

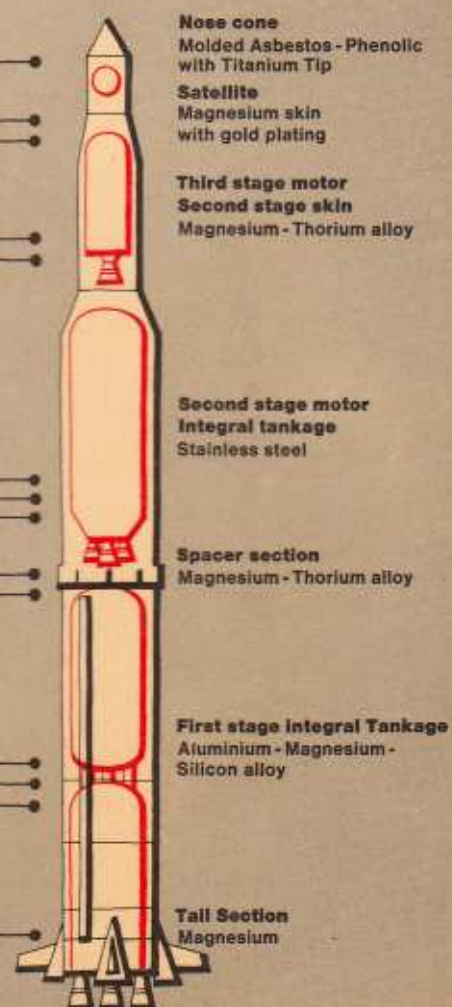


Metals and Alloys

6 C	7 N	8 O	9 F	10 Ne
14 Si	15 P	16 S	17 Cl	18 Ar
32 Ge	33 As	34 Se	35 Br	36 Kr
50 Sn	51 Sb	52 Te	53 I	54 Xe
82 Pb	83 Bi	84 Po	85 At	86 Rn

68 Er	69 Tm	70 Yb	71 Lu
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100 Fm	101 Md	102	103
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Cover illustration

Some of the metals and alloys that go into the manufacture of a rocket.

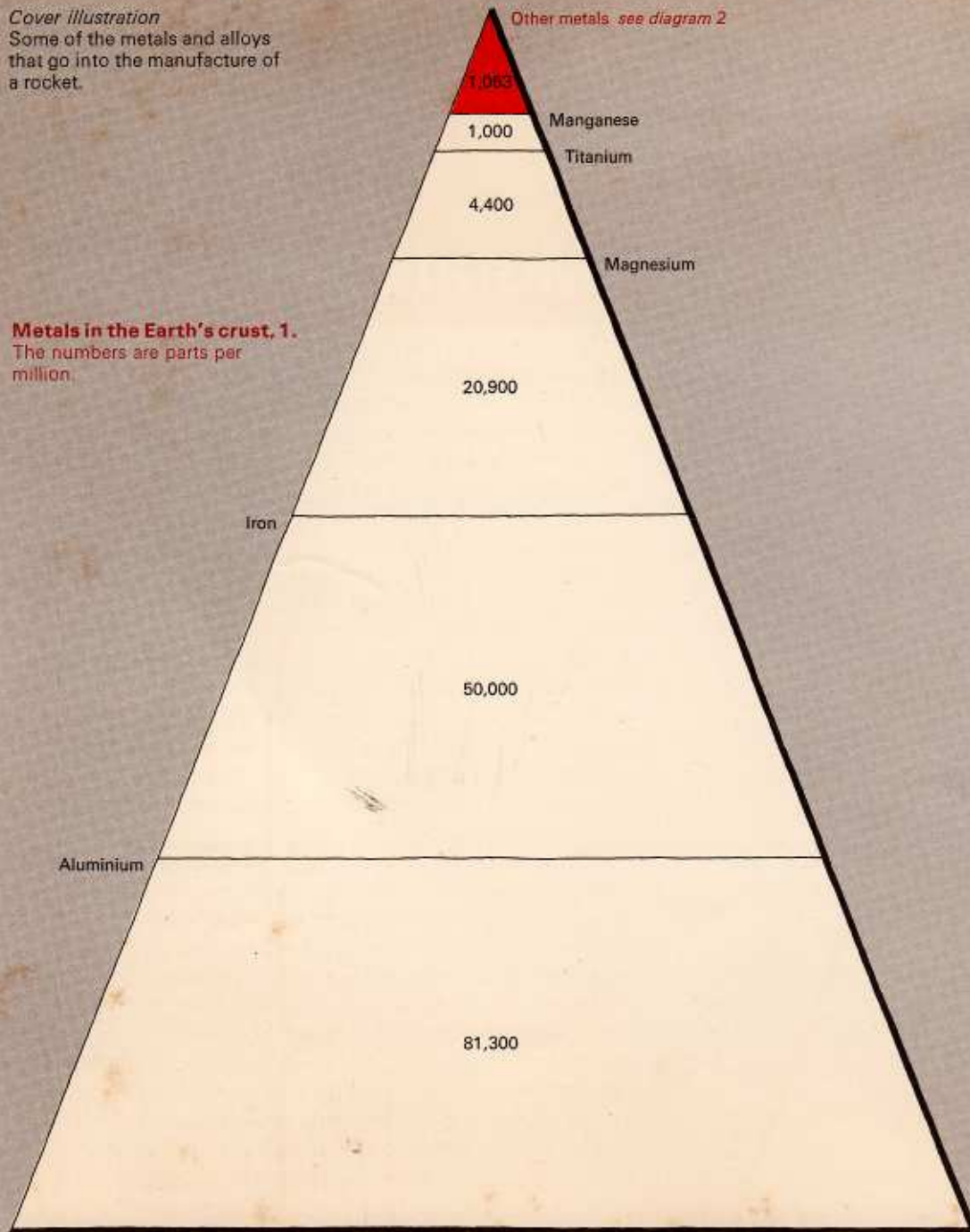
Other metals - see diagram 2

Metals in the Earth's crust, 1.

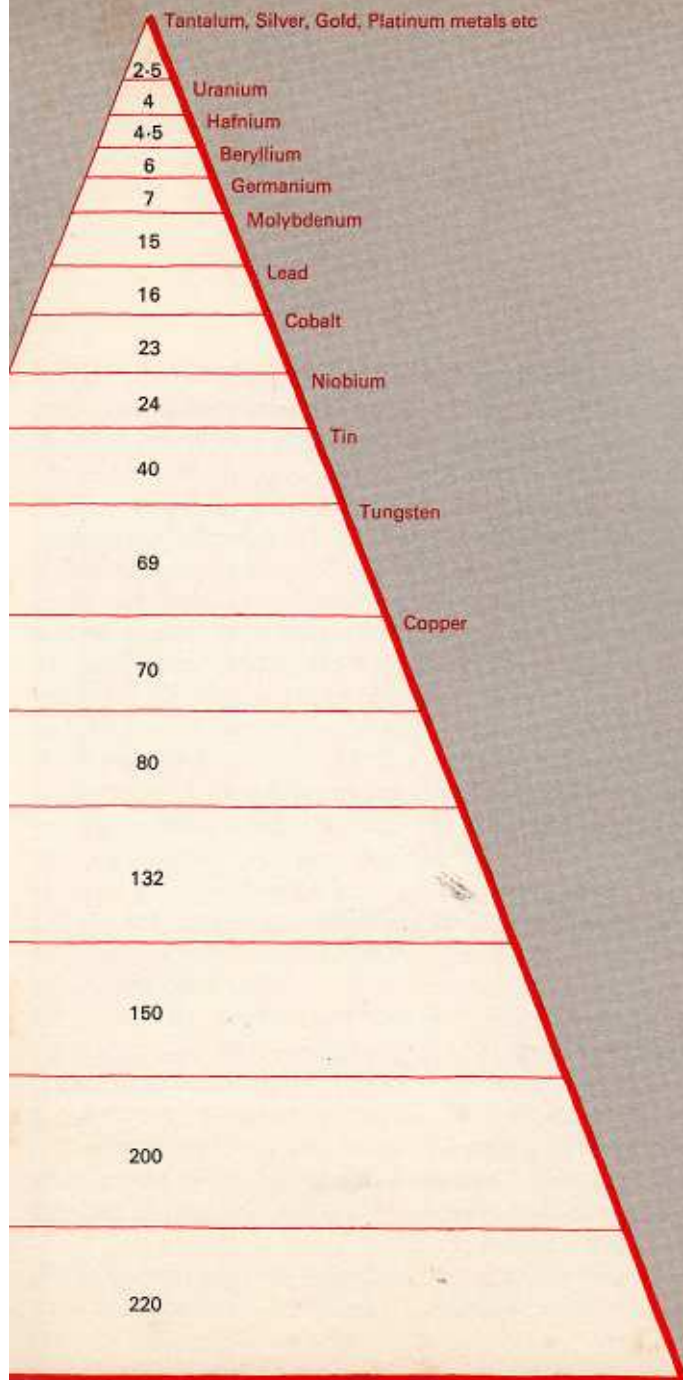
The numbers are parts per million.

Metals in the Earth's crust, 2.

The numbers are parts per million of the less common metals named, which together make up 1,063 parts per million.



METALS & ALLOYS



Of the ninety or so naturally occurring elements, about seventy are metals. Of these, over half are put to practical use, although many of them only in small amounts. Their uses are many and various. In every household there are dozens of metal implements – from water tanks to teaspoons. On a larger scale, ships, cars, aircraft, and industrial machinery are made almost entirely of metals. Metal girders provide support for buildings and metal cables carry electricity to all parts of the country. If man had not learnt to use metals, we would still be living in the Stone Age. Some metals are used in a relatively pure state: copper, for example, because of its high conductivity, for the distribution of electricity; lead, because of its plasticity and resistance to corrosion, for piping and some building purposes; and aluminium, where its lightness and corrosion resistance are especially useful. But most metals are alloyed with other elements and in this way their properties can be improved and controlled, and the range of uses to which they can be put widely extended.

Where do metals come from? About 25 per cent of the Earth's crust consists of metals – in combination with oxygen, silicon, sulphur, and other elements. Aluminium (8 per cent of the Earth's crust) is the most abundant, iron (5 per cent) the next. But many essential metals occur only in very small amounts – copper for example less than 0.01 per cent. If they were evenly distributed throughout the Earth's crust, it would be impossible to extract these metals; but high temperatures and pressures, and extremely slow solidification from the molten state in past geological ages, have caused the minerals containing the metals to separate in large masses from other rocks. The action of water has also caused the concentration of metallic ores. It is thus possible to obtain the metals either by mining or by quarrying the ores.

PART ONE EXTRACTION OF METALS

Locating metal ores and mining them is the job of the geologist and the mining engineer. The metal content of an ore may vary greatly. With iron, it may be over 60 per cent and it rarely pays to use ores containing much less than 25 per cent. With more costly metals, the ores may be far poorer. A copper ore containing 4 per cent copper is regarded as rich, although it consists mainly of 'gangue' (useless earthy matter) intimately mixed with the copper compound, generally the sulphide. Similarly, the sulphides of lead and zinc are mixed with a large proportion of gangue in ores of these metals.

Of the processes for separating the metal compound from the gangue, flotation is one of the more widely used. In this method the crude ore is finely crushed and is then agitated in water containing chemical frothing agents. The wetted gangue sinks to the bottom but the particles of sulphide or other metal compounds are held at the surface in a froth of small air bubbles. The froth is then skimmed off and dried.

Other separating processes are employed to enrich 'lean' ores (containing a high proportion of earthy matter) and convert them into rich concentrates ready for smelting. Magnetic iron ores are commonly rich enough to be smelted direct but, if not, they can be concentrated by magnetic separation.

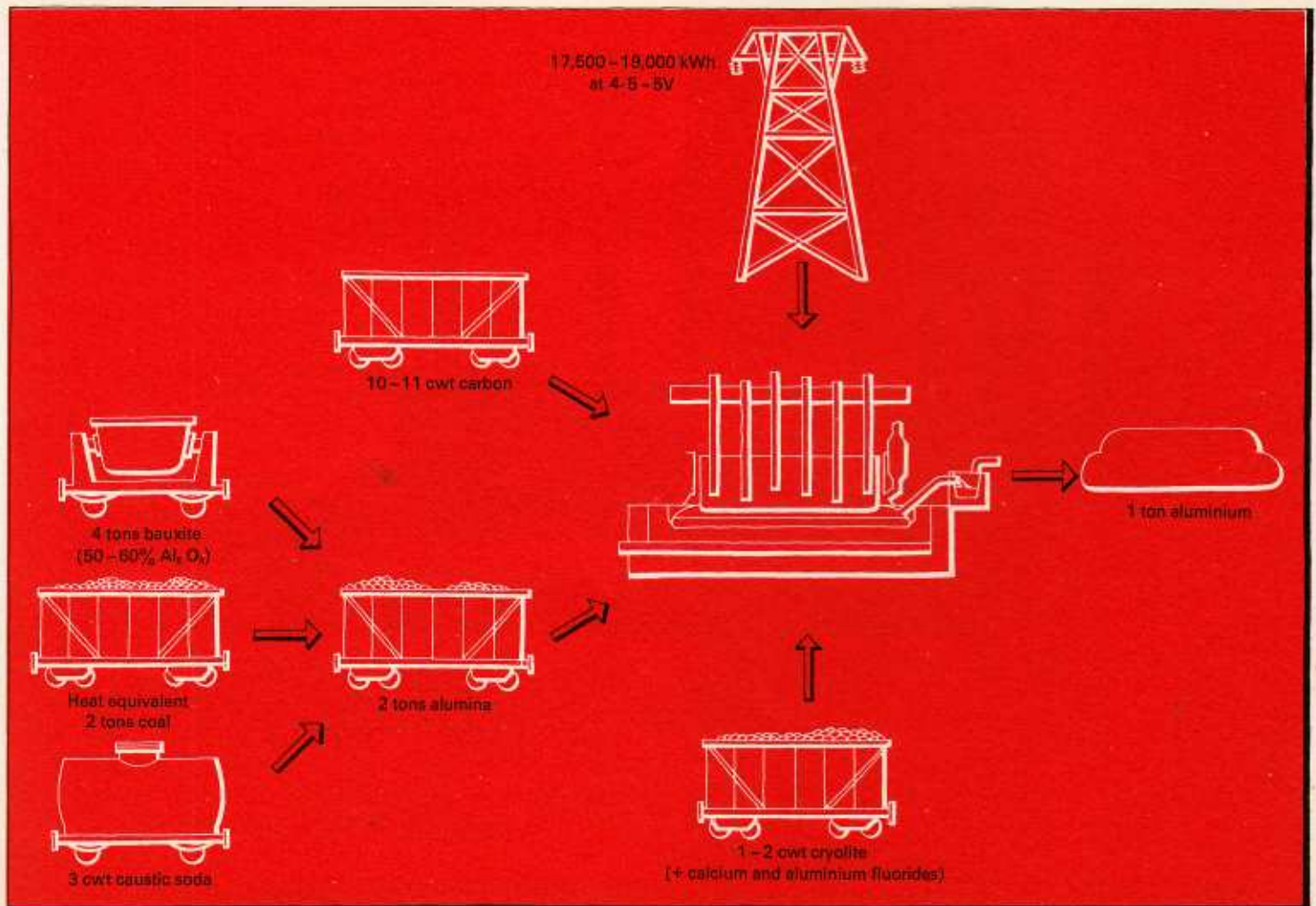
As most ores consist of the metal in combination with oxygen or sulphur, most processes for getting the metal from the ore involve reduction. The method used depends upon the nature of the ore. For example, zinc and iron ores are fairly easily reduced; these metals can be extracted by heating their ores with carbon. Aluminium and magnesium ores are less simple to reduce; it is more convenient to extract the metals by electrolysis.

We shall now look at the ways in which some of the more important metals are extracted from their ores.

Aluminium – Nearly all the vast quantity of aluminium in the Earth's crust is combined with silicon and oxygen in rocks from which the metal can only be extracted at a high cost. Bauxite, which is found in extensive surface deposits in France, the Americas, Jamaica, and West Africa, is an exception. In bauxite, the aluminium is present as its oxide (alumina), mixed with iron oxide and gangue. The bauxite is crushed and is heated under pressure with hot sodium hydroxide. The sodium hydroxide dissolves the alumina, leaving the iron oxide and gangue as a solid residue which is filtered off. On cooling, the solution deposits aluminium hydroxide from which the water is evaporated by heating. Approximately four tons of bauxite yields two tons of alumina, and this, in turn, yields one ton of aluminium. How aluminium is obtained from its oxide emphasizes the significance of the electrochemical series in the extraction of metals. Aluminium, and also magnesium, are strongly electropositive and have a powerful affinity for oxygen; therefore their oxides are difficult to reduce. Iron, lower in the series, is more easily reduced from its oxides and, still lower in the series, come nickel, tin, lead, and copper, the oxides of which readily part with their oxygen. Carbon, in the form of coke or coal, is by far the cheapest reducing agent and, at suitable temperatures, reduces iron oxide and many other oxides. Aluminium oxide cannot be reduced by carbon, or even by hydrogen, by any practical process. For this reason, it has been possible to extract aluminium on a commercial scale only within the last hundred years. The method, as outlined below, was developed in 1886.

Alumina dissolves in a mineral called 'cryolite'. This mineral, sodium-aluminium fluoride, is found in Greenland, but most of it is now produced synthetically, starting with the more abundant fluorspar, calcium fluoride. The cryolite is melted

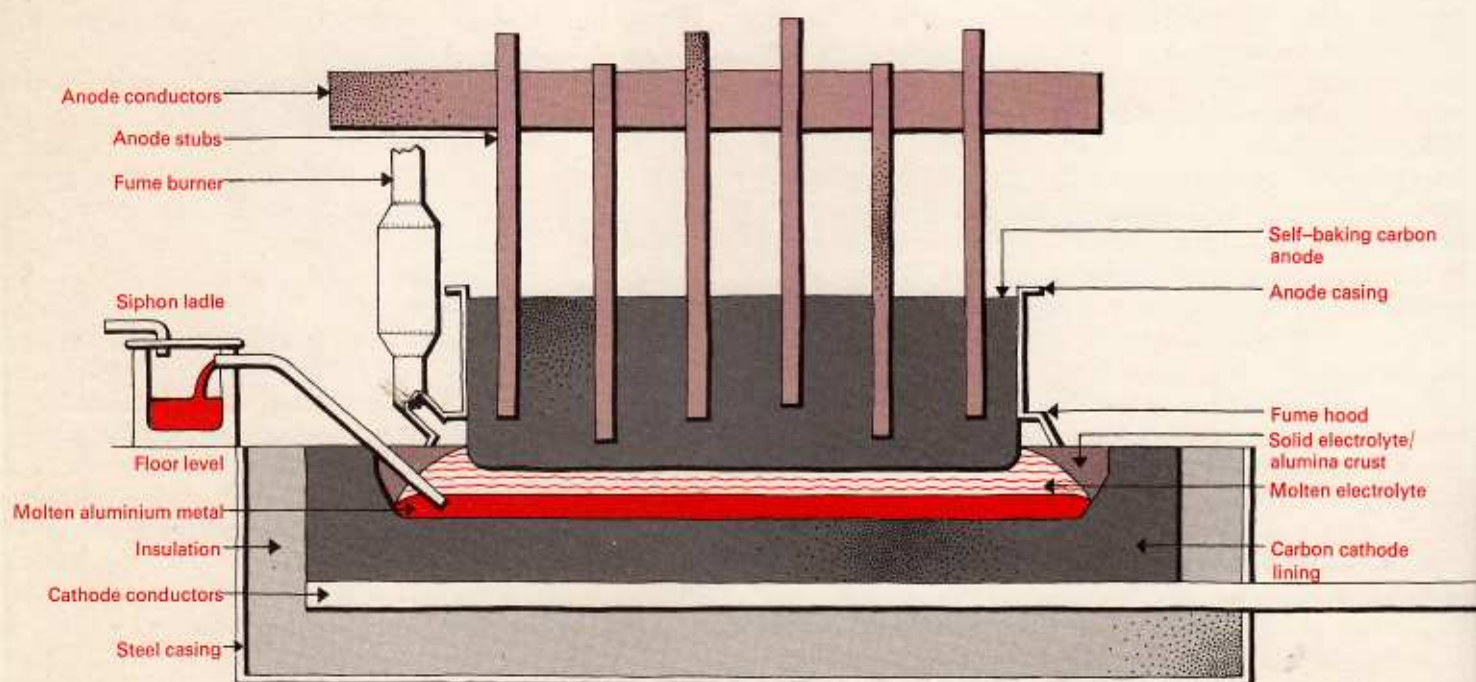
Materials used to make 1 ton of
aluminium.
Aluminium Federation



in a shallow bath lined with carbon, and alumina is dissolved in it at a temperature above $1,000^{\circ}\text{C}$. A direct electric current which may exceed 100,000 amperes, and which maintains the bath at the necessary temperature, is passed through the fused mixture by large carbon anodes; the cathode is formed by the carbon lining of the bath. As the aluminium oxide is decomposed, liquid aluminium collects at the bottom of the bath, where it is drawn off at intervals. The carbon anodes, which are steadily burnt away by reaction with liberated oxygen, are continuously renewed from the top, and fresh alumina is fed periodically into the bath. The process is thus continuous.

This electrolytic process consumes about seven kilowatt-hours of electricity, and three-quarters of a pound of anode carbon, for each pound of aluminium made. Therefore, for the large-scale production of aluminium, cheap supplies of electricity are necessary. For many years, hydroelectric installations provided the main source of power, but coal and natural gas are now coming into favour.

The cost of the chemical purification of the bauxite ore, and of the electricity and anode carbon consumed in extraction, makes the price of aluminium roughly six times that of mild steel, weight for weight.



The reduction cell in which alumina is dissolved in molten cryolite (Na_3AlF_6). Aluminium metal from the alumina is deposited on the cathode at the base of the cell.

Aluminium Federation

Poling with the trunk of a tree – the oldest and most effective method of removing oxygen in the last stage of the fire-refining of copper. Reducing gases are evolved by the action of heat on the wood.

Copper – In a typical method of extracting copper, the ore (containing, say, about 2 per cent of copper and 90 per cent gangue) is concentrated by the flotation process already described. The concentrate – generally copper sulphide with some residual gangue and minerals containing iron, arsenic, etc. – melts in a furnace to a mixture of copper sulphide and iron sulphide. The molten mixture is then transferred to a converter through which air is blown to oxidize the sulphur and the iron. The oxidized iron separates off as a slag above the liquid copper. At this stage, the impurities in the copper have been reduced to about 2 per cent. The copper is then 'fire-refined' in a furnace in which most of the remaining impurities are removed by oxidation. Fire-refined copper is suitable for many uses, but most of it still contains at least 0.5 per cent of impurities. To purify it further, it is cast into slabs which become the anodes for the wet electrolysis which follows. The electrolyte starts as dilute sulphuric acid and the cathode as a thin sheet of pure copper. A large direct current passes through the bath from the positive anode, which is progressively dissolved, to the negative cathode, on which pure copper is deposited. Some of the impurities remain in solution; others collect as a sludge at the bottom of the tank. The sludge often contains small amounts of precious metals (for example gold, silver, or platinum) which help to pay for the cost of the electrolytic refining.

This elaborate sequence of processes by which pure copper is obtained from its ores is necessary not because of its affinity for oxygen or sulphur but because the copper content of the ore is low and the copper is not easily separated from the impurities.



Iron and steel – The production of cast iron and steel from iron ore – essentially the reduction of iron oxide by carbon – is simple in principle, but highly complex in its practical details.

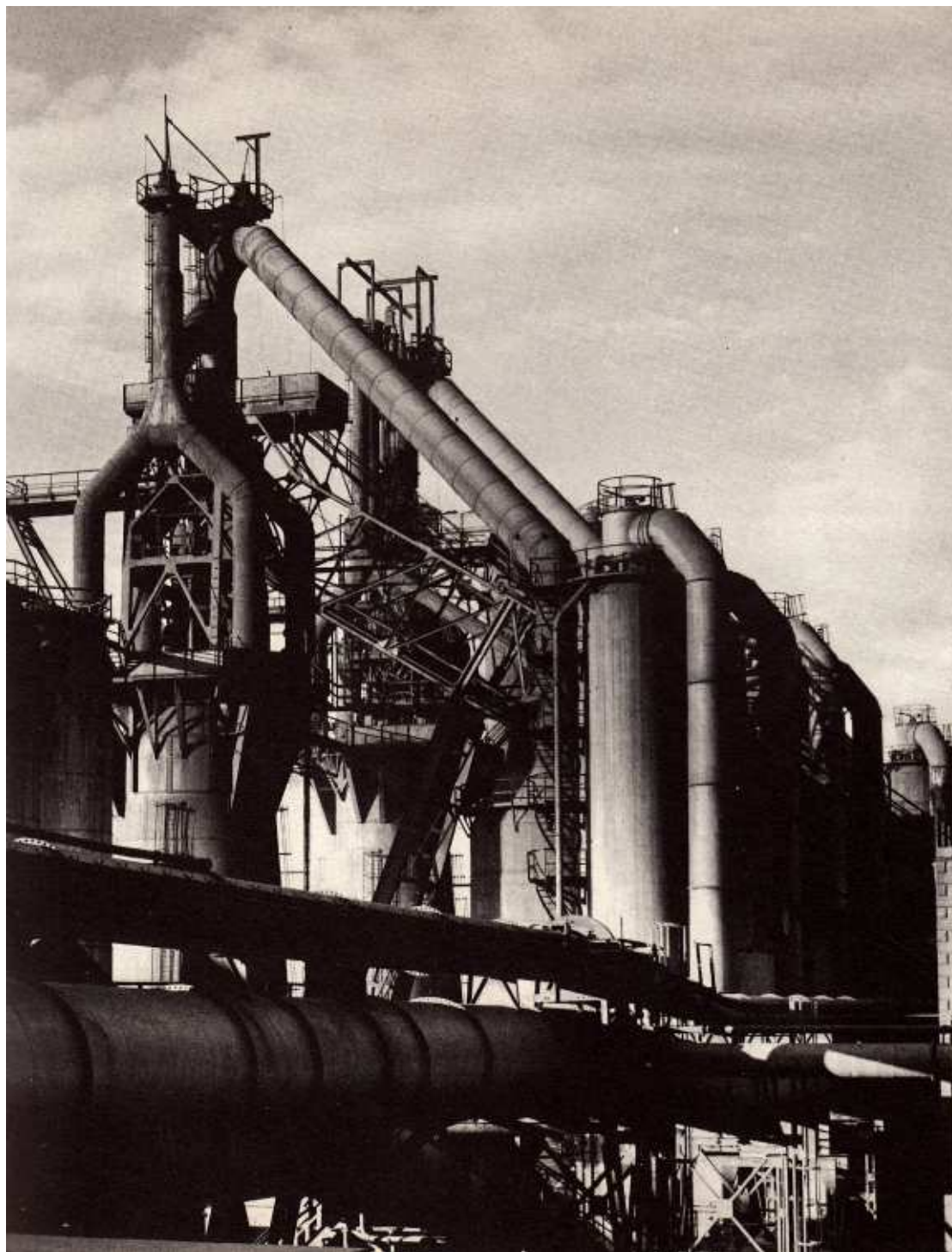
Iron accounts for at least nine-tenths of the weight of all the metals used in the world today. Indeed it is common to lump all the other metals together under the heading 'non-ferrous'. As haematite (Fe_2O_3) or magnetic oxide (Fe_3O_4), iron occurs in very large masses at or near the surface in many regions of the earth. In Sweden, Russia, India, and elsewhere, there are mountains consisting almost entirely of these iron compounds. Sedimentary ores containing less iron are also an important source of supply – for example, in Lincolnshire, Northamptonshire, and Lorraine. The ore is quarried or mined and taken to blast furnaces; with lean ores, it only pays to use them when the blast furnaces are near at hand, but with rich ores the furnace may be thousands of miles away and then the ores have to be transported by ship.

The most modern plant for the conversion of iron ore into finished steel is known as an integrated iron and steel works. The blast furnaces, towerlike circular structures, provide the first stage. A blast furnace today may be 100 feet high and 30 feet in diameter at the base. In the furnace, the iron oxides are reduced to metallic iron, using coke as the reducing agent. The carbon of the coke is oxidized to carbon monoxide and carbon dioxide, the carbon monoxide causing further reduction in the upper, cooler zones of the furnace. Limestone is also fed into the furnace to form a fusible slag with the silica and alumina which are present as impurities in the ore and the coke. This slag also carries off nearly all the sulphur in the coke.

A modern blast furnace, which may produce up to 2,000 tons of iron every twenty-four hours, operates continuously for months at a time – sometimes even years. At the top of the furnace the ore, limestone, and coke are fed in regularly, and the gases are drawn off through ducts. Above the hearth at the base hot compressed air is blown in through a ring of water-cooled nozzles arranged round the circumference of the furnace. The temperature at the hottest part of the furnace, above the blast nozzles, approaches $1,800^\circ\text{C}$ and falls to about 250°C at the top. The melted iron and slag trickle down into the hearth, where the lighter slag floats above the iron; at intervals, they are 'tapped' off separately into large ladles.

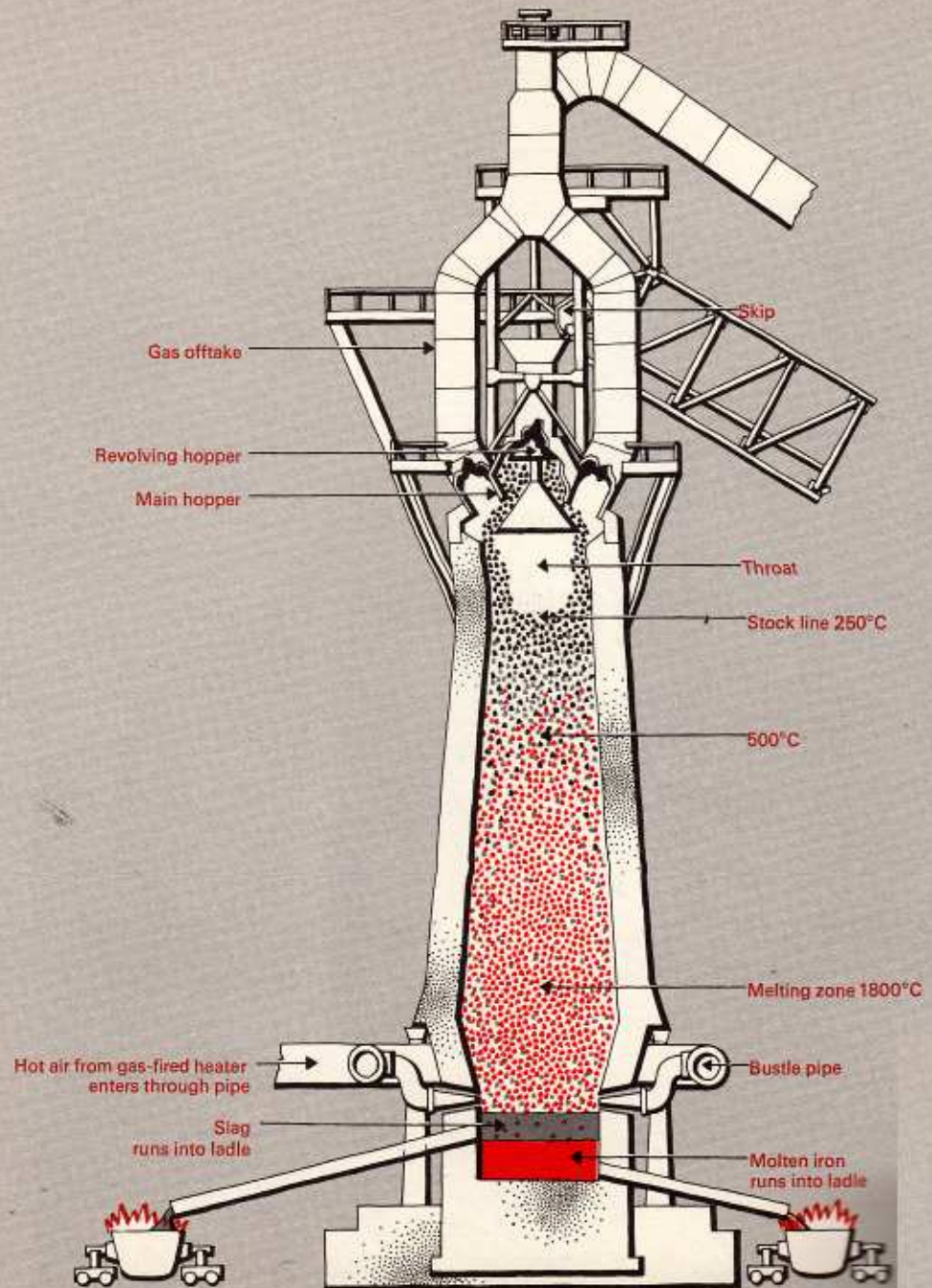
The reduction of iron oxide by carbon is accompanied by a whole series of chemical changes in the raw materials entering





Blast furnaces at a steel works.
In these furnaces, which may be
as high as 100 feet, iron is
extracted from iron ore.
British Iron and Steel Federation

Diagram of a blast furnace. The skip unloads iron ore, limestone, and coke into the top of the furnace. Molten iron and slag are tapped from different levels of the hearth.



the blast furnace, including air in greater weight than any of the others. The reduced iron takes up from 3 per cent to 4 per cent of its weight of carbon, as well as some silicon, manganese, and all the phosphorus entering the furnace.

If the iron leaving the furnace is allowed to solidify, it is called pig-iron. Pig-iron may be remelted for making iron castings or be used for one of the steel-making processes. But in a large integrated works the iron from the blast furnace is taken to the steelworks in the liquid state.

Pure iron is too soft to be of great use. In the next stage the crude iron as it comes from the blast furnace is converted into steel. Steel is an alloy of iron and carbon: with 0.05 per cent of carbon, the steel is relatively soft; with 1.5 per cent it is extremely hard; but, between 0.3 and 1.5 per cent, the hardness can be varied widely by heat-treatment (this is described on page 27). Most steels contain less than 0.5 per cent carbon. Manganese (under 1 per cent) and a little silicon are also desirable constituents in steel, while sulphur and phosphorus are impurities that cannot be kept out completely. Crude iron already contains carbon, manganese, and silicon in variable amounts. To make steel they must first be removed from the iron and then put back in carefully measured amounts.

Steel for rails and structural purposes was first produced in quantity in the 1860s by a method invented by Henry Bessemer. In the Bessemer converter (a cylindrical vessel like a giant cement mixer, lined with firebrick and with a capacity of up to fifty tons), air is blown from the bottom through liquid iron. The silicon, manganese, and a little of the iron, are completely oxidized in about fifteen minutes, and are removed as a slag. The carbon is oxidized and escapes as a gas. The molten iron is then poured into a ladle and, while this is being done, measured amounts of carbon, manganese, and silicon are added to secure the desired composition of the steel.

At about the same time as Bessemer introduced his process, the open hearth method was developed. The plant for this process consists of a closed horizontal furnace with a roof of firebrick and a hearth at the bottom to hold the metal. The furnace is heated by gas, giving a very hot flame between the bath of metal and the roof. To secure the necessary flame temperature, the gas and the air for its combustion are strongly heated before entering the furnace. Iron oxide (usually a rich iron ore) is added to the liquid iron in the bath and produces an oxidizing slag which floats on the surface of the iron; oxida-

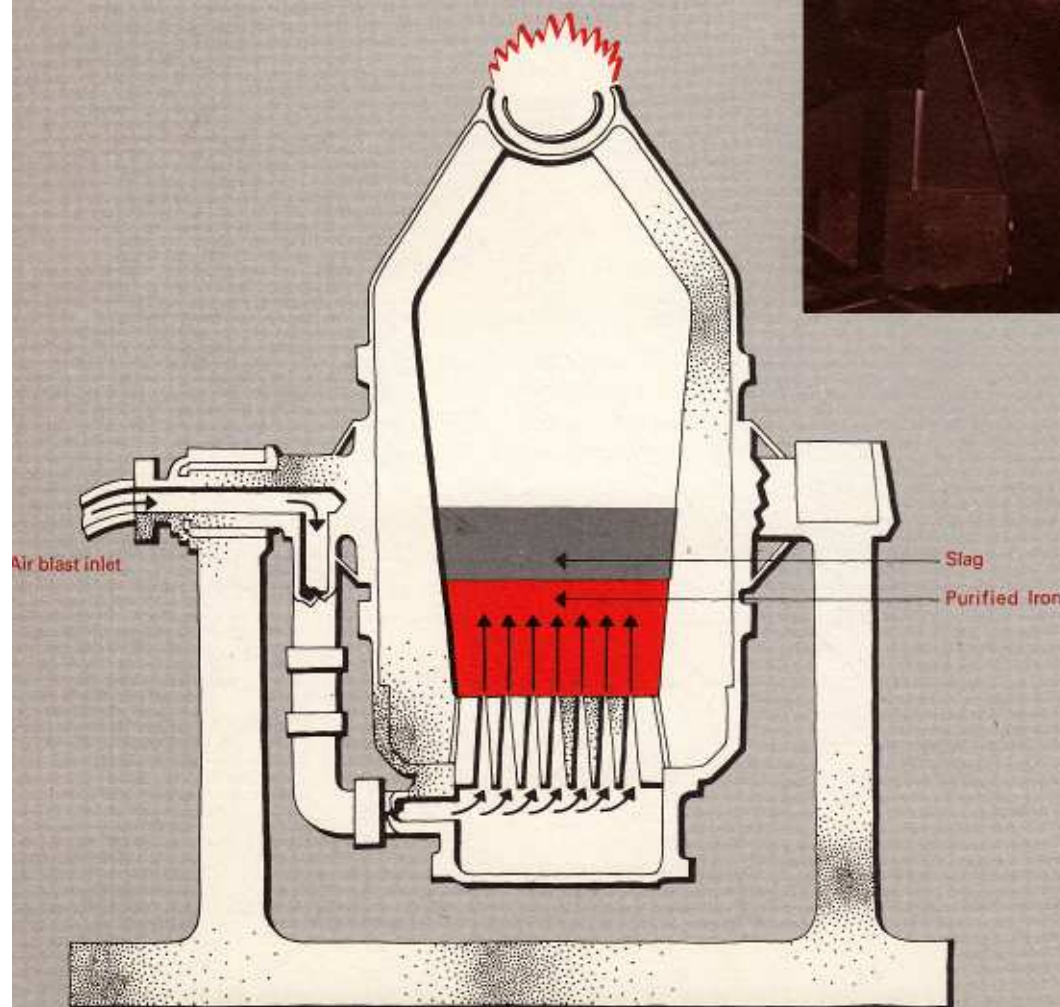
tion of the carbon, manganese, and silicon takes place by reaction between the metal and the slag. The carbon may be removed completely but the process is often stopped when the carbon has been lowered to the required value. Ferromanganese (an alloy of manganese and iron) and other necessary constituents are then added.

The open hearth process, with large furnaces holding from 100 to 500 tons of steel, takes much longer than the Bessemer. But it can deal with solid as well as with liquid charges, can be more closely controlled, and generally produces better steel. In the subsequent rolling operations, a large amount of scrap steel is produced – trimmings from ends of billets and bars, sides of plates, etc. – and this scrap, together with all sorts of worn-out steel parts, forms an important part of the charge of the open hearth furnace.

Most iron ores contain phosphorus in amounts which, if left in the finished steel, would make it brittle and useless. Phosphorus is not removed in the blast furnace or in the steel-making processes described above. The original Bessemer process could handle only low-phosphorus crude iron, and this gave British steel manufacturers an advantage over their Continental rivals because Cumberland and imported ores low in phosphorus were available. The German manufacturers benefited when, in 1879, two British inventors, Sidney Gilchrist Thomas and his cousin Percy C. Gilchrist, found that putting lime in the Bessemer converter removed phosphorus as calcium phosphate in the slag. They also found that lime could be used only if the converter was lined with a 'basic' material such as magnesium oxide, otherwise the lime would attack the siliceous (acid) firebrick lining. As a result of their findings, the *basic* Bessemer process was born and soon great quantities of steel were being made from iron containing up to 2 per cent of phosphorus. The same principle of adding lime was then applied to the open hearth furnace, and this basic open hearth process gradually became the predominant way of making steel all over the world.

In the last ten years a revolution in steel-making has taken place: oxygen is used to burn the carbon, manganese, silicon, and phosphorus out of the crude iron. The oxidation reaction is much quicker, with savings in fuel as well as time. In existing furnaces, a tube called a lance blows oxygen at extremely high velocity into the molten iron. Techniques for making the best use of the oxygen have, in turn, given rise to

The Bessemer process



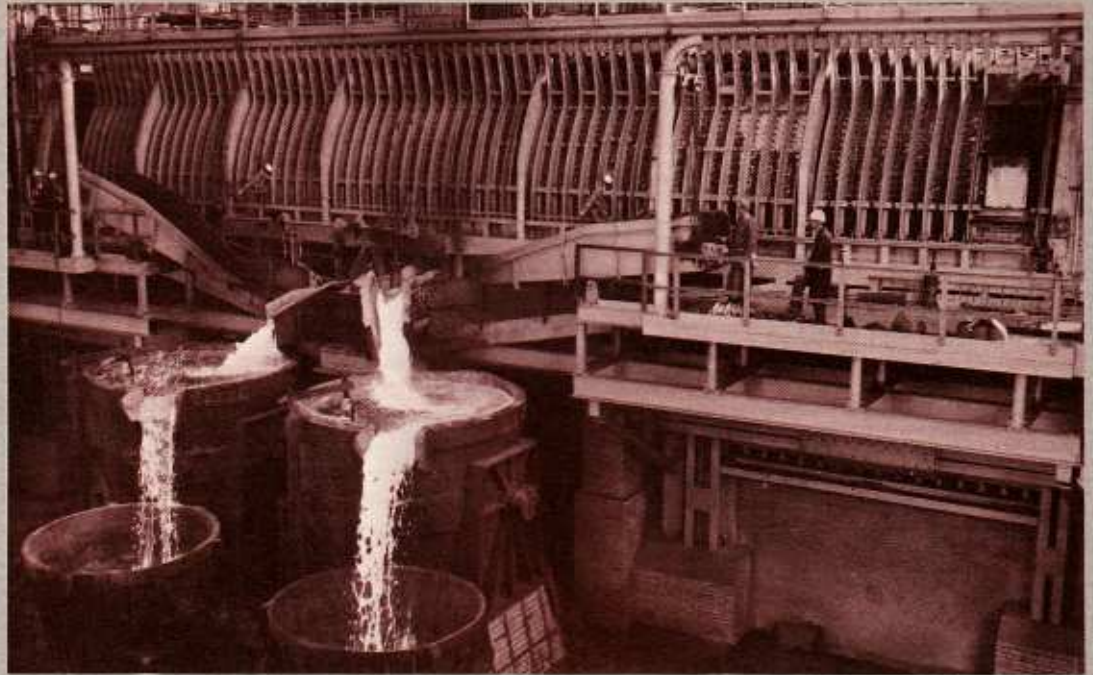
Steel manufacture: a Bessemer converter (above) is tilted to receive molten iron from a blast furnace.

Richard Thomas and Baldwins Ltd

The Bessemer converter, fifteen minutes after the molten iron was poured in: it was then brought upright and air blown upwards through holes in the bottom, causing the manganese and silicon in the liquid iron, and a little of the iron itself, to oxidize as a slag. The oxidized carbon escapes as a gas. The chemical reactions have caused heat to evolve, producing a white flame which rises to about 30 feet and suddenly dies. Then the converter is tilted again, the contents are poured into a ladle, and the slag is removed: the whole process has taken 25 to 30 minutes. The purified iron is now ready to receive the exact quantities of alloying elements to make steel of the desired composition.

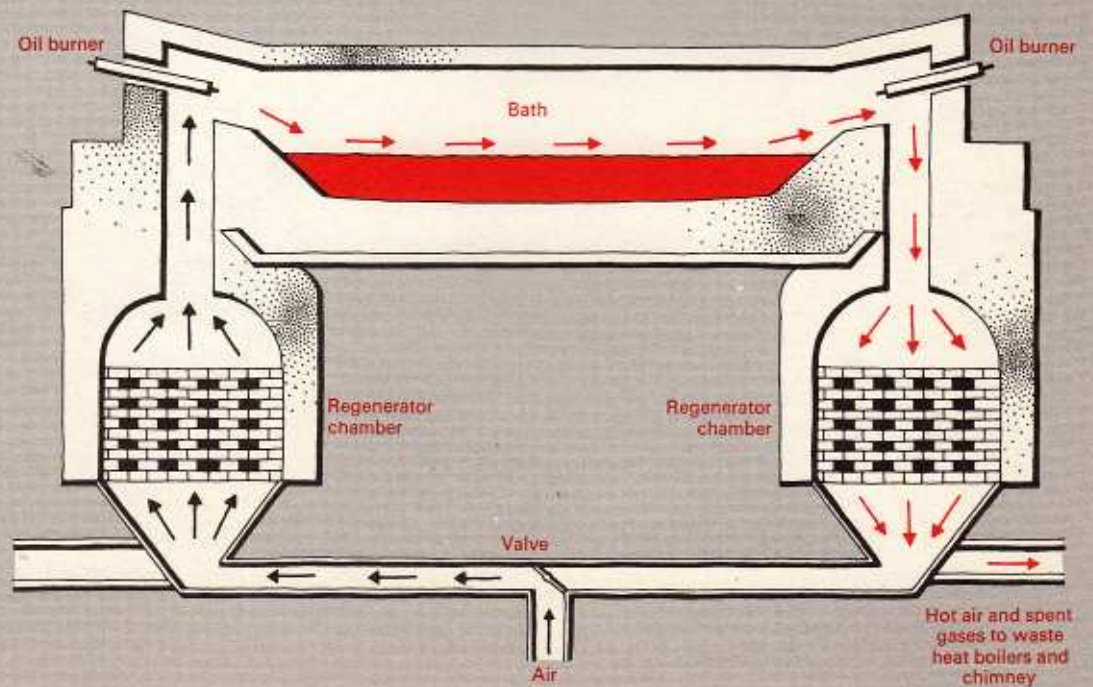
The Open Hearth process

Molten steel pours from a 400-ton open hearth furnace. There is more than one ladle can hold and two are being filled at the same time. As a ladle fills the slag floats on the steel and overflows into slag pots. A still from the British Iron and Steel Federation's film *Listen to Steel*.



Cross-section diagram of the open hearth furnace used to make steel. An oil burner on one side of the furnace (in this diagram, the left side), is fed with heated air. The very hot flame from the burner plays upon the surface of the molten iron in the bath, and impurities in the iron are oxidized. Hot waste gases pass out of the other side to waste-heat boilers. About every twenty minutes, a valve reverses the flow of air and oil so that the incoming air receives the heat recently given up by the waste gases.

British Iron and Steel Federation



new steel-making processes – for example, the L-D process (named after the two Austrian towns Linz and Donawitz) with a fixed converter, and the Kaldor process with a rotary converter on an inclined axis. In both these processes, which are rapidly replacing the older ones, a high-velocity jet of oxygen is blown on the surface of the liquid crude iron. The consumption of oxygen for steel-making is, in Great Britain alone, already about half a million tons a year.

Spray steelmaking is an even newer process, developed in Britain. It is illustrated on pages 32 and 33.

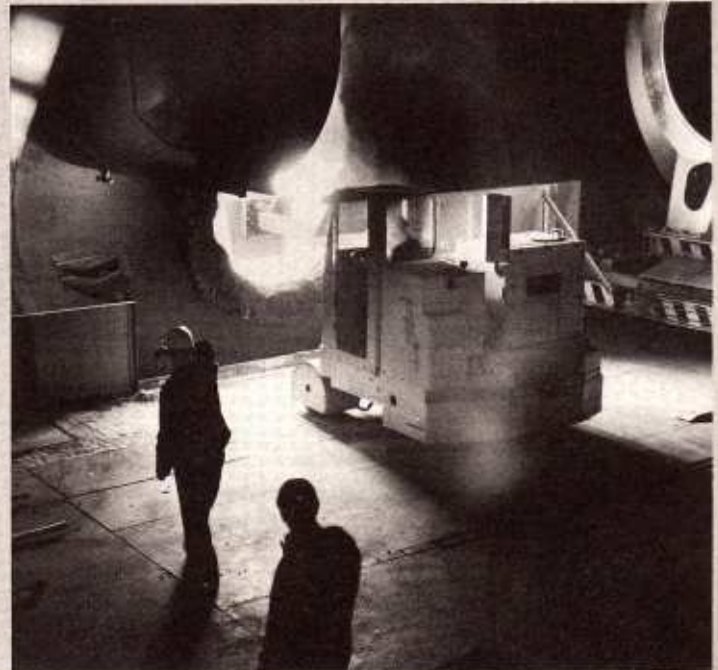
The liquid steel from the steel-making plant is solidified in cast-iron moulds. The ingots, as they are called, are removed from the moulds, and are allowed to cool to about $1,000^{\circ}\text{C}$; at this temperature the steel is very plastic and therefore suitable for rolling. Rolling is carried out in a succession of mills which vary in design according to the shape of the finished product. Plate of the kind used for shipbuilding is the simplest to roll. Shaped rolls are necessary for making rails, bars, rods, and the many section shapes of beams and girders. Many of these rolling processes are automatically controlled.

The manufacture of finished steel from iron ore has many variations in practice, and is accompanied by numerous chemical and metallurgical operations. As well as skilled and experienced workmen, a large staff of chemists, metallurgists, and engineers is required for the planning, direction, and control of a steelmaking plant.

Thus the processes by which three of our chief metals – aluminium, copper, and iron – are obtained from their ores differ very widely. It is broadly true that, in extraction metallurgy, the methods used are tailored to the peculiarities of each metal – the composition of its ore and the chemical and physical properties of the metal. For instance, the relatively low boiling point of zinc enables it to be finally purified by distillation. Many nickel ores contain a large proportion of copper, and the separation of the two metals, which have very similar characteristics, requires special chemical and electrolytic processes. Small amounts of the metals of the platinum group (comprising platinum, palladium, rhodium, ruthenium, iridium, and osmium) may be found, together with silver and gold, in the residues from the electrolytic refining of nickel and copper. Because of the similarity of their chemical and physical properties, they can be separated only by an elaborate sequence of chemical processes.

The Kaldor process

Charging lime into a 120-ton Kaldor converter in an oxygen steelmaking plant.
Consett Iron Co. Ltd.



Sequence of operations for manufacturing steel by the Kaldor process. This is one of the newer methods, specially designed to make use of pure oxygen for blowing into the molten iron. The British iron and steel industry already uses about half a million tons of oxygen yearly in steelmaking alone.
British Iron and Steel Federation

1 Charging with lime
and ore or scrap



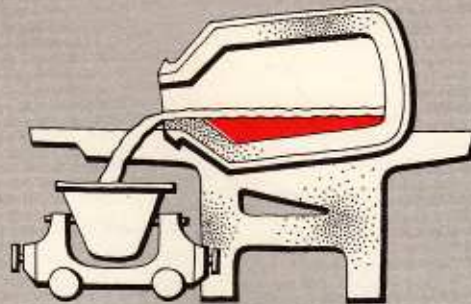
2 Charging with molten iron



3 First oxygen blow



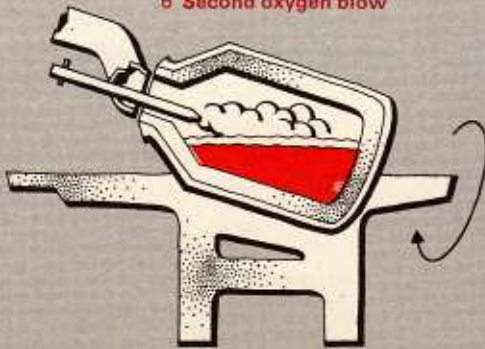
4 Removing primary slag



5 Adding lime to
make new slag



6 Second oxygen blow



7 Pouring the finished steel



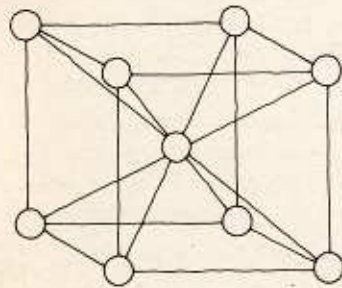
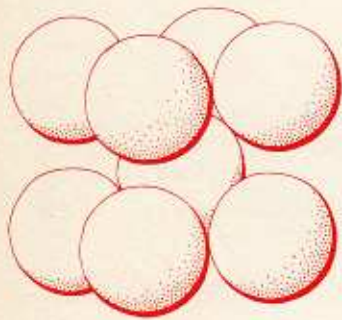
PART TWO THE STRUCTURE OF METALS

If you examine the surface of polished metal, you will probably think it looks smooth and all of one piece. But, if the surface is etched with dilute acid and you look at it under a microscope, you will see a pattern such as that in the right-hand illustration on page 22. In fact, the metal is made up of crystal grains. You may see brass door handles that have been etched by frequent use and on which the crystal grains are clearly visible. Large zinc crystals, sometimes several centimetres across, can be seen on galvanized iron – look at a new dustbin. These crystal

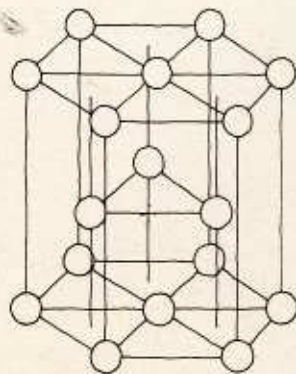
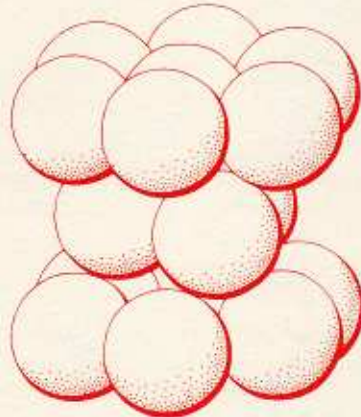
grains in metals have not the straight edges and flat faces of other crystals but their internal structure is just as regular.

The regular structure of metal crystals indicates a regular packing of the atoms of which the crystals are composed. X-ray diffraction shows that the packing of the metallic atoms depends on the nature of the metal. Copper has a face-centred cubic structure; iron and chromium have a body-centred cubic structure; and the softer metals zinc and magnesium have a close-packed hexagonal structure (see below).

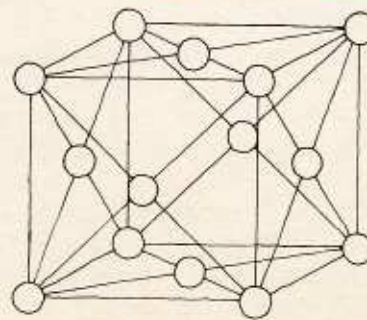
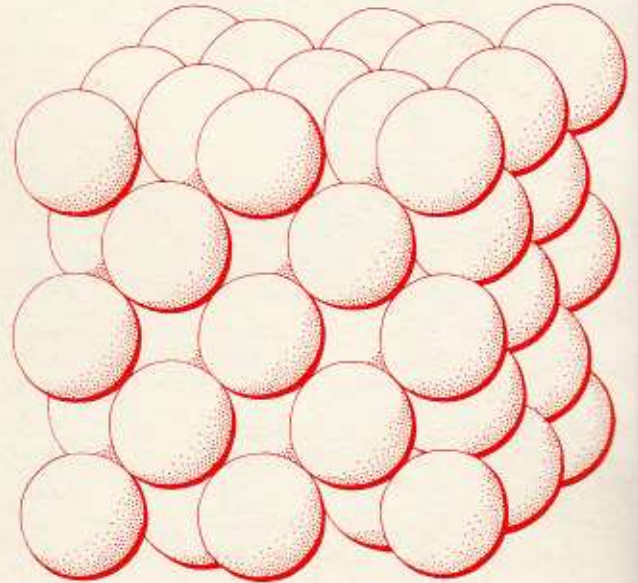
The three main ways in which ions are packed in metal crystals.



Body-centred cubic structure – as in chromium.



Close-packed hexagonal structure – as in zinc.

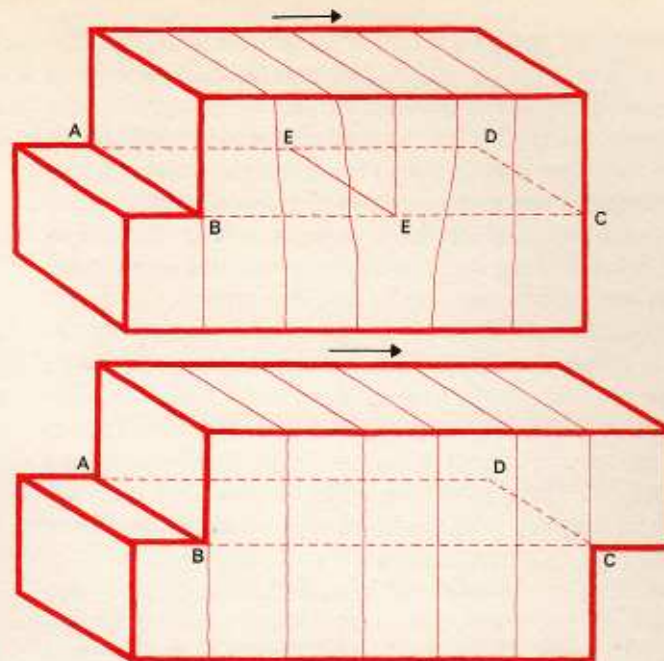


Face-centred cubic structure – as in copper. Note in the model above the pattern of five is repeated.



(Left) Deformation of a crystal by slip. Groups of atoms in the crystal break their bonds at one place, slip into a new position, and re-establish their bonds.

(Right) The upper diagram represents a simple form of dislocation, line EE lying in the slip plane ABCD of a small crystal block. When the upper part of the crystal is stressed (as indicated by the arrow), slip takes place (as shown in the lower diagram) by movement of the dislocation line to the surface at CD, producing an overhang there.



The properties of metals are intimately linked with their crystalline structure. One particularly useful property we associate with metals is strength. But, in fact, most pure metals are weak and ductile. They can be hammered or pressed into shapes or drawn out into wire. If you bend a strip of metal slightly it behaves like elastic and springs back; but if you bend it far enough its shape is permanently altered: under sufficient stress some groups of atoms in the crystal break their bonds at one place, slip into a new position, and re-establish their bonds. The movement of the atoms is called 'slip'.

Although the slip movement (as illustrated above left) resembles that of a pack of cards which has been pushed lengthwise, the actual mechanism by which slip takes place is more like the movement of a ruck in a carpet. It is found that crystals slip at stresses very much below those which would be required to move two perfect crystal planes past one another: in fact, metal crystals are between 1,000 and 10,000 times weaker than this assumption of perfect crystal planes would predict.

A more realistic picture of the slip process would be to imagine slip beginning in one small area of a slip plane and then spreading over the rest of the plane. While this is taking

place, the slip plane will be divided into a slipped area and an unslipped area, and the line of demarcation (called a *dislocation line*) will be moving across the slip plane. The passage of a dislocation line across a slip plane of a crystal is like the movement of a ruck in a carpet – it obviously needs more force to pull a carpet over the floor by dragging one end of it, than to make a ruck in the carpet and to move the ruck along. The ruck separates the 'slipped' from the 'unslipped' part of the carpet in the same way that a dislocation line separates the slipped and unslipped regions of a slip plane in a crystal.

The upper diagram, above right, represents a simple form of dislocation line EE lying in the slip plane ABCD of a small crystal block. When the upper part of the crystal is stressed (as indicated by the arrow), slip takes place as shown in the lower diagram by the movement of the dislocation line to the surface at CD – producing an overhang there as in the diagram.

Many metal objects are made by melting the metal and pouring it into a suitably shaped mould. But the shapes most generally useful and produced in by far the largest quantities are obtained by working the metals – by forging, rolling (page 28), drawing, or extruding them. It is *slip* that allows us to

shape metals by these methods. But, ultimately, we require metals to be strong – we wish to prevent slip. Several ways of strengthening metals are outlined below:


1. Slip does not readily extend from one crystal grain to the next and therefore a metal with a fine grain size will be harder to deform than a coarse-grained metal. Grain size can be controlled by the rate at which liquid metal is cooled – in general, the faster the cooling the smaller the grain size – and, after solidification, by working and by heat-treatment.

2. Slip increases the number of regions of dislocation: there may be a hundred thousand times more such regions after a metal has been severely deformed. The result of this is to make the metal stronger – because slip planes meet, obstruct each other's motion, and build up into a 'traffic jam'. Working a metal between rolls, especially when the metal is cold, increases the number of dislocations and so makes the metal stronger. This process is known as 'work hardening'.

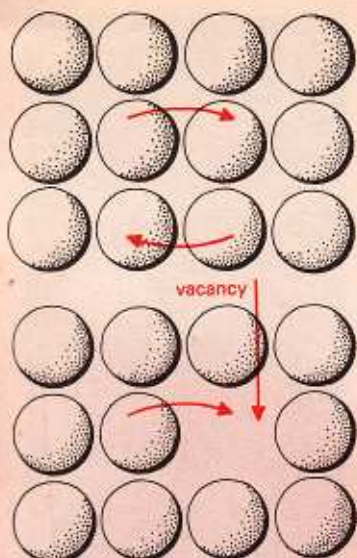
If the metal is subsequently heated, there is an increased movement of atoms within each crystal and many of the dislocations disappear. Through this movement, new unstrained crystals grow and replace the original deformed structure. This is an example of diffusion in the solid state. The cause of diffusion is simply that the atoms in a solid are continually jumping from one position in the structure to a neighbouring position. It is believed that this process occurs less by direct exchange of places by two atoms (below, left) than by the pre-

sence of vacant sites in the crystal structure (below, right). Such vacant sites are a normal feature of a crystal at any temperature above absolute zero, and the right-hand diagram shows how they allow adjoining atoms to jump. Since the number of vacancies in a crystal rises steeply with increasing temperature, the rate of diffusion rises in a similar way. The process of softening a metal by heat is called annealing. Cold rolling increases the strength of a metal but tends to make it hard and brittle. If the metal after cold rolling is suitably annealed, the brittleness can be removed and much of the hardness retained.

3. Recently, crystals with no dislocations at all have been grown: this has been done with carbon, silica, and alumina, and also with metals. The crystals are grown by condensation from the vapour, by electrodeposition, and by several other methods. One of the first uses has been found in the preparation of tiny hair-like crystals, called 'whiskers', but they are many times stronger than the same thickness of the ordinary metal. For example, pure iron whiskers less than 0.0001 inches in diameter have a tensile strength of about 1,000 tons per square inch compared with about twenty tons for ordinary soft iron. In spite of the great cost of producing large quantities of these whiskers, experimental work is being done, for example, to embed whiskers of alumina in aluminium alloys. A light but extremely strong material produced in this way might be of great value in space exploration.



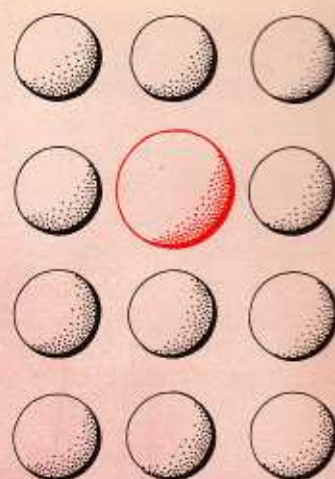
Metal whiskers. These hair-like crystals of pure iron without any dislocations have about fifty times the tensile strength of the same thickness of ordinary soft iron.



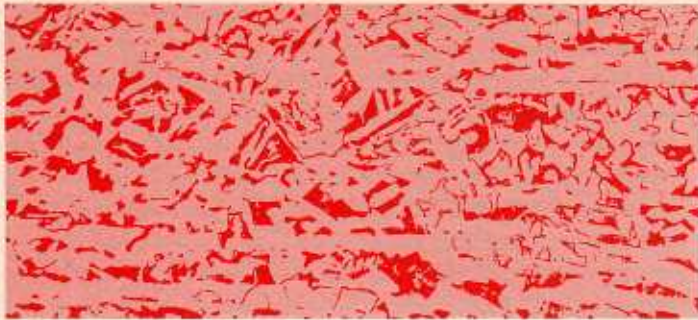
Atomic diffusion in a crystal: upper diagram, by direct interchange; and below, through vacant sites in the crystal structure. Heating a metal increases the rate of atomic diffusion, resulting in the growth of new crystal grains. This process, called annealing, softens the metal.

4. One of the commonest methods of strengthening a metal is to alloy it with small quantities of another element. We shall be looking at alloys in more detail shortly. When a small amount of alloying element is added to a metal, it will usually form a solid solution – the atoms of the new element taking their place within the existing crystal structure of the ‘parent’ metal. The presence of a foreign atom in a crystal (see right) will locally disturb the perfection of the arrangement and may well make it more difficult for a dislocation to go past that point, so that such a solid solution would be stronger than a pure metal. This kind of reasoning accounts, for example, for the fact that brass containing up to 30 per cent of zinc dissolved in copper is stronger than pure copper.

When larger amounts of alloying metal are added, however, the limit of solubility may be exceeded, and crystals of a different arrangement (containing atoms of each metal) will appear in the structure. In many cases metallurgists have devised methods of heat treatment of alloys so that crystals of a hard phase may be precipitated in the alloy as very fine particles. In the unprecipitated state the alloy will be relatively soft and may be forged into shape fairly easily. The subsequent formation of particles of precipitate will make the alloy hard by presenting obstacles which the dislocations must overcome if slip is to occur. Some particles may tend to form in rows along the dislocations themselves and thus anchor them in position.



In metal alloys another element is dissolved in the metal. The presence of ‘foreign’ atoms in the crystal structure of the metal (as shown here) often has the effect of preventing the spread of dislocations, so strengthening the metal.



The etched surface of a piece of steel showing the boundaries of the grains or crystals (magnification $\times 200$).

National Physical Laboratory

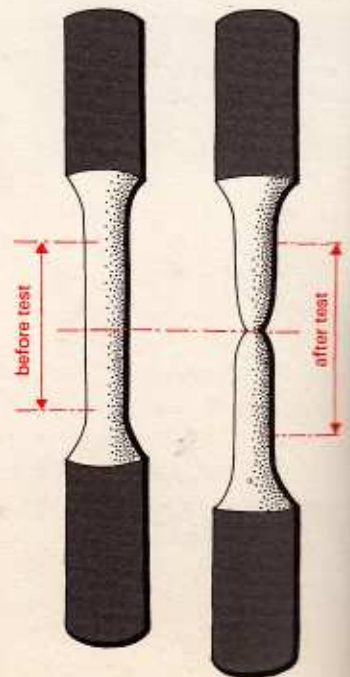
Iron-silicon alloy showing slip lines in the grains (magnification $\times 1300$).

National Physical Laboratory

Measuring the tensile strength of a metal. A test piece of the metal is gripped at each end and slowly pulled apart by the machine. Load stress and extension are carefully measured.

A steel test piece before and after test.

British Iron and Steel Federation



Measuring strength, hardness, and other properties

We have seen how the structure of a metal influences its strength. Another important property of a metal, closely related to strength, is its hardness. There are various standard tests for measuring strength and hardness.

A simple kind of load is a direct pull, as in the coupling of one railway wagon to the next. A weight hanging on a straight wire produces a 'tensile stress' in the wire and, if the weight in pounds is divided by the area of cross section of the wire in square inches, the tensile stress is expressed as pounds per square inch. Tons per square inch is the usual system of units in Britain for strong metallic materials.

In tensile testing, which measures the strength and ductility of a metal, an accurately machined test piece of the metal is pulled with a carefully measured load and the extension noted as the load is increased. All metals are elastic within a range of stress which varies greatly from one metal or alloy to another. In steel the elastic stretch per unit load is very small and a delicate 'extensometer' is used to measure the extensions. The ratio of load to elastic stretch is the 'modulus of elasticity', the value of which is much higher for iron and steel than for any other common metal or alloy. The modulus of elasticity is a remarkably constant property of each metal, little affected by alloying, working, heat treatment, or other treatment.

At a certain point in the loading called the elastic limit, some of the stretch becomes permanent. On further loading, different metals and alloys behave in various ways. Many steels have a definite yield-point, at which rapid stretching takes place. The load must be increased further to break the test piece and, except in very hard or brittle materials, a large amount of stretching occurs before breaking. In all tensile tests, it is customary to record the yield-point (or alternatively the load at which a definite permanent stretch is measured) the breaking load, and the elongation up to breaking. The two measurements of load are broadly regarded as indicating the strength of the material, and the elongation its ductility.

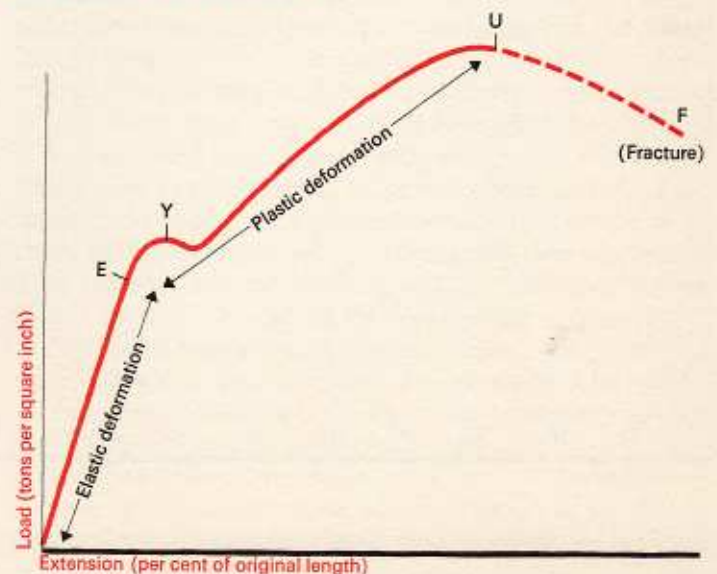
Hardness is now commonly measured by pressing the point of a diamond pyramid into the polished surface of the metal; the ratio of the load to the impression, measured under the microscope, gives the 'indentation hardness'. In most metals and alloys there is an approximately linear relation between this hardness number and the tensile breaking load.

However, it is rare for engineering structures and the parts

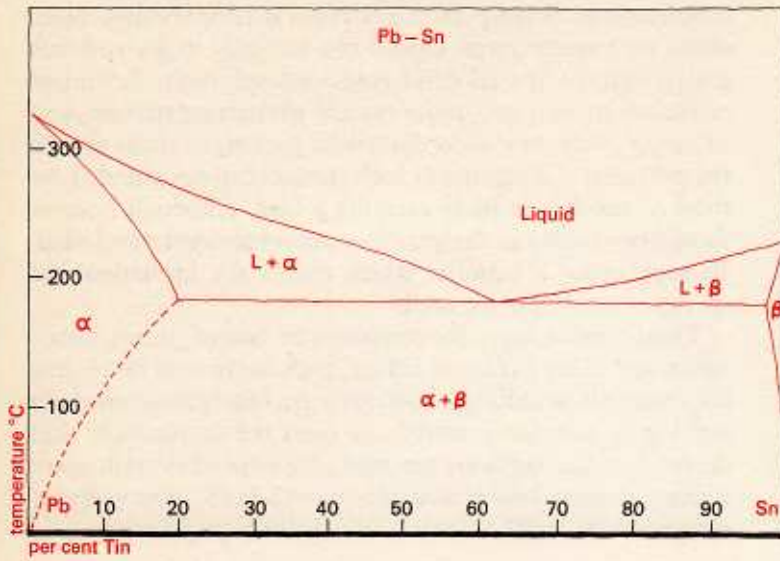
of engines, machines, etc., to be stressed in just one way. Bending loads, in which the stress changes from maximum tension to maximum compression, are common. Engine components have to endure very rapid alternations of tensions and compressions. Some parts are stressed at temperatures much above air temperatures, indeed at a red heat in gas turbines and jet engines. Special tests have been developed to determine resistance to 'fatigue' (under rapidly alternating stresses) and to 'creep' (very slow distortion under prolonged stress at high temperatures). Dangerously high stresses can be caused at the roots of notches in parts carrying a load. Although notches should be avoided in designs, they cannot always be excluded. In such cases, a material which resists the formation and spread of cracks can be used.

These special tests, for resistance to fatigue, creep, notch effect, and other causes of failure, have become of increasing importance in metallurgical research. Metallurgists, constantly striving to produce materials to meet the increasingly stiff demands of the engineers designing high-speed aircraft, space rockets, nuclear-powered engines, as well as the more ordinary constructions, make extensive use of these special tests.

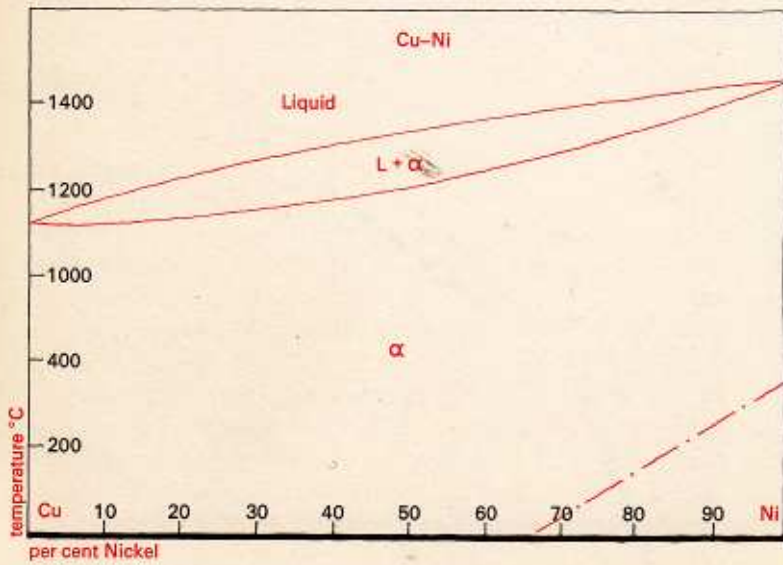
The stress-strain curve that results from extending a piece of metal to breaking point.
British Iron and Steel Federation



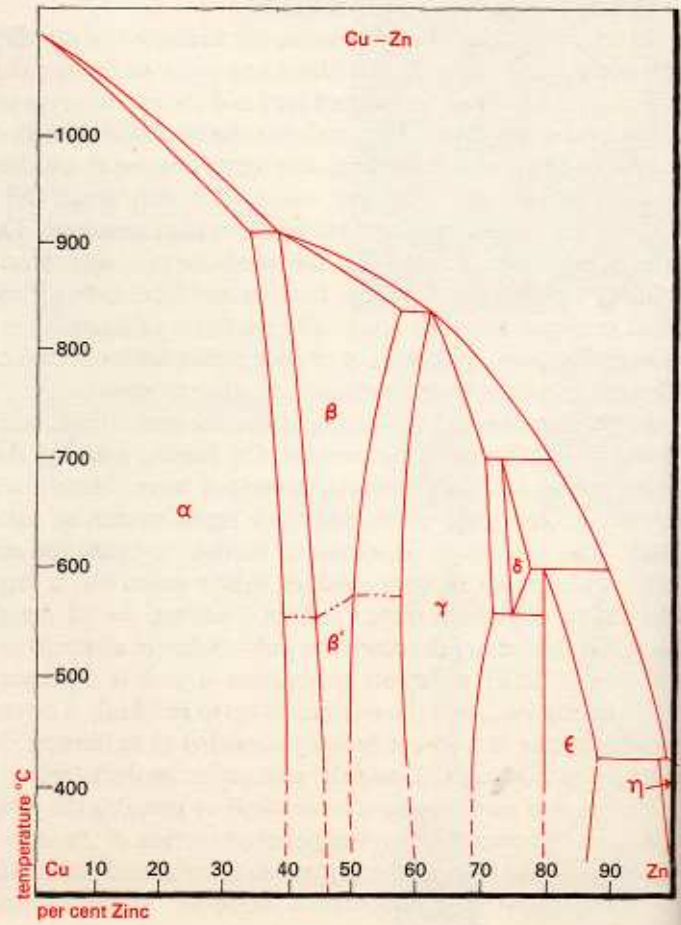
PART THREE ALLOYS



Lead-tin constitutional diagram.



Copper-nickel constitutional diagram.



Copper-zinc constitutional diagram.

Alloys are produced when an element (usually a metal) dissolves in a molten metal. If the element does not dissolve, no alloy is formed. Such alloys as bronze (copper and tin), brass (copper and zinc), and some steels (iron and carbon) have been made for many centuries by trial-and-error methods. Nowadays the making of alloys is an exact science. Our knowledge of them has been gained largely by microscopical study of their structure and by observing the changes in their constitution when they cool from liquids to solids. Other techniques, such as X-ray diffraction, have also helped to further our knowledge.

The changes that occur when an alloy in the liquid state is cooled, solidifies, and goes on cooling, may be very varied. When a liquid consisting of two substances solidifies, they may stay mixed within each crystal in the solid state. This is called a solid solution. A simple case is copper-nickel. These two metals are completely soluble in each other in both the liquid and the solid state. Both crystallize in the face-centred cubic system. Thus the solid alloy has the same composition throughout as the liquid and, under the microscope, has the structure of a single metal, with the nickel and copper atoms regularly distributed in the symmetrical crystals.

At the other extreme, cadmium and bismuth are completely soluble in each other when liquid, and separate completely when solid. Neither of these extremes is usual, but the lead-tin series of alloys – important because they are used as solders – approaches the cadmium-bismuth series in its behaviour. In the solid state, nearly 20 per cent of tin is soluble in lead and 2.5 per cent of lead in tin. The behaviour of the lead-tin alloys throughout the whole range of composition is shown on the opposite page. Diagrams of this kind are called 'constitutional diagrams'. They have been worked out for many alloys, including alloys involving more than two metals. They provide a great deal of valuable information as to how alloys can be best made and used.

Almost always, the freezing point of a metal is lowered by alloying it with another metal. Thus the freezing point of lead is lowered by the addition of tin, and the freezing point of tin is lowered by the addition of lead. The mixture that freezes at the lowest temperature is called the 'eutectic'. The freezing point of the tin-lead eutectic is 183°C. This eutectic is a mixture of lead saturated with tin and tin saturated with lead. Let us now have a look at the alloys of some of the more important metals.

Copper – Copper alloys freely with many metals, and several groups of copper alloys – for example, the brasses – have important industrial uses. Pure copper in the annealed condition (that is, not hardened by cold-working) is soft and plastic. Any element alloyed with copper hardens and strengthens it; this hardening is much greater with some elements than with others. The high electrical conductivity of copper is lowered by alloying, and this effect also varies according to which element is added. At least fourteen different elements are alloyed with copper in proportions ranging from little more than a trace to over 40 per cent. To their various effects, the strengthening influence of cold work can be added. The control of properties in this way is very wide indeed. Some of the principal alloys of copper are considered below under the headings of the alloying metals:

1. *Zinc*. Alloys of copper with zinc are known as brass. With up to 36 per cent zinc in solid solution, alpha brass is formed and, under the microscope, this differs little in appearance from a pure metal. However, the larger zinc atoms slightly distort the arrangement of copper atoms in the crystal structure and, by increasing the resistance to slip, have a hardening effect upon the copper.

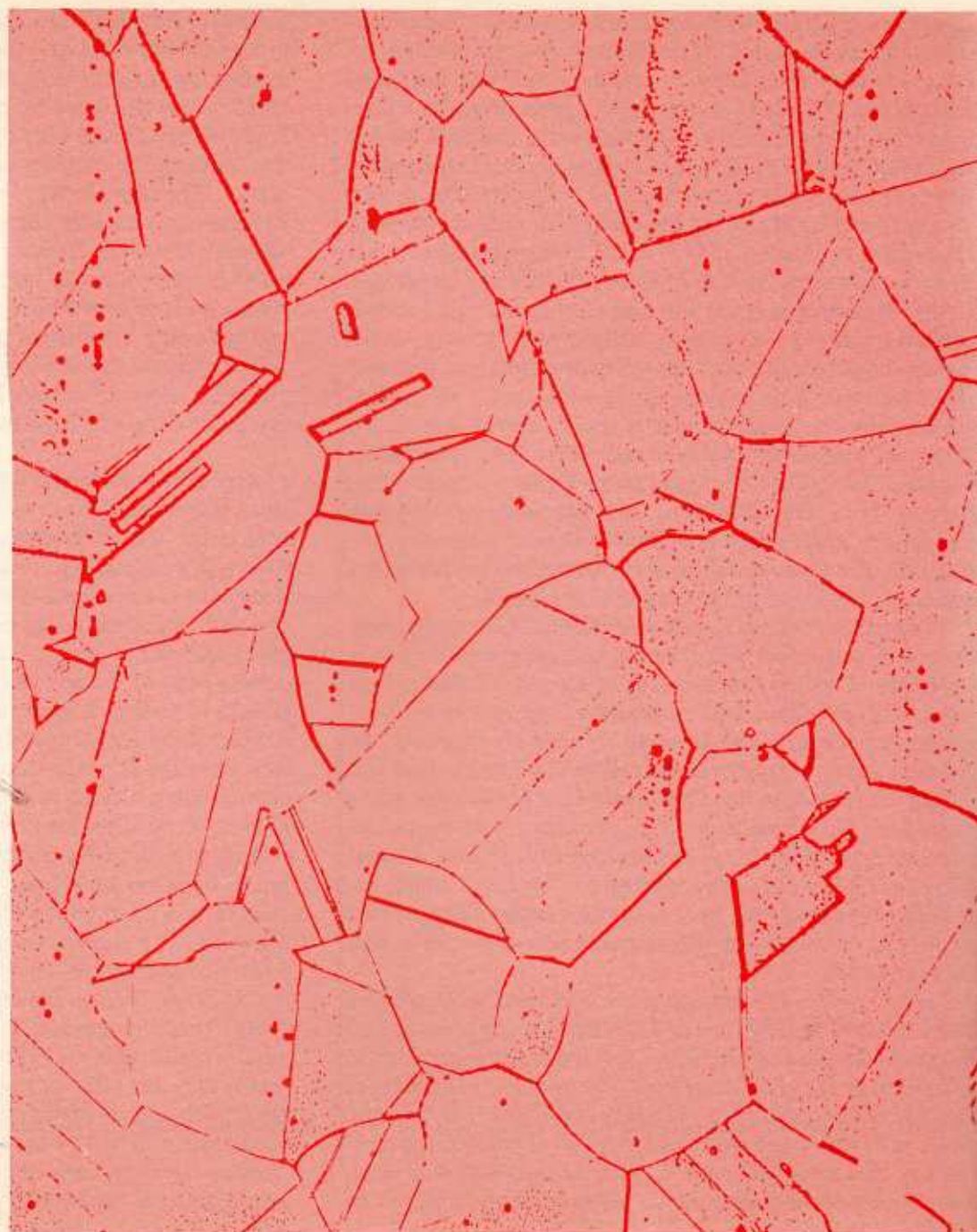
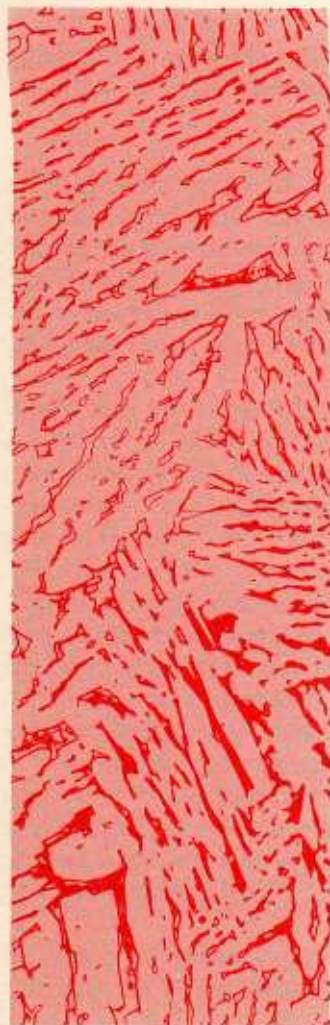
Beta brass is formed when more than 36 per cent zinc is added; beyond this limit, a slight distortion of the copper lattice is no longer able to accommodate all the zinc and, therefore, a change occurs in the packing of the atoms – from face-centred cubic packing in alpha brass to body-centred packing in beta. At ordinary temperatures beta is much the stronger.

A most useful alloy contains 40 per cent zinc, and is commonly known as 60/40 brass. At room temperature 60/40 brass consists of a mixture of alpha and beta. But, at temperatures above 760°C, it consists wholly of beta and is then very plastic. This permits easy hot-working and, at temperatures over 800°C, 60/40 brass is one of the easiest alloys to extrude.

70/30 brass (containing 70 per cent copper and 30 per cent zinc) is plastic at room temperatures and is especially suitable for drawing into tubes and cartridge cases. However, it hardens rapidly when cold-drawn and, depending on its final use, may need to be softened by annealing.

Other elements are often added to brass to modify its properties. For example, a brass containing 22 per cent zinc and 2 per cent aluminium is almost identical with 70/30 brass

Photomicrograph of copper-
zinc alloy (60/40 brass)
(magnification $\times 150$).
National Physical Laboratory



(Left) Photomicrograph of a copper-nickel-zinc alloy (18 per cent nickel) (Magnification $\times 400$). These three metals are completely soluble in each other in both the liquid and the solid state. The alloy crystals contain both copper, nickel and zinc atoms. National Physical Laboratory

Photomicrograph of a lead-tin alloy (magnification $\times 300$). National Physical Laboratory



in drawing properties and strength but has a far greater resistance to a troublesome kind of corrosion that used to put the condensers of ships' engines out of commission after short service. (See the Background Book *Corrosion*.) Iron and manganese each add strength to 60/40 brass, and a little lead makes it easier to machine.

2. Nickel. Copper and nickel alloy in all proportions.

The red colour of copper rapidly disappears as nickel is added and, at 15 per cent nickel, the alloy is white. This colour change is made use of in the nickel brasses, which contain about 60 per cent copper and 40 per cent zinc and nickel in varying proportion. When polished, the nickel brasses are silvery in appearance, and are commonly called nickel silvers.

Excellent properties, including resistance to corrosion, are found throughout the whole range of copper-nickel alloys. Those British coins which were formerly made of silver are now made from an alloy containing 75 per cent copper and 25 per cent nickel.

3. Beryllium.

Some alloys can be age-hardened – that is, they can be so treated that their hardness and strength increase with lapse of time. This effect was first observed in aluminium alloys, in particular 'duralumin' containing 4 per cent copper and about 0.5 per cent each of magnesium and silicon. Beryllium-copper is a simpler and an even more striking case of age-hardening. At 864°C, copper can hold 2.7 per cent of beryllium in solid solution, but this solubility steadily falls as the alloy cools; another solid solution (known as 'gamma') then precipitates out. If an alloy containing, say, 2 per cent beryllium is cooled quickly from 800°C, and if it is then gently heated for one hour at 300°C, this change takes place almost completely, the gamma solid solution being precipitated in fine particles which greatly interfere with slip on the crystal planes. The alloy is strengthened to a remarkable degree. Beryllium-copper treated in this way is used for springs, cutting tools, and hard non-sparking tools.

Since the discovery of precipitation-hardening (called 'age-hardening' if it occurs at ordinary temperatures), it has been applied to a number of other alloy systems. One very ancient process – hardening and tempering of steel – is now regarded as a complicated instance of precipitation-hardening. (See page 27.)

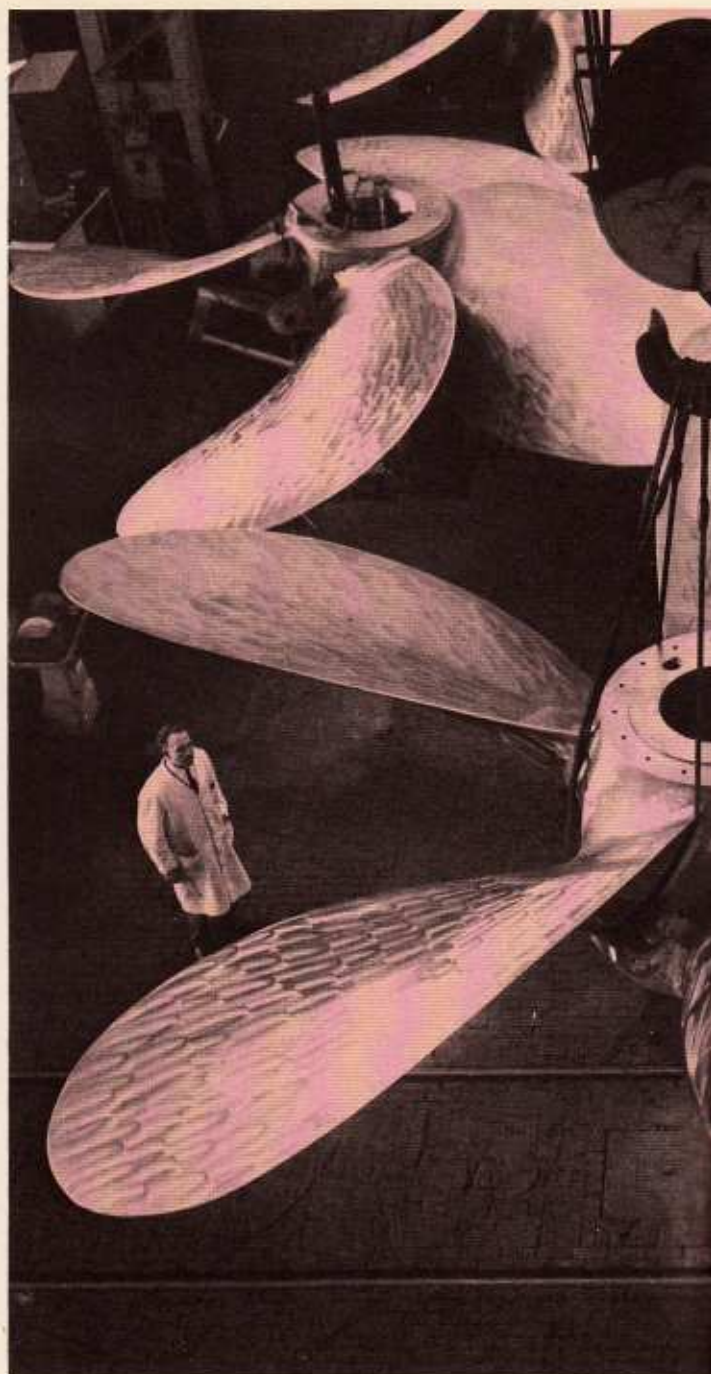
Bronze, an alloy of copper, tin, and other metals, is used to make these huge ship's propellers weighing over 30 tons.
The Times

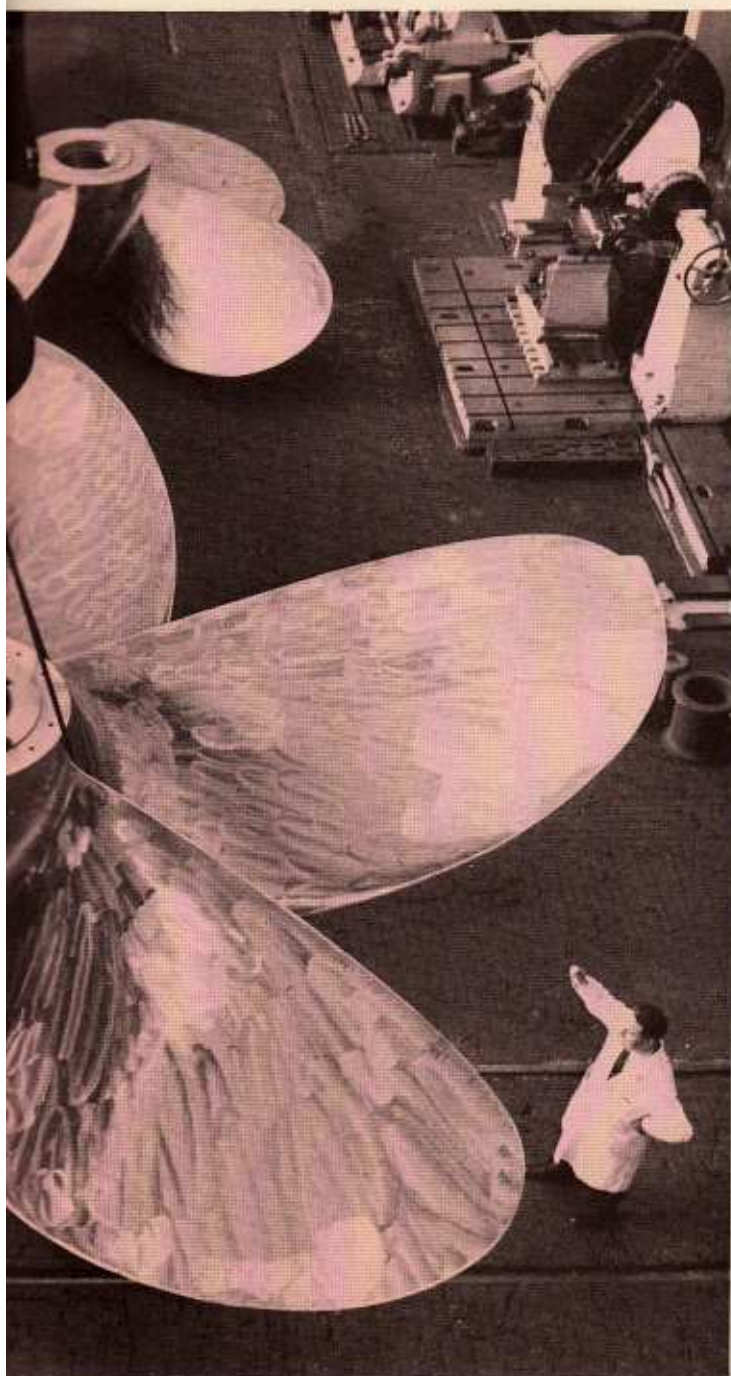
4. *Tin.* Alloys of copper with tin are known as bronze. Bronze has an ancient history although it seems likely that the bronze mentioned by Homer was simply impure copper. In modern times, confusion has arisen from describing as bronze several alloys other than those of copper and tin, such as manganese bronze (really a complex brass), silicon bronze, and beryllium bronze.

In bronze, copper is alloyed with up to 12 per cent of tin. Tin has a much greater strengthening effect in copper than zinc, and the bronzes are very strong materials. To reduce any oxides that may be present (oxides are harmful to copper alloys), phosphorus is often added to bronze – to produce an alloy called phosphor bronze. Zinc is a good deoxidizer so that the brasses and other copper alloys containing zinc rarely need any further deoxidizing. The gun-metals are copper-tin-zinc alloys.

Aluminium – Like most pure metals, aluminium is soft and very ductile. It can be strengthened by cold work, but much more by alloying. A disadvantage of cold work is that the added strength begins to fall off when the aluminium is heated.

The specific gravity of aluminium is less than half that of iron and, although the strongest aluminium alloys are much weaker than the strongest steels, lightness in weight is often more important. Light weight is obviously desirable in aircraft and is advantageous too in many other constructional applications – for example, the superstructure of ships where lightness lowers the centre of gravity as well as the total tonnage. Weight for weight, aluminium costs about six times as much as mild steel, but it may still be economic to use aluminium because a ton of it will build so much more than a ton of steel.





Aluminium has a strong affinity for oxygen, and so one might expect that it would corrode very easily, but this is not so. A perfectly clean surface of aluminium exposed to air immediately becomes coated with a strong and continuous film of aluminium oxide protecting the surface from further oxidation. This film – less than one-millionth of an inch thick – is transparent and invisible, and does not affect the silvery brightness of the surface. Some other metals, notably chromium, show a readiness to form a protective oxide film and both aluminium and chromium can protect alloys in which they are present against corrosion. It is the chromium in stainless steel which makes it resist rusting.

Aluminium is alloyed with several metals – one or more in varying proportions – and the number of possible alloys is enormous. Of particular interest are those containing copper, magnesium, manganese, and silicon, which, as mentioned before, can be considerably strengthened by age-hardening. The tensile strength of these alloys, suitably heat-treated, may be as much as six times that of pure aluminium.

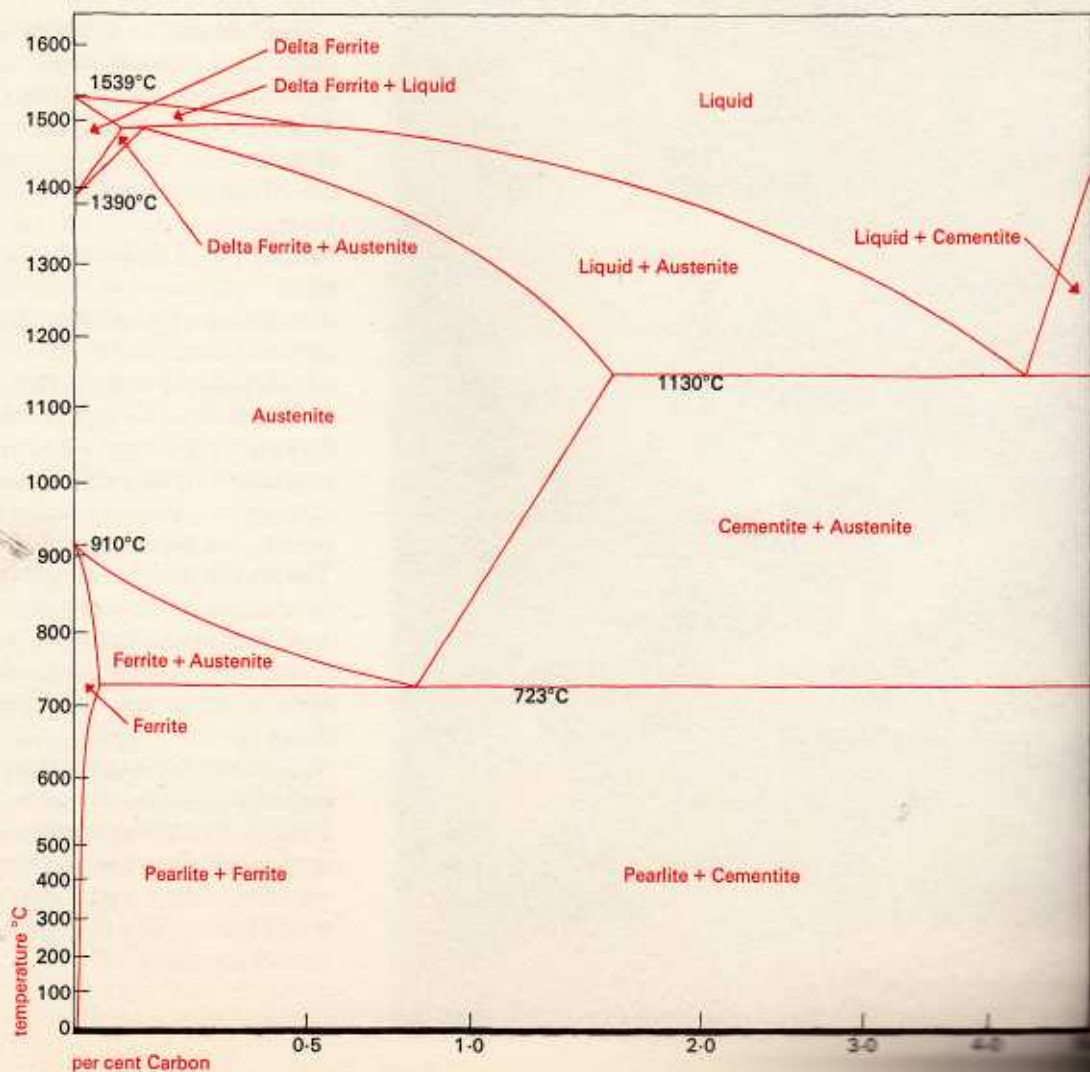
Although aluminium is used mainly in the form of alloys, there are important applications for the pure, or nearly pure, metal. Aluminium, which has an electrical conductivity two-thirds that of copper, is extensively used for electric cable. Aluminium foil is used for packaging; and the brilliant reflecting surface of suitably processed aluminium makes it especially suitable for such applications as headlamp reflectors and the mirrors of giant astronomical telescopes. Aluminium alloys are often coated with a thin adherent layer of the pure metal which thus confers its high resistance to corrosion on the more corrodible alloys.

Iron – Iron is the only common metal that will dissolve an appreciable quantity of the non-metal carbon: liquid iron will hold over 5 per cent carbon in solution and solid iron up to 2 per cent. The series of iron-carbon alloys so formed is the basis of all the steels, by far the most important alloys we use. Pure iron is soft and weak, but the addition of carbon progressively strengthens it – owing to the formation of the very hard compound iron carbide (Fe_3C – ‘cementite’). Control of the changes in structure that occur on cooling from temperatures of about 900°C provides a further wide range of strength and other properties.

Carbon steels, so called to distinguish them from *alloy steels* containing nickel, chromium, tungsten, or other special elements, are the main product of the heavy steel industry. The most important carbon steel is mild steel containing not more than 0.3 per cent of carbon – more steel of this kind is made than all other kinds together. It is worked, usually by hot-rolling, into the many shapes used in constructional work, where its strength, ductility, and low cost are all in its favour.

A typical mild steel is ship plate containing 0.2 per cent carbon, 0.7 per cent manganese, 0.2 per cent silicon – all steels

Iron-iron carbide constitutional diagram.



**From iron to steel:
photomicrographs**

Pure iron *top*
(magnification $\times 200$).

0.2 per cent carbon *bottom*
(magnification $\times 200$).



0.5 per cent carbon *top*
(magnification $\times 200$).

'Pearlite' structure of a carbon
steel *bottom*. The iron and iron
carbide are in very thin
alternate layers (magnification
 $\times 2000$).
National Physical Laboratory



contain manganese and silicon which, among other things, free the steel from injurious oxide. For bridge and building girders, the carbon content is a little higher; for car-body sheet, which is pressed into curved shapes, the carbon content is lower. These are merely a few examples of the many varieties of plain steel in which the carbon content, and thus the strength and hardness, are adjusted to fit a particular application.

When a carbon steel is slowly cooled, iron carbide separates out of solid solution at a temperature around 700°C . Under the microscope, it can be seen that the iron and iron carbide are in very thin alternate layers. This structure is known as 'pearlite'. With a carbon content of 0.83 per cent, the structure of the alloy is pearlitic throughout. With a carbon content of less than 0.83 per cent, the alloy is a mixture of iron and pearlite. With a carbon content greater than 0.83 per cent, the carbide is in excess: because the carbide is extremely hard, high-carbon steels are correspondingly hard.

However, if the steel (carbon over 0.7 per cent) is cooled very rapidly as by plunging it into cold water, there is not time for the iron and carbide to separate into thin plates, and the carbide separates as extremely small particles. These small particles prevent slip on the crystal planes of the iron, and so make this quenched steel glass-hard – and also brittle. When the steel is heated to 150°C , slight softening takes place and this softening proceeds more and more quickly as the temperature is raised. Suitable 'tempering', as this heating is called, makes, say, a steel tool less brittle but still hard enough to take and keep a sharp cutting edge.

The hardening of steel by rapid cooling from high temperatures is another instance of 'precipitation hardening'. The final hardness and strength can be controlled by the temperature used in the tempering process that follows the hardening. A fine-grained steel of uniformly good properties results from such heat-treatment. Most of the steel used for constructional purposes (ships, buildings, railway rolling stock etc.) is not heat-treated in this way because the required properties can be obtained simply by rolling at the correct temperature and cooling in air.

Alloy steels – Every kind of steel is an alloy, but not all steels are alloy steels. The term alloy steels is restricted to steels which contain (in addition to carbon, silicon, and small amounts of manganese) one or more of the metals nickel, chromium, tungsten, molybdenum, and vanadium, or more than 2 per cent manganese. Other elements that are sometimes added to alloy steels include cobalt, copper, niobium, zirconium, selenium, and lead.

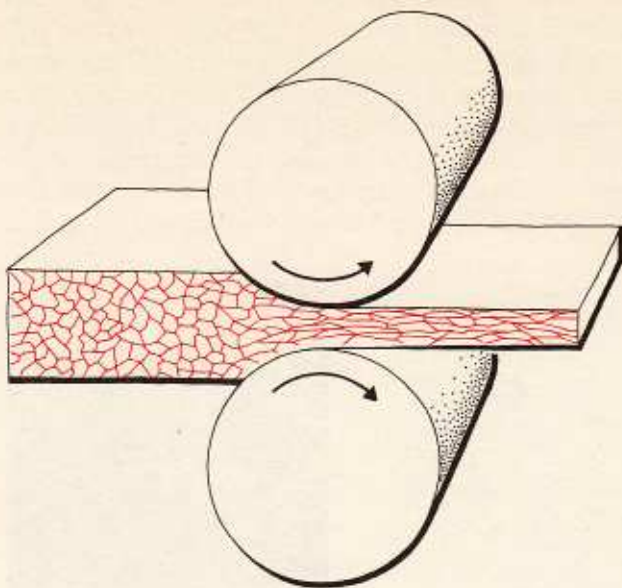
It has long been known that the addition of nickel (say 3.5 per cent), or nickel and chromium together (say 3 per cent nickel and 1 per cent chromium), confers better properties on carbon steel. With such compositions, high strength can be combined with toughness, and the addition of a little molybdenum prevents brittleness. By ringing the changes throughout a range of content of carbon, nickel, chromium, and, if used, molybdenum, a variety of very strong steels can be produced which are particularly suitable for such applications as large forgings and thick plates.

Chromium added in substantial proportion (from 10 to 20 per cent) to steel greatly reduces the steel's corrodibility, and is the essential element in the many kinds of stainless steel. When a durable cutting edge is needed (as in cutlery), about 12 per cent of chromium with a little nickel is used. Because of the high chromium content and special care needed in manufacture, all types of stainless steel are costly and, for most purposes, it is more economical to use carbon steels protected from rusting by a coating of paint, zinc, tin, etc. There are, however, many applications, for example in chemical plant, where protective coatings cannot be used, and here stainless steels are being used in increasing quantities.

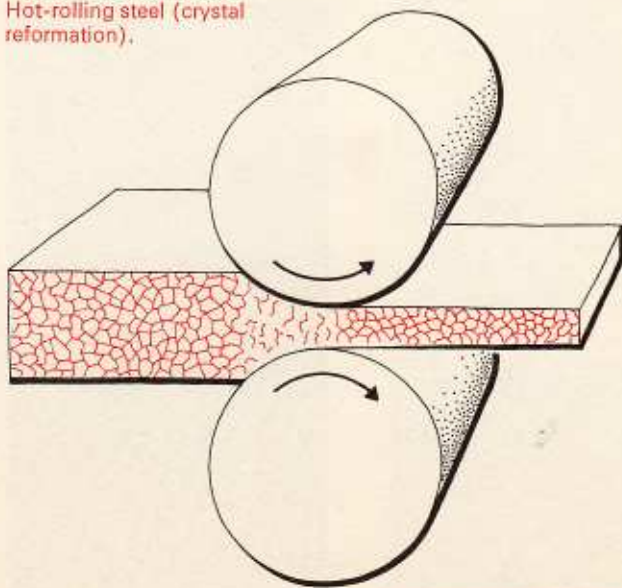
Tungsten has the remarkable power of making steel cutting-tools keep their edge and cutting power at temperatures which would make carbon-steel tools soft and useless. 'High-speed steels', containing up to 20 per cent of tungsten, are used in the rapid machining of steel and cast iron where the tool may become red-hot.

Special care is needed to make alloy steels. The electric-arc furnace is usually used for their manufacture because this permits close control of temperature, atmosphere, and slag, and of the oxidation, reduction, and alloying processes. The charge, which may be more than 100 tons, is melted on a hearth by the arcs struck between the metal and heavy vertical carbon electrodes suspended through the roof of the furnace.

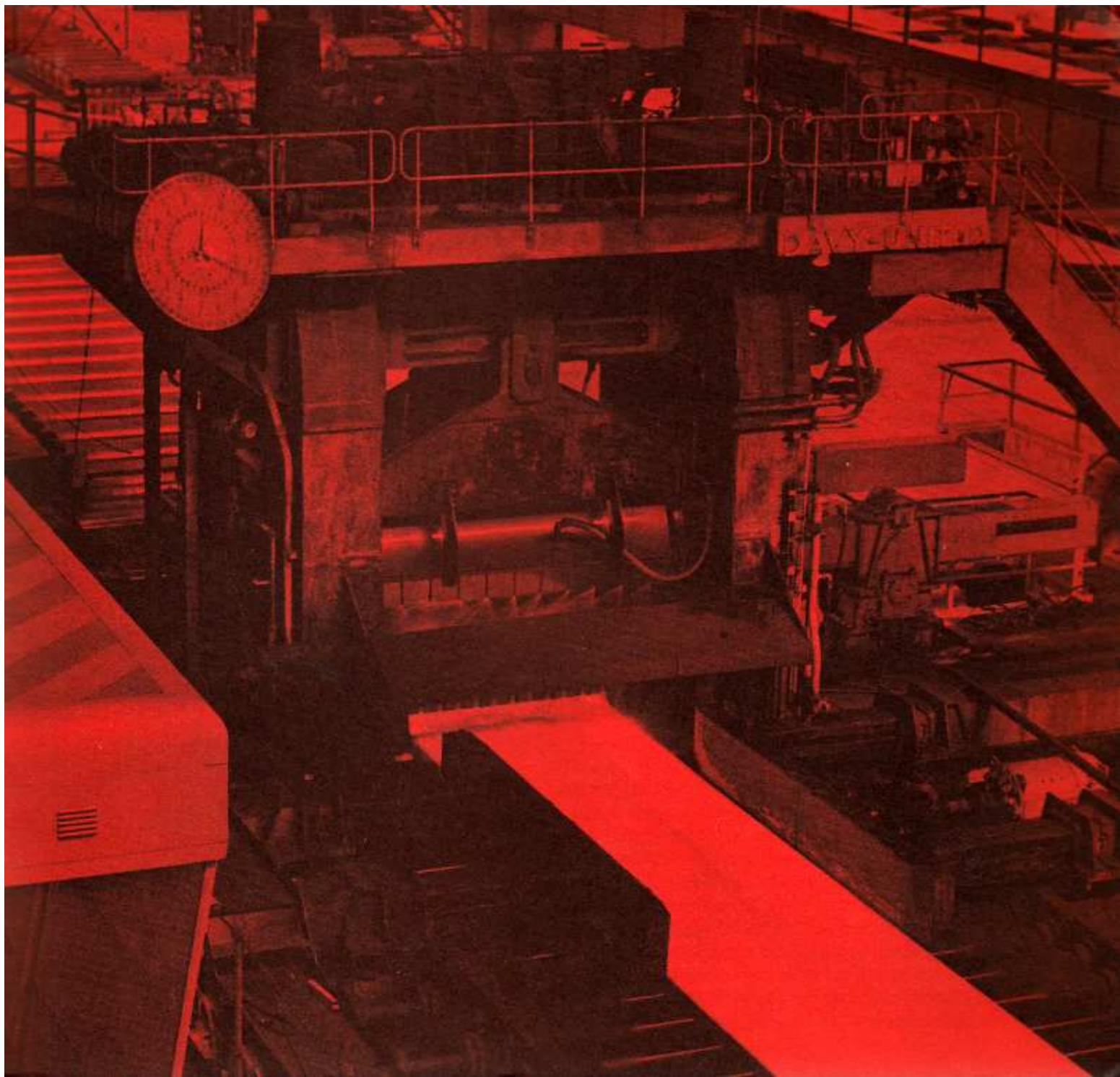
Cold-rolling steel (crystal deformation).



Hot-rolling steel (crystal reformation).



Hot-rolling of steel to produce steel plate that is strong but not brittle (right).



PART FOUR SOME OTHER METALS

The Van Arkel process for purifying titanium – by converting crude titanium into titanium iodide gas, from which pure titanium is deposited on a tungsten filament. Here a filament, coated with titanium, is being withdrawn from the deposition furnace. A.E.I.

So far we have considered a few of the better-known metals. Other well-known and useful metals are lead, zinc, and tin, each produced on a similar scale to copper. Manganese, too, is produced in large quantities, but nearly all of it goes into the manufacture of steel. Chromium, tungsten, and molybdenum are, like manganese, extensively used in steel manufacture but have, in addition, important applications of their own. Tungsten, for example, is used to make electric light filaments – because the metal's high melting point enables it to withstand high temperatures for a long time. For the same reason, nickel-chromium alloys are used to make the heating elements of electric fires. Both chromium and nickel are commonly used for plating, and, as we have seen, nickel forms a number of useful alloys with other metals. Magnesium is another familiar metal that forms useful alloys – especially for constructional materials where extreme lightness is needed. All these metals have been used by industry for a long time. Let us now look at some of the newer metals – those that have come into prominence in recent years.

Titanium, which is comparatively abundant in the Earth's crust, has emerged as a useful metal only recently because it is very difficult to extract from its ores. This difficulty is due to its high melting point ($1,670^{\circ}\text{C}$) and its reactivity at this temperature with oxygen, nitrogen, carbon, and crucible materials. Titanium occurs in its ores as the oxide (TiO_2). The oxide cannot be reduced with hydrogen or carbon, and therefore it is converted into the tetrachloride (TiCl_4) which is usually reduced with magnesium; magnesium chloride and excess magnesium are then separated from the titanium by distillation. If further purification is necessary, the ingenious Van Arkel method can be used. In this method, the titanium is



converted into the gaseous iodide (by heating with iodine) from which pure titanium is deposited on a tungsten filament at about 1,300°C; the process is cyclic, and a small amount of iodine can purify a very much larger quantity of titanium. High melting point and reactivity also necessitate special precautions in all remelting and hot-working operations, adding further to the cost of production.

Titanium and its alloys possess a combination of valuable properties – lightness, strength, ductility, resistance to corrosion, and high melting point – found in no other engineering material. These properties are especially attractive to designers of high-speed aircraft. Aluminium, together with tin, zirconium, iron, manganese, or chromium, is alloyed with titanium to increase its strength. The cost of titanium and its alloys, however, remains very much higher than that of, for example, stainless steel.

Beryllium also has properties that make it attractive as a structural material, and it is much lighter than titanium – nearly as light as magnesium. Its high melting point (1,284°C) enables it to retain its strength at high temperatures and its resistance to oxidation is good, again, like that of aluminium, because of the formation of a protective oxide film. The combination of these properties leads to the use of beryllium in structural parts of aircraft, space vehicles, and missiles, and in the manufacture of small components where strength, rigidity, and lightness make the high cost worth while. Permeability to X-rays (because of the metal's low atomic weight) makes beryllium an excellent material for X-ray 'windows', and it also has applications in nuclear reactors. However, beryllium is still mostly used to make the alloy beryllium copper (page 23).

Beryl (beryllium aluminium silicate), a rare mineral, is the main source of the metal. A succession of chemical processes produces the pure oxide which is converted into the fluoride. The fluoride is then reduced with magnesium metal; the molten beryllium floats on the magnesium fluoride slag. But the poisonous nature of beryllium and its compounds (in the form of dust, vapour etc.) has retarded its use and makes troublesome precautions necessary in manufacture.

Zirconium, very rare until recently, is now produced in thousands of tons. It confers useful properties on certain steels, copper alloys, and magnesium alloys. But the main use

of the metal, and of zirconium-rich alloys, is in the construction of nuclear reactors. The uranium fuel must be surrounded by materials which do not absorb neutrons because neutrons are responsible for bringing about the energy-giving chain reaction; of all metals, zirconium has almost the lowest absorbency of neutrons. Zirconium, too, strongly resists corrosion (owing to the formation of an oxide film) and for this reason is sometimes used in the construction of the more vulnerable parts of chemical plant. To make it stronger, zirconium is often alloyed with small amounts of tin, iron, chromium, and nickel.

According to the latest estimates, there is more zirconium in the Earth's crust than nickel, copper, tin, and lead together. Zircon sand, from which titanium is also extracted, is the main source of supply. A little hafnium is usually present as well, and the chemical similarity of zirconium and hafnium makes their separation very difficult. But, for zirconium to be used in nuclear reactors, it is essential to remove the hafnium, because the latter's neutron absorption is about 500 times as great.

The extraction resembles that of titanium, and is responsible for the high cost. Zirconium tetrachloride is reduced with magnesium and the iodide decomposition process can be used for final purification.

Uranium has the highest atomic number (92) and atomic weight (238.03) of all the naturally occurring elements. It came into prominence at the end of the nineteenth century when, in one of its compounds, radioactivity was first observed. (See the Background Book *Inside the Atom*.) Subsequently, uranium minerals became valuable for their content of radium. Nowadays the great importance of uranium lies solely in its use as a nuclear fuel – it is the only naturally occurring element from which energy is obtained by fission of the atomic nucleus.

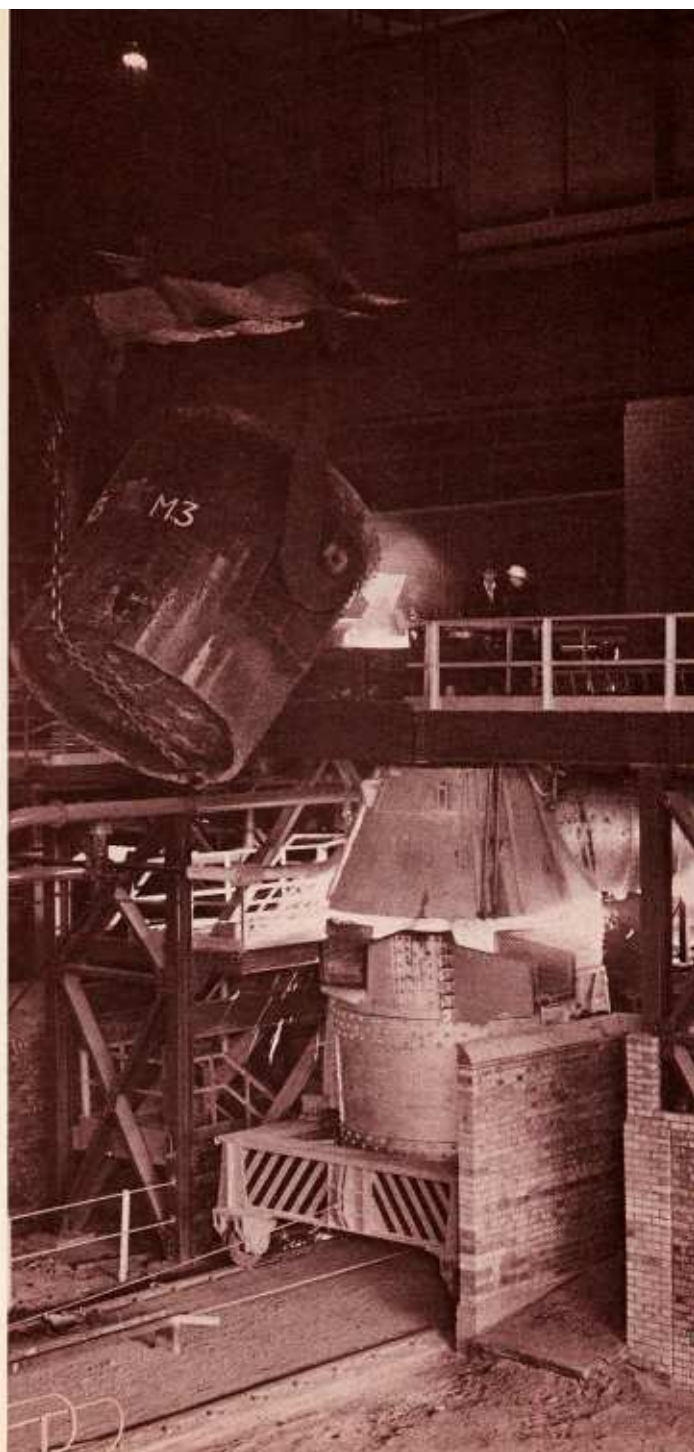
The energy is initially derived wholly from the isotope uranium 235 (of which less than 1 per cent is present in the metal) and, although the complex and costly business of separating the isotope must be done to make a bomb, it is unnecessary to do so to use the uranium in nuclear reactors.

Uranium is much more abundant in the earth's crust than silver, gold, or platinum, but is widely distributed through the rocks so that uranium ores contain only a small percentage of the metal. Mechanical, thermal, and chemical methods are

necessary for its extraction and purification, and the process, which requires special precautions against radioactivity, is both long and costly. In the later stages, uranium oxide is converted into the fluoride and this is reduced with magnesium or calcium. Many tons of the metal are produced annually, and are melted, cast and hot-worked into sheet, rod, and other forms required in reactors.

Rare metals – Titanium, beryllium, zirconium, and uranium are four of the so-called 'rare' metals of which some thirty are now being developed industrially. Nuclear energy has inspired some of this industrial interest – for example, in metals having especially high or low neutron absorption for different parts of nuclear reactors. The replacement of thermionic valves by transistors – with a useful reduction in the size of such electrical equipment as radios, hearing aids, and computers – has resulted from study of the semi-conducting properties of germanium. In the manufacture of transistors, the less metallic silicon is germanium's chief rival. The use of niobium as an alloy element in steel, conferring greater strength and other useful properties, has already been mentioned. In America, niobium is known as columbium. Stability at high temperatures makes the use of niobium and its alloys attractive for jet engines, gas turbines, missiles, etc. Indium is one of several rare metals present in residues from the extraction of commoner metals. Silvery-white with a brilliant metallic lustre, indium is softer than lead, and is an essential constituent of the germanium transistor. Complex bearings for severe service have a lead-indium alloy lining with remarkable anti-friction properties. Tantalum combines a very high melting point with great strength and resistance to corrosion, which is why it is used in the manufacture of special chemical equipment. Tantalum's application in electrolytic capacitors is based on the rectifying and dielectric properties of its oxide-surface film.

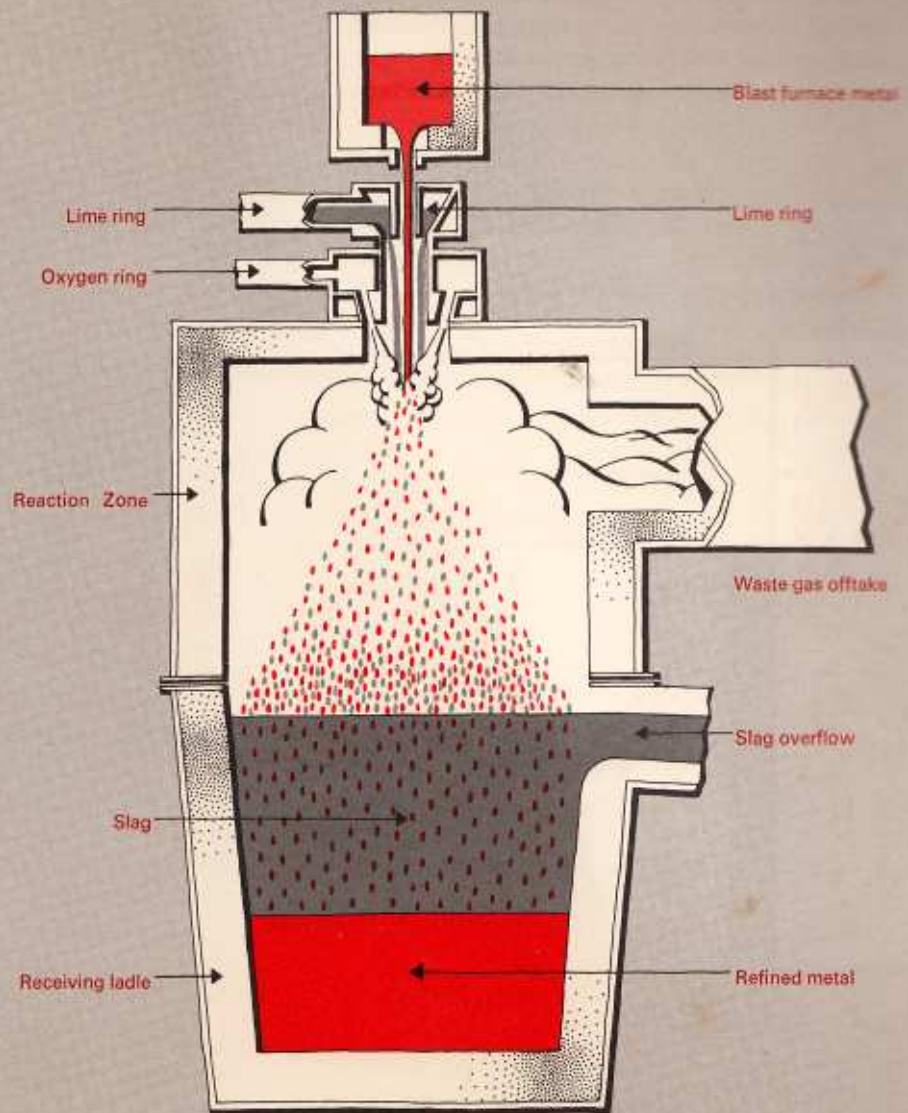
In this brief survey of an immense subject, it has been possible to outline only some of the more significant aspects of metals and alloys. Future work in metallurgy will probably be concentrated on the following three areas: exploring further the relationship between a metal's properties and its structure; improving extraction techniques – especially for the extraction of metals from lean ores; and developing new alloys to meet the demands of space travel and nuclear power.



Spray Steelmaking Process

Spray steelmaking is a revolutionary new process for the conversion of iron from the blast furnace into steel. It has been developed at the Sheffield laboratories of the British Iron and Steel Research Association and is just being introduced into production. Unlike conventional steelmaking processes, spray steelmaking treats the molten iron in the form of a falling stream, not as a batch of so many tons in a container. High velocity jets of oxygen atomize this stream and burn out unwanted elements. Lime and fluxes are continuously fed in, to form a slag with these oxidized elements. The spray of refined material is collected in a receiving ladle and the slag is run off, continuously. Up to 40 per cent scrap can be added to the receiving vessel before or during the operation. This cools the refined metal, whose temperature rises from about 1550°C to $2000\text{--}2200^{\circ}\text{C}$ as it passes through the oxygen jet, and is thus more than hot enough to melt the scrap; it also helps to reduce the cost of the process in materials.

Left, is the spray steelmaking unit at the Lancashire Steel Manufacturing Co. Ltd. Right, the spray steelmaking process can be seen in condensed form, British Iron and Steel Research Association



Chemistry Background Books

The diagram illustrates the periodic table with handwritten lines connecting elements to their corresponding electron shells. The shells are represented by concentric circles around a central point. The connections are as follows:

- First Shell:** H (1), He (2)
- Second Shell:** Li (3), Be (4)
- Third Shell:** Na (11), Mg (12)
- Fourth Shell:** K (19), Ca (20), Sc (21), Ti (22), V (23), Cr (24), Mn (25), Fe (26), Co (27), Ni (28), Cu (29), Zn (30)
- Fifth Shell:** Rb (37), Sr (38), Y (39), Zr (40), Nb (41), Mo (42), Tc (43), Ru (44), Rh (45), Pd (46), Ag (47), Cd (48)
- Sixth Shell:** Cs (55), Ba (56), La (57), Hf (72), Ta (73), W (74), Re (75), Os (76), Ir (77), Pt (78), Au (79), Hg (80)
- Seventh Shell:** Fr (87), Ra (88), Ac (89), Th (90), Pa (91), U (92), Np (93), Pu (94), Am (95), Cm (96), Bk (97), Cf (98)