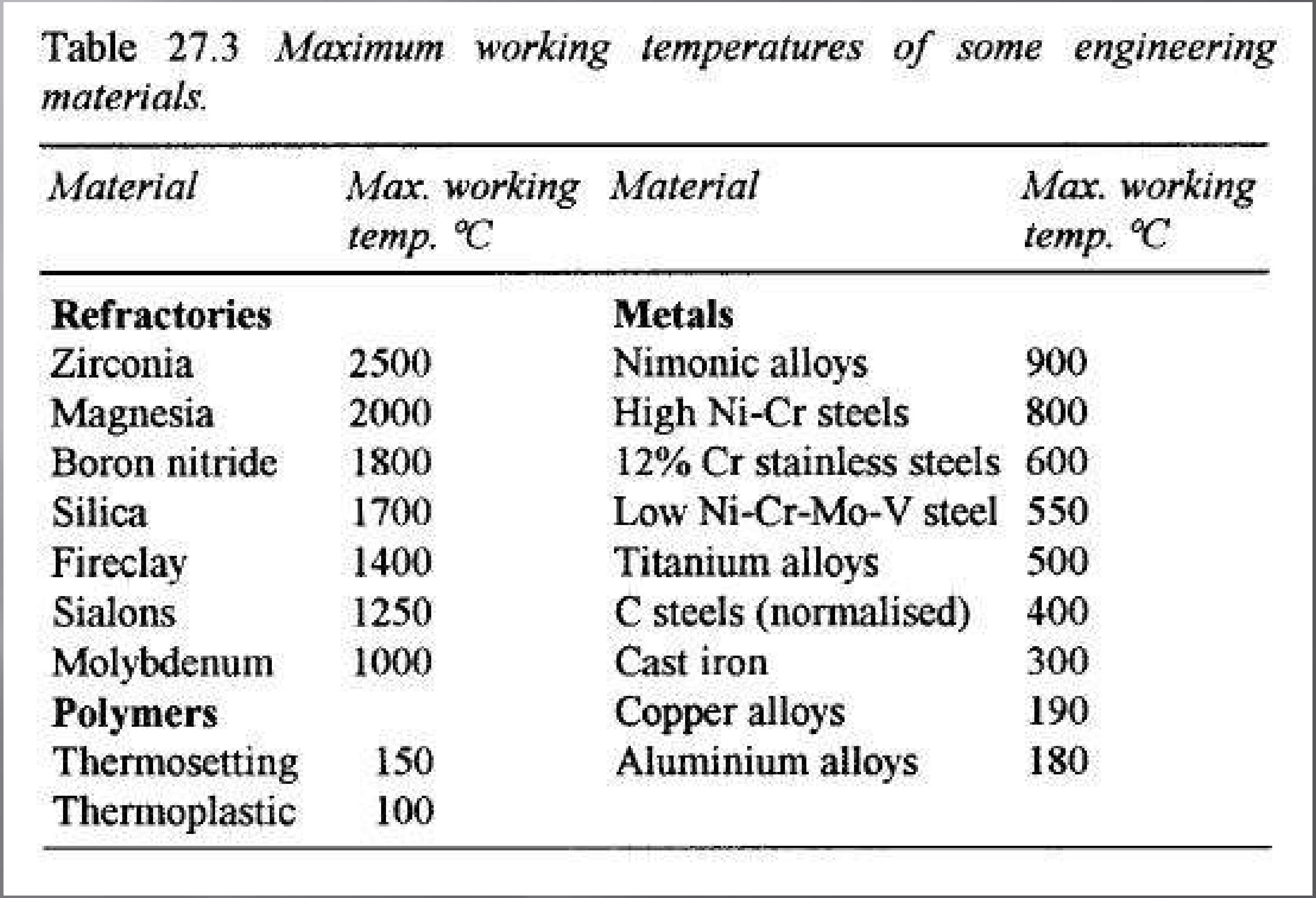
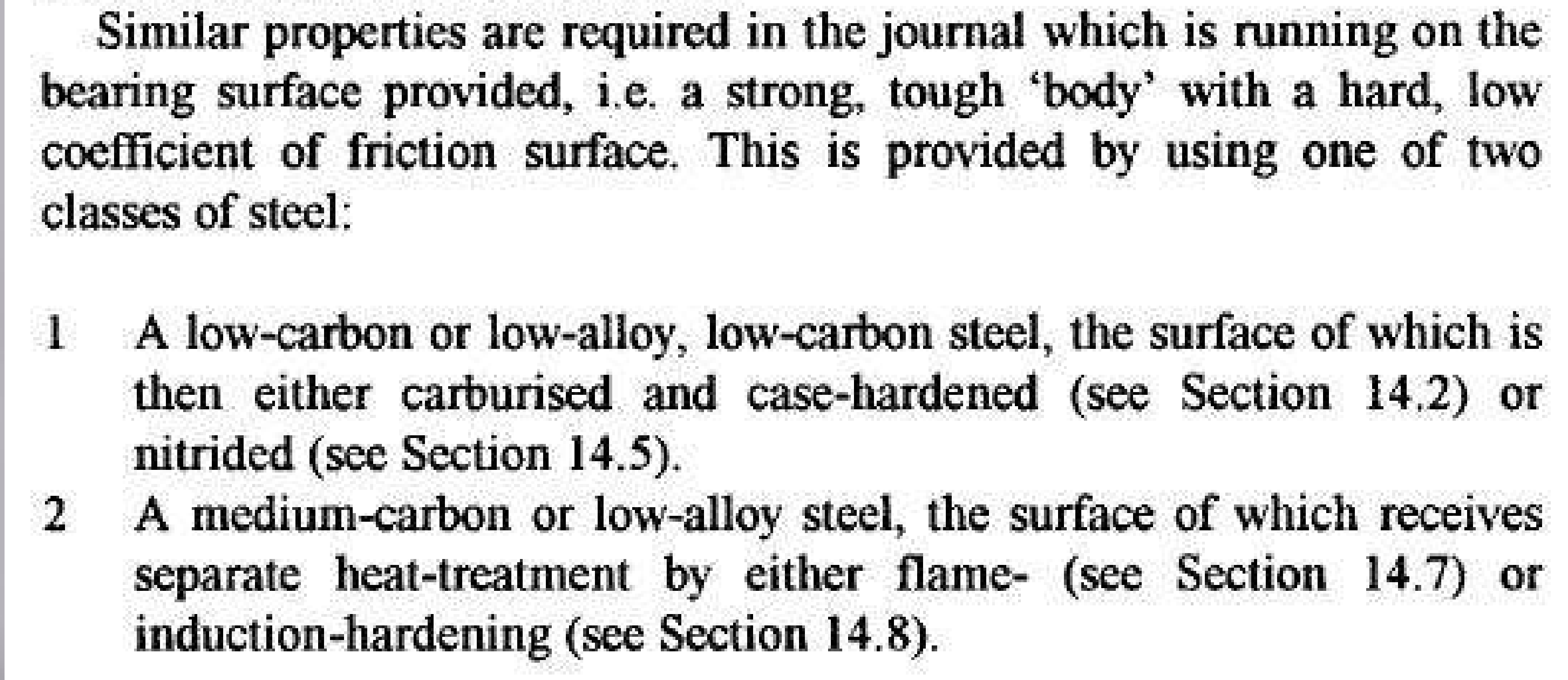


Table 27.3 *Maximum working temperatures of some engineering materials.*

Material	*Max. working temp. °C*	*Material*	*Max. working temp. °C*
Refractories		**Metals**	
Zirconia	2500	Nimonic alloys	900
Magnesia	2000	High Ni-Cr steels	800
Boron nitride	1800	12% Cr stainless steels	600
Silica	1700	Low Ni-Cr-Mo-V steel	550
Fireclay	1400	Titanium alloys	500
Sialons	1250	C steels (normalised)	400
Molybdenum	1000	Cast iron	300
Polymers		Copper alloys	190
Thermosetting	150	Aluminium alloys	180
Thermoplastic	100		



Similar properties are required in the journal which is running on the bearing surface provided, i.e. a strong, tough 'body' with a hard, low coefficient of friction surface. This is provided by using one of two classes of steel:

1. A low-carbon or low-alloy, low-carbon steel, the surface of which is then either carburised and case-hardened (see Section 14.2) or nitrided (see Section 14.5).
2. A medium-carbon or low-alloy steel, the surface of which receives separate heat-treatment by either flame- (see Section 14.7) or induction-hardening (see Section 14.8).

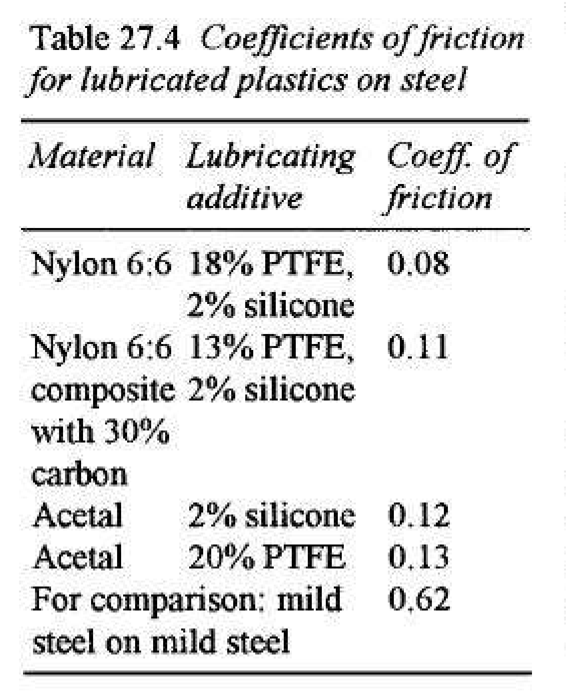
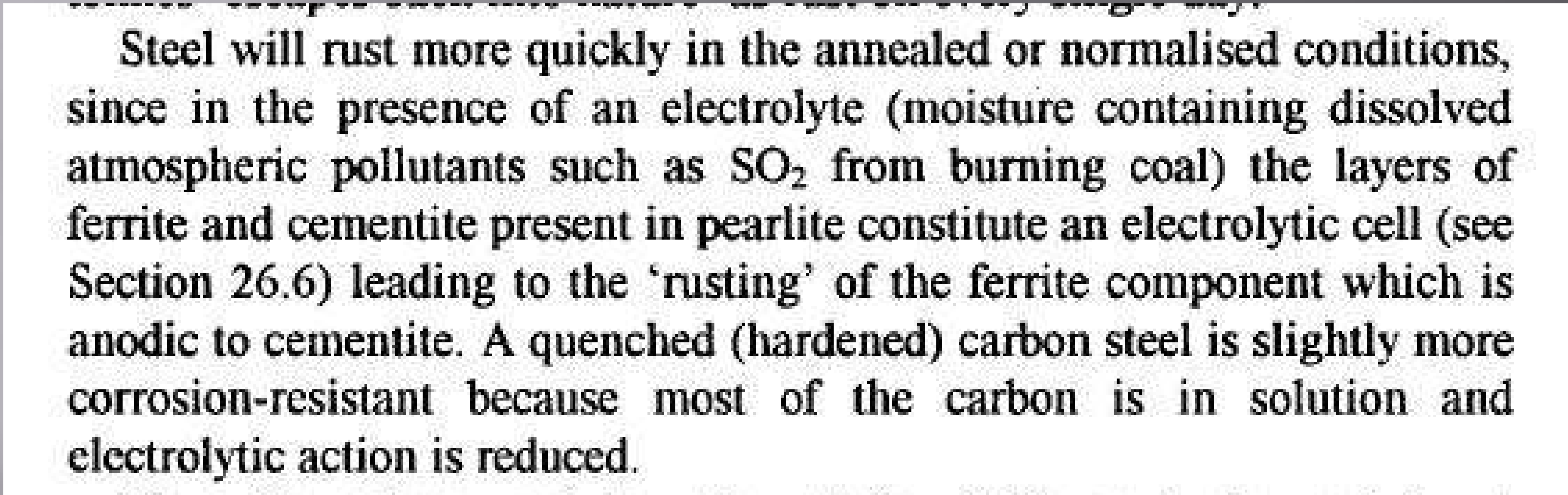


Table 27.4 *Coefficients of friction for lubricated plastics on steel*

Material	*Lubricating additive*	*Coeff. of friction*
Nylon 6:6	18% PTFE, 2% silicone	0.08
Nylon 6:6 composite with 30% carbon	13% PTFE, 2% silicone	0.11
Acetal	2% silicone	0.12
Acetal	20% PTFE	0.13
For comparison: mild steel on mild steel		0.62

Stability in the environment



Steel will rust more quickly in the annealed or normalised conditions, since in the presence of an electrolyte (moisture containing dissolved atmospheric pollutants such as SO_2 from burning coal) the layers of ferrite and cementite present in pearlite constitute an electrolytic cell (see Section 26.6) leading to the 'rusting' of the ferrite component which is anodic to cementite. A quenched (hardened) carbon steel is slightly more corrosion-resistant because most of the carbon is in solution and electrolytic action is reduced.

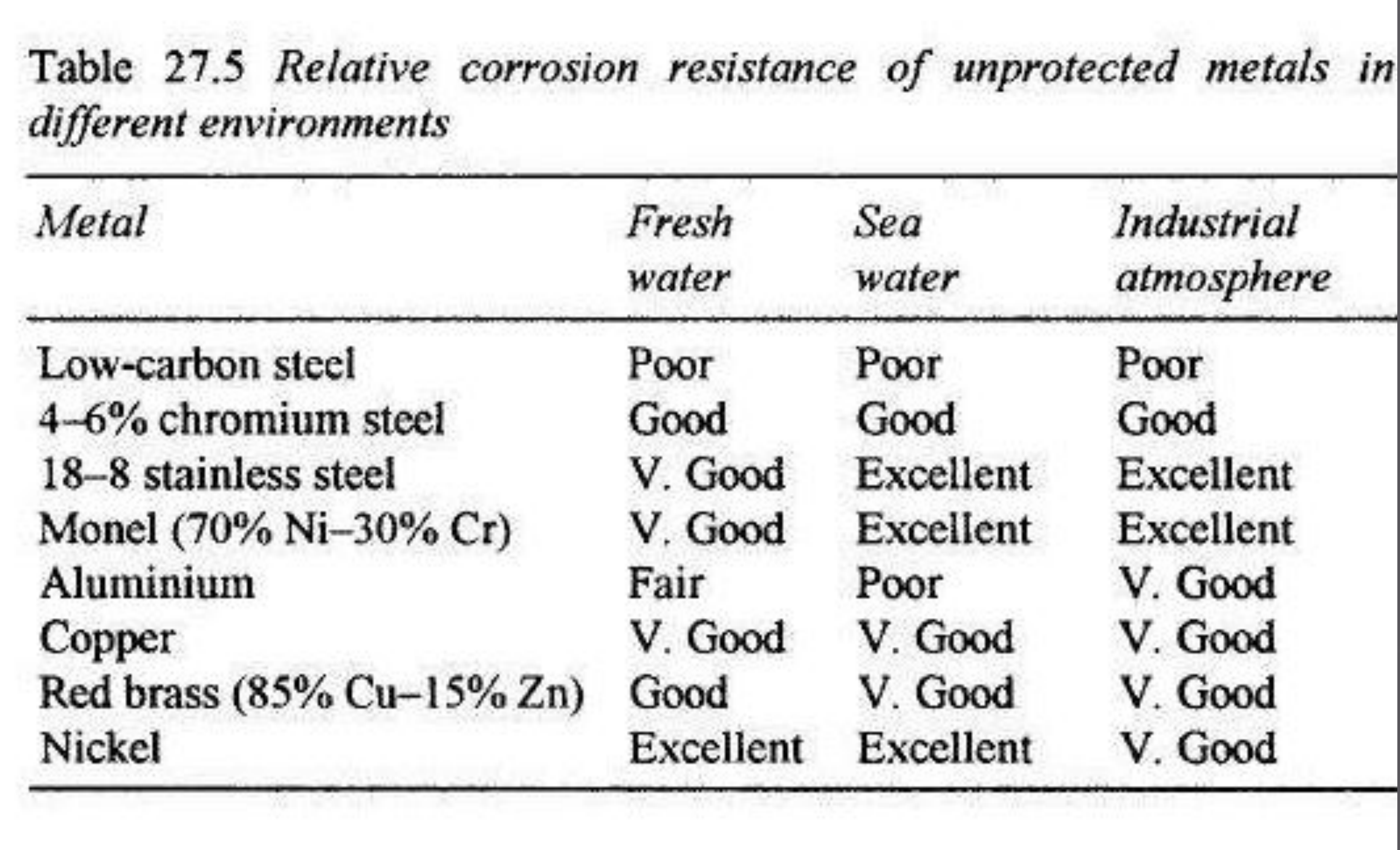
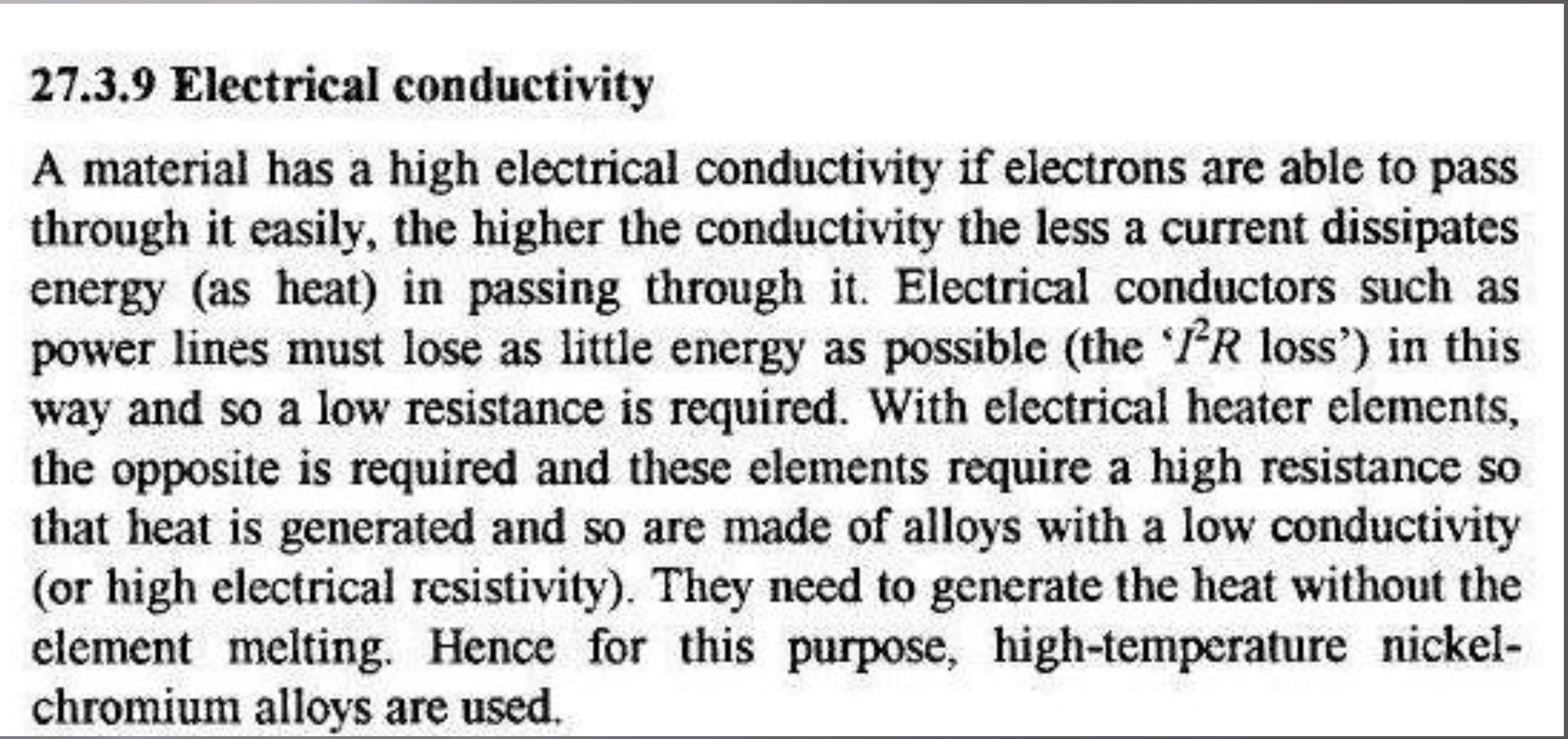


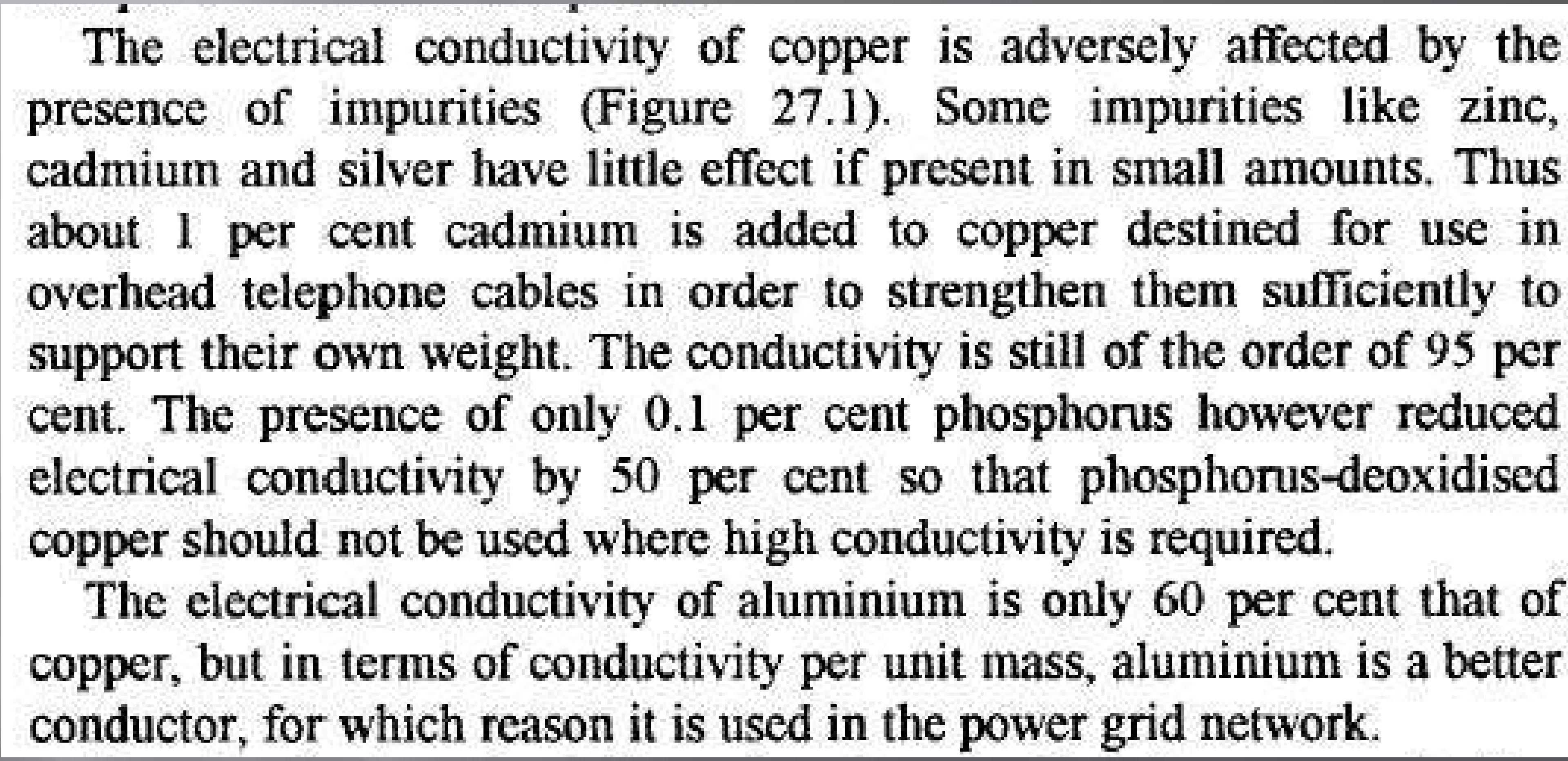
Table 27.5 *Relative corrosion resistance of unprotected metals in different environments*

Metal	*Fresh water*	*Sea water*	*Industrial atmosphere*
Low-carbon steel	Poor	Poor	Poor
4–6% chromium steel	Good	Good	Good
18–8 stainless steel	V. Good	Excellent	Excellent
Monel (70% Ni–30% Cr)	V. Good	Excellent	Excellent
Aluminium	Fair	Poor	V. Good
Copper	V. Good	V. Good	V. Good
Red brass (85% Cu–15% Zn)	Good	V. Good	V. Good
Nickel	Excellent	Excellent	V. Good



27.3.9 Electrical conductivity

A material has a high electrical conductivity if electrons are able to pass through it easily, the higher the conductivity the less a current dissipates energy (as heat) in passing through it. Electrical conductors such as power lines must lose as little energy as possible (the 'I^2R loss') in this way and so a low resistance is required. With electrical heater elements, the opposite is required and these elements require a high resistance so that heat is generated and so are made of alloys with a low conductivity (or high electrical resistivity). They need to generate the heat without the element melting. Hence for this purpose, high-temperature nickel-chromium alloys are used.



The electrical conductivity of copper is adversely affected by the presence of impurities (Figure 27.1). Some impurities like zinc, cadmium and silver have little effect if present in small amounts. Thus about 1 per cent cadmium is added to copper destined for use in overhead telephone cables in order to strengthen them sufficiently to support their own weight. The conductivity is still of the order of 95 per cent. The presence of only 0.1 per cent phosphorus however reduced electrical conductivity by 50 per cent so that phosphorus-deoxidised copper should not be used where high conductivity is required.

The electrical conductivity of aluminium is only 60 per cent that of copper, but in terms of conductivity per unit mass, aluminium is a better conductor, for which reason it is used in the power grid network.

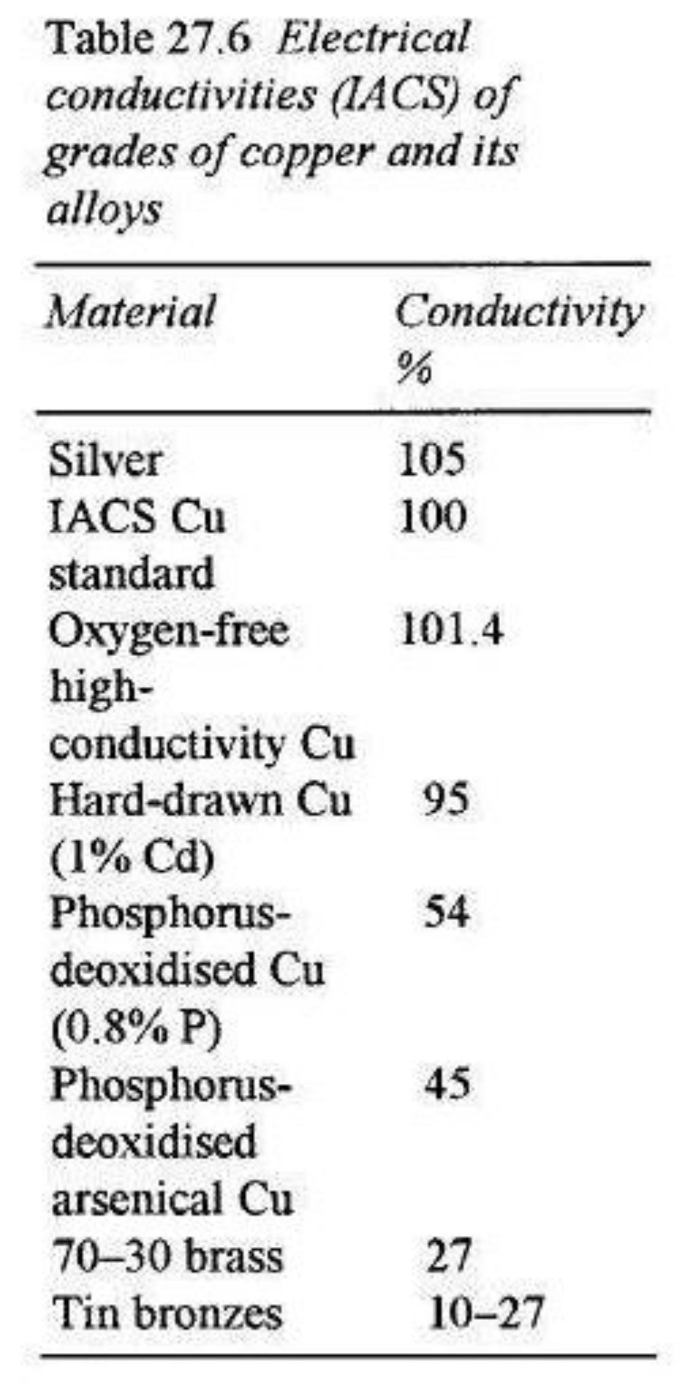


Table 27.6 *Electrical conductivities (IACS) of grades of copper and its alloys*

Material	*Conductivity %*
Silver	105
IACS Cu standard	100
Oxygen-free high-conductivity Cu	101.4
Hard-drawn Cu (1% Cd)	95
Phosphorus-deoxidised Cu (0.8% P)	54
Phosphorus-deoxidised arsenical Cu	45
70–30 brass	27
Tin bronzes	10–27

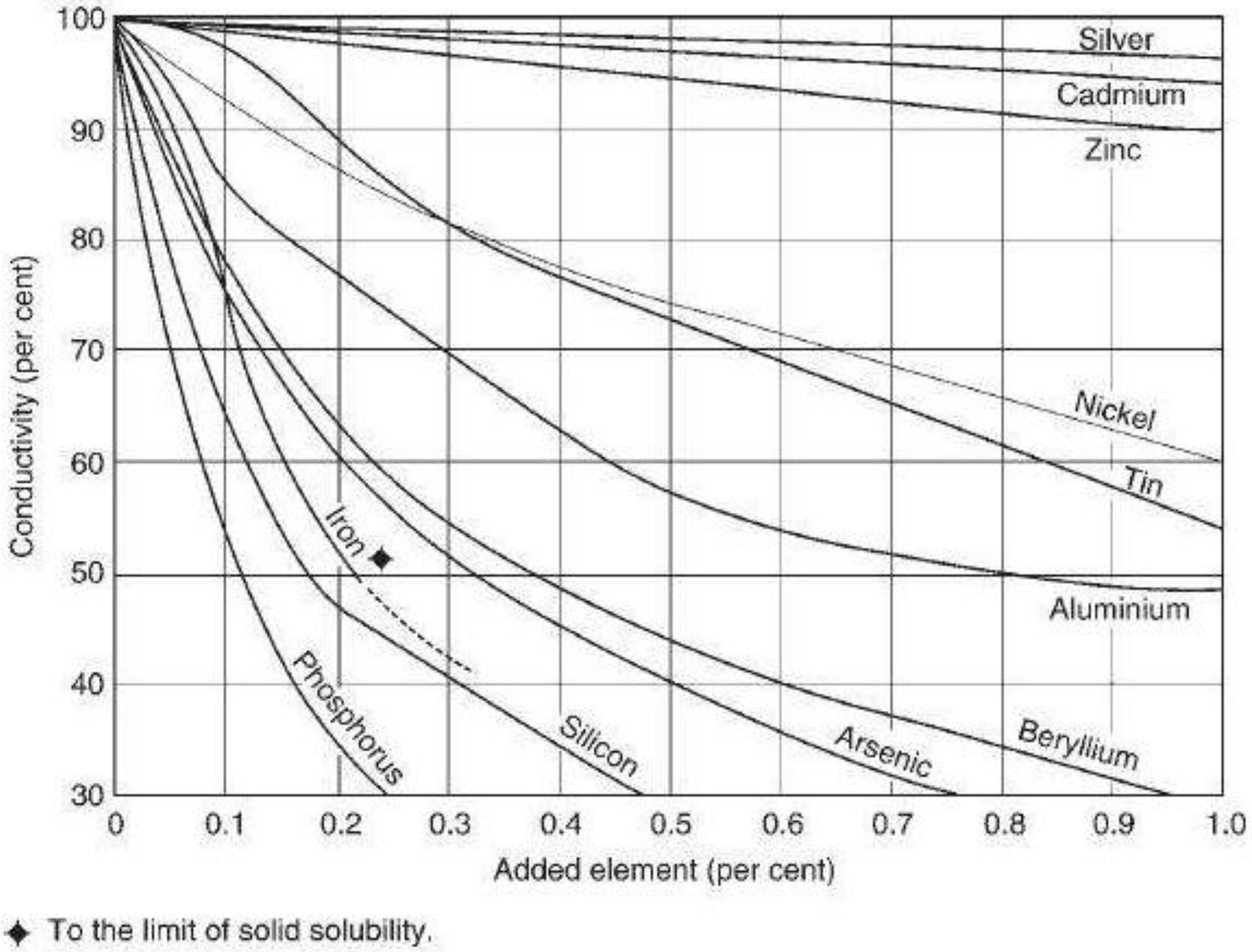


Figure 27.1 *The effect of impurities on the electrical conductivity of copper.*

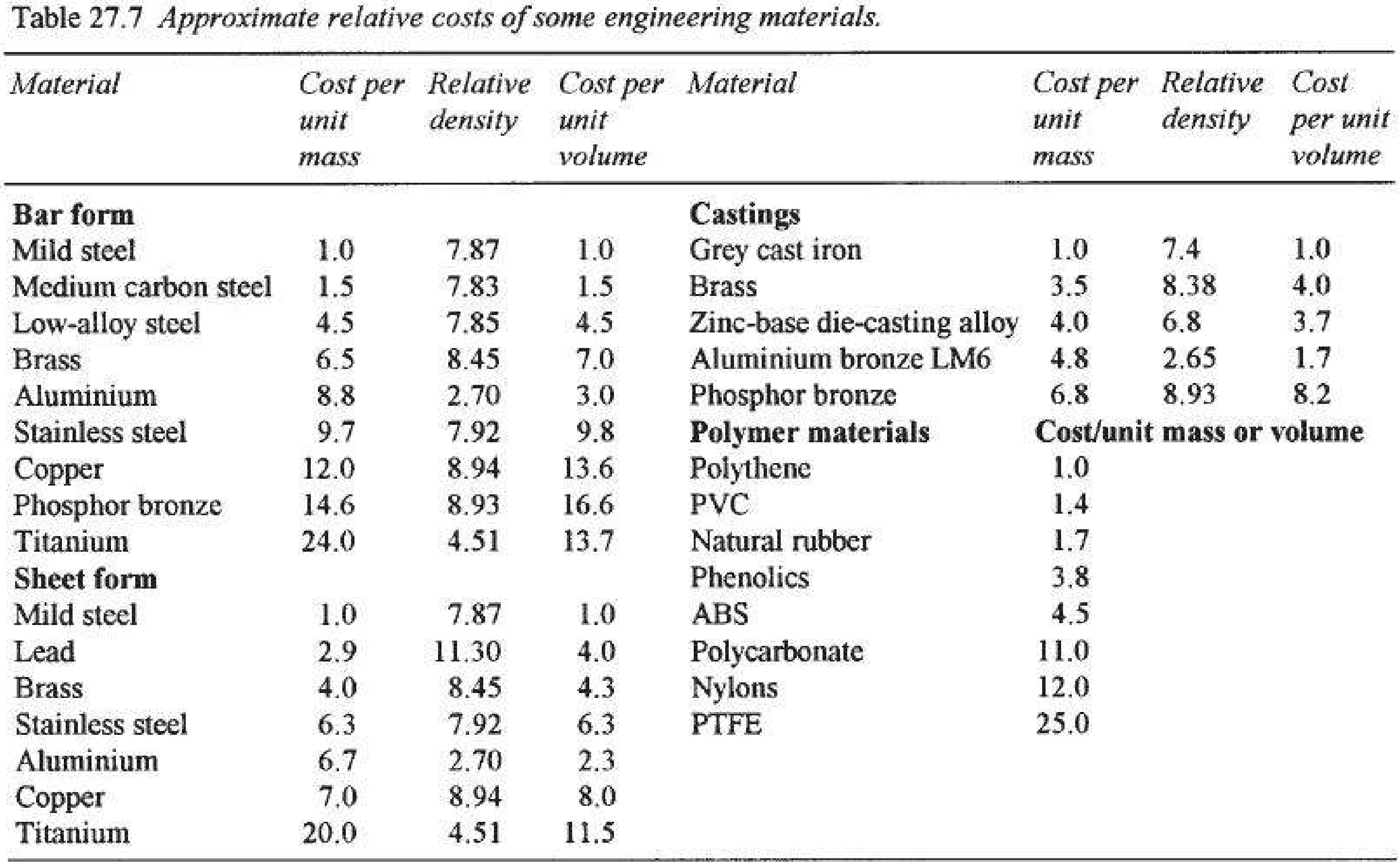
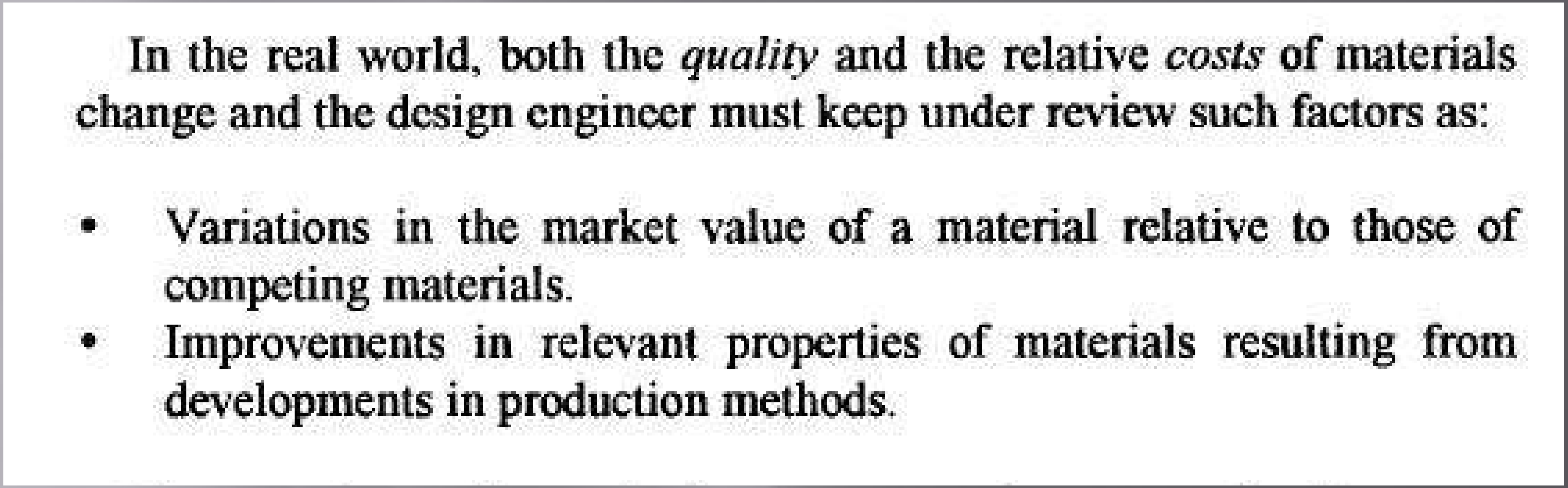


Table 27.7 *Approximate relative costs of some engineering materials.*

Material	*Cost per unit mass*	*Relative density*	*Cost per unit volume*	*Material*	*Cost per unit mass*	*Relative density*	*Cost per unit volume*
Bar form				**Castings**			
Mild steel	1.0	7.87	1.0	Grey cast iron	1.0	7.4	1.0
Medium carbon steel	1.5	7.83	1.5	Brass	3.5	8.38	4.0
Low-alloy steel	4.5	7.85	4.5	Zinc-base die-casting alloy	4.0	6.8	3.7
Brass	6.5	8.45	7.0	Aluminium bronze LM6	4.8	2.65	1.7
Aluminium	8.8	2.70	3.0	Phosphor bronze	6.8	8.93	8.2
Stainless steel	9.7	7.92	9.8	**Polymer materials**	**Cost/unit mass or volume**		
Copper	12.0	8.94	13.6	Polythene	1.0		
Phosphor bronze	14.6	8.93	16.6	PVC	1.4		
Titanium	24.0	4.51	13.7	Natural rubber	1.7		
Sheet form				Phenolics	3.8		
Mild steel	1.0	7.87	1.0	ABS	4.5		
Lead	2.9	11.30	4.0	Polycarbonate	11.0		
Brass	4.0	8.45	4.3	Nylons	12.0		
Stainless steel	6.3	7.92	6.3	PTFE	25.0		
Aluminium	6.7	2.70	2.3				
Copper	7.0	8.94	8.0				
Titanium	20.0	4.51	11.5				



In the real world, both the *quality* and the relative *costs* of materials change and the design engineer must keep under review such factors as:

- Variations in the market value of a material relative to those of competing materials.
- Improvements in relevant properties of materials resulting from developments in production methods.

The properties of a metallic material which affect its suitability for forming and shaping operations include:

- Malleability
- Ductility
- Strength
- The effects of temperature on the above properties
- Castability
- Machinability
- Capacity, if any, for heat treatment
- Methods by which the material can be joined

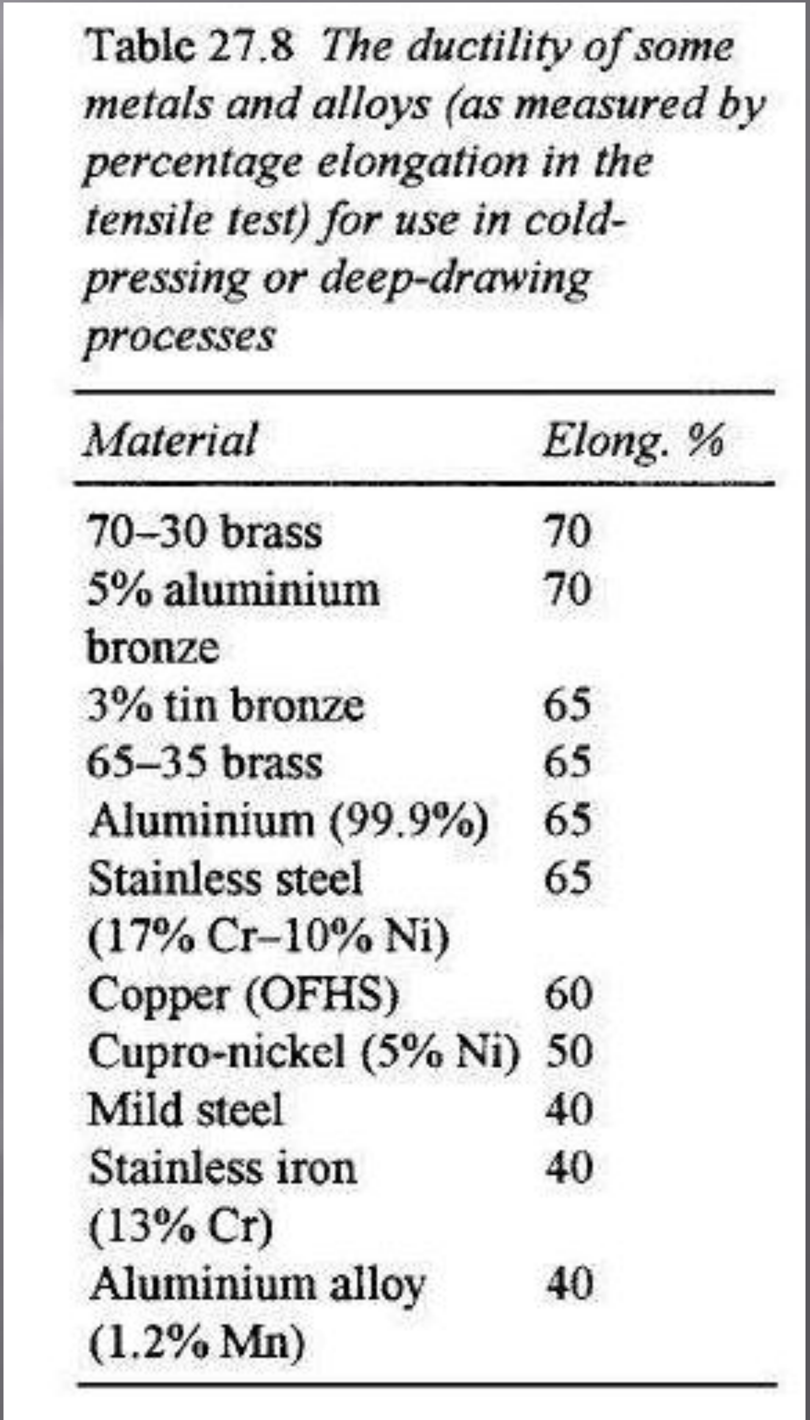
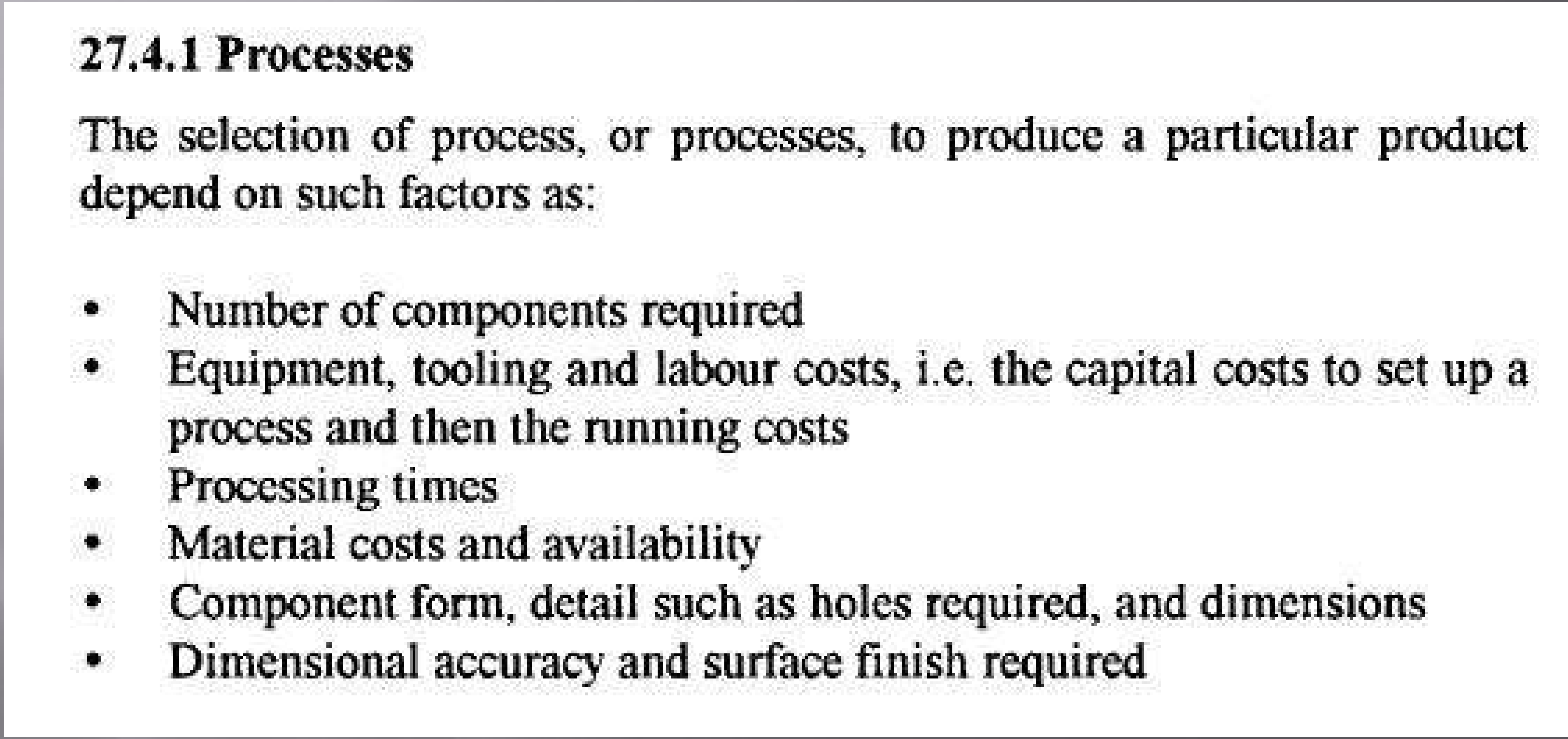


Table 27.8 *The ductility of some metals and alloys (as measured by percentage elongation in the tensile test) for use in cold-pressing or deep-drawing processes*

Material	*Elong. %*
70–30 brass	70
5% aluminium bronze	70
3% tin bronze	65
65–35 brass	65
Aluminium (99.9%)	65
Stainless steel (17% Cr–10% Ni)	65
Copper (OFHS)	60
Cupro-nickel (5% Ni)	50
Mild steel	40
Stainless iron (13% Cr)	40
Aluminium alloy (1.2% Mn)	40



27.4.1 Processes

The selection of process, or processes, to produce a particular product depend on such factors as:

- Number of components required
- Equipment, tooling and labour costs, i.e. the capital costs to set up a process and then the running costs
- Processing times
- Material costs and availability
- Component form, detail such as holes required, and dimensions
- Dimensional accuracy and surface finish required

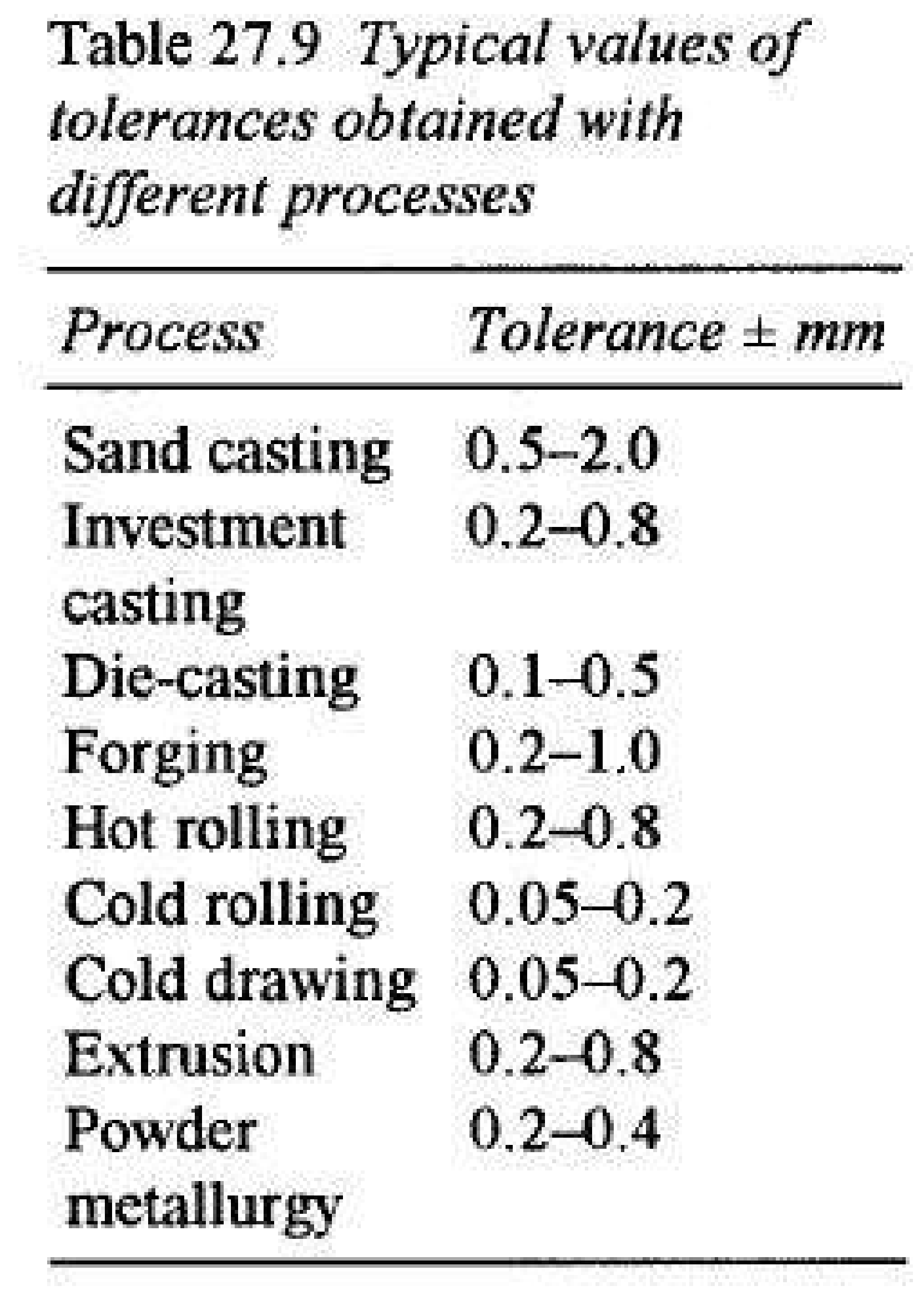
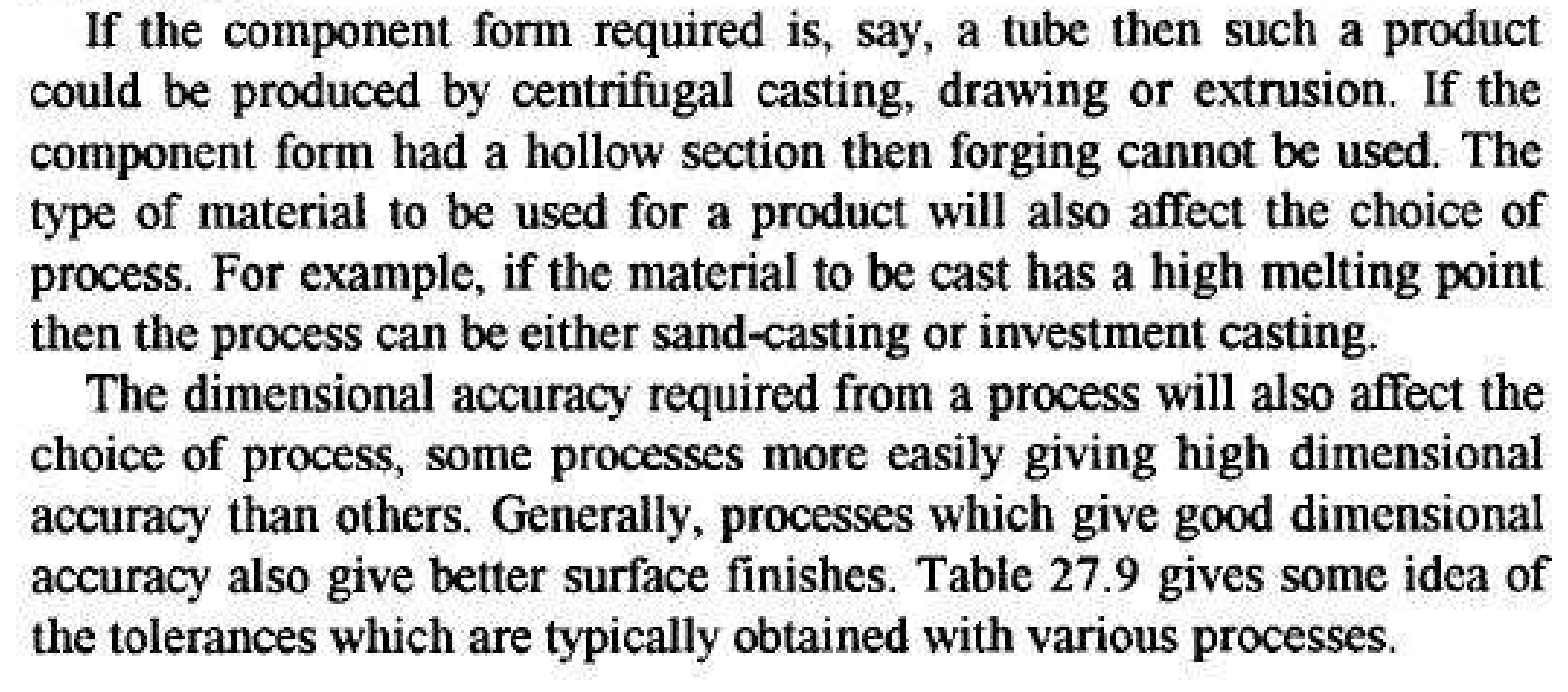


Table 27.9 *Typical values of tolerances obtained with different processes*

Process	*Tolerance ± mm*
Sand casting	0.5–2.0
Investment casting	0.2–0.8
Die-casting	0.1–0.5
Forging	0.2–1.0
Hot rolling	0.2–0.8
Cold rolling	0.05–0.2
Cold drawing	0.05–0.2
Extrusion	0.2–0.8
Powder metallurgy	0.2–0.4



If the component form required is, say, a tube then such a product could be produced by centrifugal casting, drawing or extrusion. If the component form had a hollow section then forging cannot be used. The type of material to be used for a product will also affect the choice of process. For example, if the material to be cast has a high melting point then the process can be either sand-casting or investment casting.

The dimensional accuracy required from a process will also affect the choice of process, some processes more easily giving high dimensional accuracy than others. Generally, processes which give good dimensional accuracy also give better surface finishes. Table 27.9 gives some idea of the tolerances which are typically obtained with various processes.