3 Our uses of steel and aluminium

and why we choose them

To understand what options we might have to change the way we use materials, we need to find out what we use them for at present and this requires some detective work. We also need to look at the key properties of the materials we use, to find out why they're so attractive

We're going to focus mainly on steel and aluminium, so obviously our first question is "what are we using them for?" No one else can tell us the answer, so we need to do some detective work. Fortunately help is at hand...

"Elementary, my dear Watson"

> *… and the elite crowd of metal detectors gathered in the Beaufort Bar at the Savoy. In the silence, broken only by her quiet clicking, Miss Marple stood to reveal that at last she had solved the riddle of the long products, but as she reached for her dénouement, stumbled, her (steel wire) knitting needles silenced forever as they plunged through her heart. Hercule Poirot, reacting with the slightest lift of an eyebrow, and having arrived only that afternoon on the (17,000 tonnes of hot rolled steel plate) Cunard Princess, took a pinch from his (deep drawn cold rolled steel strip) snuff box, ready to reveal the locations of the world's rolled strip and plate, choked, and was silent—the wax of his skin finally matching that of his perfect moustache. The (aluminium and steel) ambulance drew to a halt as the doctor ran to the terrible scene, pausing only to ask his companion about the fundamental basis of such metal variety. "Elementary, my dear Watson."* [1]*…*

OK—that's not going to work, we'll have to do the detective work ourselves. There is no catalogue of current metal products, because of the number of different businesses involved in making them. The terms "steel industry" and "aluminium industry" are used to describe the companies that transform ore or scrap metal, via a molten liquid stage, into 'intermediate' stock products such as plates, coils of thin strip and standard bars, for which we have good data[2]. These products are 'intermediate' because no final consumer wants them in that form—"would you like to come up and see my bar stock?" Instead, through manufacturing, fabrication and assembly they are converted into final goods. But this conversion involves a huge range of different businesses, and there is no co-ordinated data from there on. So we've assembled the best data we can find, and used it to estimate where steel and aluminium end up. The result is the two catalogues on the next two double pages—one for each metal.

Transport

Cars and light trucks

93 Mt

9 %

An average car contains 960 kg of steel and iron. 34 % is in the body structure, panels and closures (doors and bonnets), consisting of welded, profiled sections produced by stamping formable cold rolled sheet. This provides high strength and energy absorption in case of a crash. 23 % is in the drive train, consisting of grey cast iron for the engine block and machinable carbon steel for the wear resistant gears. 12 % is in the suspension, using rolled high strength steel strip. The rest is spread between the wheels, tyres, fuel tank, steering and braking systems.

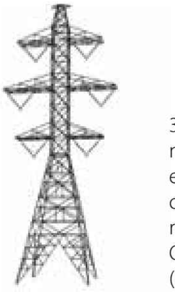
Trucks and ships

28 Mt

3 %

The basic steel components described for the car also apply to trucks, but unlike cars, all truck engine blocks are steel. Frame rails and cross members are usually high tensile steel, and the cab structure and outer skin is often made from galvanized steel. Steel for the ship hull is rolled primary mild steel, providing strong, tough, dimensionally consistent plates that are welded together.

Industrial equipment



Electrical equipment

27 Mt

3 %

30 % of steel in electrical equipment is high silicon content electrical steel forming the cores of transformers or the stator and rotor parts of electrical motors. Other major uses include pylons (constructed from bolted, cold-formed, galvanized L-sections forming a light-weight durable tower); and steel reinforced cables (where wound galvanized steel wires provide the strength to carry conducting aluminium in long span transmission cables).

Mechanical equipment

137 Mt

13 %

This covers a wide range of equipment from small workshop tools to large factory-based robotic machinery and rolling mills. 40 % of the steel is plate or hot rolled bar; tubes contribute a further 22 %, as do hot and cold rolled coils. Cast products and wire rod contribute the remainder.

Figure 3.1—**Steel product catalogue**

We make over 1,000 Mt of steel products every year, equivalent to a 1 metre square band of steel wrapped around the equator more than three times. Global steel production is divided into 4 sectors and 9 categories of end-use products. The amount of steel in each category is given in millions of tonnes Mt and the fraction of global steel as a percentage %, with the images sized to reflect this fraction. The end-use of steel is dominated by construction (56 %). These numbers are derived from data for 2008.

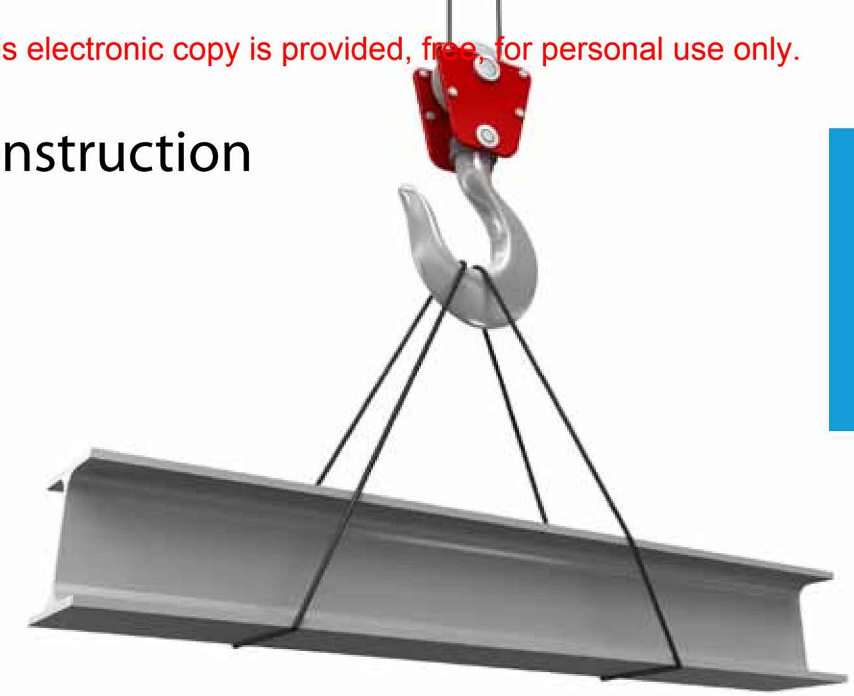
Construction

Infrastructure

150 Mt

14 %

For infrastructure: 24 % of steel is in structural sections; 54 % is reinforcing bars; 6 % is hot rolled train rails (providing a strong, wear and fatigue resistant contact surface); 16 % is in pipes formed by welding rolled steel, with high corrosion and fatigue resistance, and high strength to resist internal pressure and installation stresses.



Buildings

433 Mt

42 %

25 % of the steel in buildings is in structural sections, mainly hot rolled sections but also some welded plate. Sections form a strong, stiff structural frame. 44 % is in reinforcing bars, adding tensile strength and stiffness to concrete. Steel is used because it binds well to concrete, has a similar thermal expansion coefficient and is strong and relatively cheap. 31 % is in sheet products such as cold-formed purlins for portal frame buildings and as exterior cladding.

Metal products

Metal goods

134 Mt

12 %

Other metal goods include a multitude of products, from baths and chairs to filing cabinets and barbed wire. 30 % of steel entering this product group is hot rolled coil; 20 % is hot rolled bar; and the remainder is either plate, narrow strip, or cast iron.

Consumer packaging

9 Mt

1 %

Steel use in packaging is dominated by tin-plated rolled steel, which doesn't corrode. 60 % of this steel is made into food cans, providing durable packaging for the subsequent cooking and distribution. 40 % is used for aerosols.

Domestic appliances

29 Mt

3 %

Appliances are dominated by white goods (up to 70 %). The vast majority of steel used here is cold rolled coil, often galvanized or painted. Most of this steel is used for panelling. Other applications including washing machine tubs (welded rolled steel strip), motors, expanders in fridge/freezers and cast parts for transmissions.

Aluminium product catalogue

Transport

Cars

8 Mt
18 %

An average car contains 120 kg of aluminium. 35 % is in the cast engine, requiring high strength and wear resistance. 15 % is in the cast transmission casing, providing stiffness for gear teeth alignment and thermal conductivity for dissipation of frictional heat. 15 % is in the cast wheels, giving a lightweight aesthetic design. The remaining aluminium is mainly in the heat exchanger (requiring high thermal conductivity) and forgings in the chassis and suspension. Aluminium is increasingly used in car engines and bodies to save weight.

Trucks

3 Mt
7 %

Many of the basic aluminium components described for the car also apply to trucks, with the exception that aluminium cast engines are rare. Aluminium is used in trucks for corrosion resistance and weight saving. Applications include the cab structure and outer skin, chassis and suspension parts, tipping bodies and sliding side doors.

Other

1 Mt
2 %

Aluminium, used extensively in the aerospace industry for its high specific strength, fracture toughness and good formability, typically makes up 80 % of the airframe. Common alloys are AA2024 and 7xxx. Rail carriages are made from aluminium welded extrusion frames (AA5083/6061) and sheet sidewalls (5xxx/AA6061), giving light, non-corroding vehicles.

Industrial equipment

Electrical equipment

2 Mt
4 %

Electrical equipment includes conduits (often AA6063) and sheathing (Alclad 5056) to strengthen and protect electrical wiring. Other applications include wide strip aluminium in bus bars (1xxx) to conduct electricity around switchboards.

Electrical cable

4 Mt
9 %

Cables are made from concentrically stranded aluminium wire (typically AA1350-H19) wound in multiple layers around a steel core. The aluminium has conductivity around 60 % that of copper, but is cheaper and lighter.

Mechanical equipment

3 Mt
7 %

Mechanical equipment includes products such as heating and ventilation systems. Aluminium is widely use in heat exchangers for its high thermal conductivity, good corrosion resistance and low cost. Drawn or extruded tubes are either brazed or mechanically fastened to sheet (both 1xxx or 3xxx alloy).

Packaging

6 Mt
13 %

Aluminium is used in packaging, and provides an attractive outer package and inert inner surface. Half of this aluminium is used in light-weight drinks cans (14 grams each), where rolled (AA3104) aluminium strip is drawn to form the can body, the lid attached (AA5182) and inside sprayed with an epoxy-based lacquer. The other half is thin aluminium foil used in household foil, food and drink pouches and semi-rigid containers to provide an inert and flexible package.

Construction

Buildings

11 Mt
24 %

Most aluminium in construction is made from extrusions or sheet. 45 % of it is used for extruded frames in windows, doors and curtain walls (projected, non-load bearing façades on commercial buildings). Another 40 % is used in corrosion resistant roofing and cladding, for which aluminium strip is cold formed to a profile.

Metal products

Other

4 Mt
9 %

Approximately half of this is powdered aluminium used in powder metallurgy, paints and pigments. Other applications are the deoxidation of steel: aluminium has a high affinity for oxygen, so is used to reduce formation of gas bubbles in steel casting. Lithographic plate (1xxx and 3xxx series) is another significant use, for which aluminium is chosen because of the criteria for flatness and high surface quality.

Appliances

3 Mt
7 %

The main use of aluminium in consumer durables is in household white goods. Most aluminium in white goods is in fridges/freezers and washing machines. AA5754 is a common sheet alloy of medium strength used for appliance bodywork, and AA3003 and AA3103 are common sheet materials used as fridge/freezer linings. Fridge/freezers also require heat exchangers where the fins, and sometimes tubes, are aluminium.

Figure 3.2—**Aluminium product catalogue**

We make approximately 45 Mt of aluminium products every year. We have shown the uses of global aluminium production divided into 4 sectors and 10 categories of end-use products. The amount of aluminium in each category is given in millions of tonnes Mt and the fraction of global aluminium as a percentage %, with the images sized to reflect this fraction. The end-use of aluminium is more evenly spread across the 4 sectors than for steel. These numbers are derived from data from 2008. (Aluminium alloy codes, e.g. 1xxx are described at the end of this chapter).

By mass, we make around 25 times more steel than aluminium each year. By volume, because aluminium is three times less dense than steel, we make about eight times more steel than aluminium. However, aluminium products are around five times more energy intensive than steel, which is why aluminium is one of our top five materials. The average life expectancy for a steel product is 34 years, and for aluminium is 21 years, predominantly due to the use of steel in longer lasting construction and the use of aluminium in short-lived one-way packaging.

The catalogues show that we can conveniently group the uses of steel and aluminium into four main areas: construction (of buildings and infrastructure), transport (cars, trucks, trains, planes and ships), equipment used in industry, packaging and a range of consumer and business goods. The last category is the most amorphous, and spans what's in your kitchen, what's in your office, and the multitude of other final goods we all buy. As construction is such a dominant application, we'll explore that in more detail shortly.

Vehicles are predominantly made from steel, and at present more than 70% of the mass of typical cars is steel, in the body, engine and drive train. The aluminium industry has for 30 years wanted to expand the use of aluminium in cars, promoting it as a means to save weight and so increase fuel economy. At present this is leading to significant growth in aluminium production. Most aluminium in cars is used to make engine blocks, but a few cars such as recent Jaguar models, have aluminium bodies. Ships are predominantly welded together from plates of steel, trains are made with a combination of the two materials, and aeroplanes are mainly aluminium. Despite aerospace being the most obvious and iconic use of aluminium, it only accounts for a small fraction of total use.

Nearly one fifth of global output of both metals is used to make industrial equipment: whether in sewing machines, robots, paper machines, drills or ovens, the world's factories depend on steel and aluminium equipment to produce goods in all materials. Steel is of course primarily used to provide strong stiff structures on which equipment is built, as well as moving parts and drive trains. Aluminium is widely used for its good thermal or electrical conductivity, particularly because it is both cheaper and lighter than copper. Heat exchangers in air conditioning units and at the back of fridges and freezers contain tubes (that would previously have been made from copper) connected to aluminium fins that dissipate the heat. Electrical distribution cables made from drawn strands of aluminium acting as the conductor, wrapped around a steel core. The strength of the steel core combined with the lightweight and conductive aluminium, allows long spans between supporting towers (pylons).

Aluminium, is used extensively for packaging, particularly for drinks cans (beverage cans in the US) and foil food containers. In fact we make as many steel cans as aluminium ones—although the steel cans are mainly used for food not drinks, and the steel has a thin coating of tin to avoid corrosion on contact with food. However packaging is a smaller fraction of steel use, because we produce so much more steel than aluminium.

Construction is the largest application of the two metals, so we've examined that area in more detail, and our next double page spread gives a further catalogue of the uses of the two metals in construction, followed by a more detailed breakdown by component of steel use in a 'typical' building. Using the word 'typical' is of course rather brave, because each country has quite different traditions in building, so really this building is 'typical' of those for which we've been able to find the relevant data.

Over half of the world's steel is used in construction, and perhaps surprisingly, the single largest area of application is for rebar in concrete. Concrete is strong in compression but weak in tension, so is almost always reinforced with steel to improve its overall performance. In the UK we make many of our tall buildings using steel frames, so use a high volume of steel sections, but other countries, for instance many of our European neighbours, currently prefer reinforced concrete construction, as do rapidly developing China and India. The remaining uses of steel in buildings are largely to do with surfaces. For example, steel sheet is often used for the exterior walls of industrial warehouses, factories, and large retail stores, and the 'purlins' of framed structures (which support the roof between the major frames) are usually formed from sheet steel.

Steel reinforcing bars, used to provide strength and stiffness in tension in concrete structures

Construction is often split between buildings projects and the infrastructure which provides our transport network, and the distribution of utilities. This is a major driver of steel use, with rebar required to make roads and tunnels, sections needed for bridges, and shaped rails needed for tracks. We also use significant and growing volumes of steel line pipe to transport the world's oil, gas and water. As our demand for these resources grows, we are extracting oil and gas from ever deeper water in more hostile environments, and this is driving demand for higher quality line pipe production, in greater volumes.

Perhaps surprisingly, construction is also a major end use for aluminium, nearly all for buildings rather than infrastructure. The main applications are to provide frames for windows but also for external cladding, and internal ducting. Exactly as we saw with steel, patterns of aluminium use in buildings vary among different

Aluminium

Windows and doors

3 Mt

27%

Window and door frames must be strong enough to provide security, and be durable and attractive. A wide range of cross-sections is required, so they are extruded from alloys AA6060 and AA6063 which allow design flexibility and efficient material use.

Curtain walls

2 Mt

18%

Curtain walls are not part of the structural frame of a building but must carry their own weight and survive wind loads. They are made from aluminium because it is attractive, stiff and has both a high strength-to-weight ratio and good corrosion resistance. The same alloys used for windows and doors are used to make curtain walls by extrusion.

Roofing and cladding

4 Mt

37 %

Roofing and cladding must provide a thermal barrier while also being weather proof, light and attractive. It is typically made with sheet alloys AA3003 and AA5005, which are cold-rolled into corrugated shapes and used to sandwich an insulation layer.

Other (gutters, spouts)

2 Mt

18 %

Aluminium is used in various other building components such as gutters, spouts, signage and internal fittings. In most cases a strong but lightweight material is required, often with good corrosion resistance and a high quality surface finish.

Figure 3.3—**Construction product catalogue**

The largest application of steel is in construction which is also the second largest use of aluminium. Most steel in construction is used for reinforcing bars (rebar), structural sections (I-beams) and sheet. Aluminium is used either in extruded profiles or rolled sheets. The images on this page are scaled to reflect the proportions of their use in construction, which is also shown as a % and given in millions of tonnes Mt.

Steel buildings

Commercial

129 Mt

22 %

Multi-storey commercial buildings are designed around structural frames constructed either from steel sections (30% of steel-use in this category) or reinforced concrete. Reinforced concrete is also used to provide deep foundations and basements, so 40% of steel-use is as rebar. Steel is also used as sheet for purlins and internal fittings, and occasionally for facades.

Industrial

145 Mt

25 %

Most industrial buildings for factories, warehouses and large retail stores, are single-story portal frame designs. The frame is made from sections (40% of steel) while roofing and facades use corrugated steel sheet (55%) supported by steel purlins.

Residential

90 Mt

16 %

Individual houses mainly require steel in reinforced concrete foundations with some light sections for supporting floors. However, the main use of steel for residential buildings is to construct apartment blocks, largely from reinforced concrete, so that 90% of steel use in this category is for rebar.

Other

69 Mt

12 %

Other buildings include stadia, hospitals, schools all with diverse designs, but mainly made with reinforced concrete.

Steel infrastructure

Roads and rail

107 Mt

18 %

Transport networks require steel for bridges, tunnels and rail track and for constructing buildings such as stations, ports and airports. 60% of steel-use in this application is as rebar and the rest is sections and rail track.

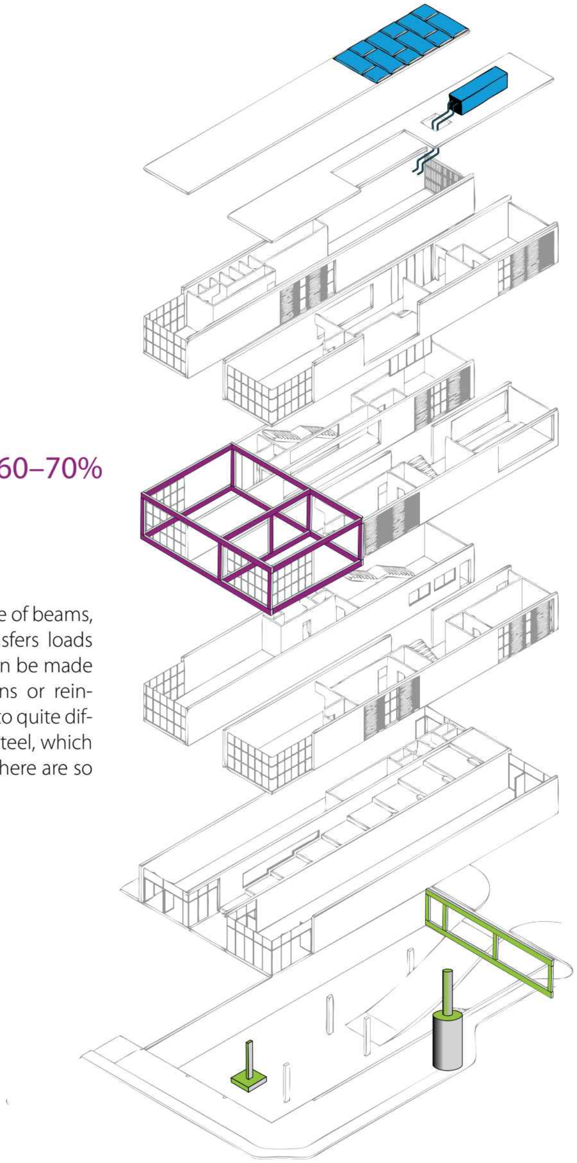
Utilities (fuel, water, power)

43 Mt

7 %

Underground pipelines distribute water to and from houses, and distribute gas to final consumers. These pipes use just over half of the steel in this category and the rest is mainly rebar for associated constructions including power stations and pumping houses.

Steel use in a building



Non-structural 20–30%

Mechanical equipment: 5–10 kg/m^2

Fixtures, fittings + façades: 5–10 kg/m^2

Buildings are heated and cooled by large equipment, in the basement or on the roof, connected to the interior by ducting, and both equipment and ducting require steel. Some internal fixtures and fittings including rails, shelving, and stairways are also made from steel.

Superstructure 60–70%

Columns: 2–7 kg/m^2

Beams: 5–40 kg/m^2

Slabs: 10–30 kg/m^2

The building frame, made of beams, columns and slabs, transfers loads to the substructure. It can be made either from steel sections or reinforced concrete leading to quite different requirements for steel, which is why the ranges given here are so broad.

Substructure 10+%

Shallow foundations: 60–70 kg/m^3

Basements: 100–300 kg/m^3

Deep foundations: 35–65 kg/m^3

Low buildings stand on concrete foundation strips that distribute loads from the structure to the ground. However, taller buildings, or those built on poor soil, require foundation piles: reinforced concrete columns plunged deep into the ground to provide stability. These piles support high loads, must outlast the building, and cannot be repaired in use, so are steel-intensive. For the same reason, walls below the surface which hold back soil and water to create basements, also use steel at high densities.

Figure 3.4—**Construction product catalogue**

No building is truly 'typical' however this image demonstrates the main uses of steel in commercial buildings, identified from a survey of recent building projects and published reports. The percentages are representative averages after we excluded unusual features such as basements, deep foundations and steel facades. The rates of steel use above the surface are averaged over the total floor area of the building. However foundation design depends so strongly on local geology that the rates of steel use below the surface are given per cubic metre of reinforced concrete.

countries, so for instance southern European homes contain over 10 times as much aluminium as those in northern Europe. Aluminium window and door frames were popular in houses in the 1970's and 80's, but now have largely been displaced by cheaper plastic extrusions. However, they remain common in commercial buildings.

Our detective work has given us an estimate of where steel and aluminium are used, and we've shown that these two metals pervade every aspect of our lives: in effect everything we touch either contains one of these two metals, or was manufactured with equipment made from them. Why do we find them so useful, and is there anything else we could use instead? We'll spend the rest of this chapter looking at those two questions.

The useful properties of steel and aluminium

If the Eiffel Tower were made of rubber, it would bend in the wind like a tree. It doesn't because it's made from wrought iron, a relative of steel, which is *stiff*. When the traffic grinds to a halt in San Francisco, and the line of trucks with the day's supply of sourdough bread backups up over the Golden Gate Bridge, it doesn't collapse because the steel from which it is made is *strong*. The miracle of commercial flight occurs because the planes are light enough to take off—they're largely made from aluminium, which has a low *density*. If you sit in the back row of a 747 as it takes off, you see the wing tips move two metres upwards as the plane leaves the ground. They continue bending up and down during any turbulence in flight, and if made of ceramics would snap off, but they don't because aluminium is *tough*—cracks don't grow quickly. However the aeroplane's jet engines are largely made from special steels and nickel alloys, because the engines are most efficient when running hottest, and these alloys have a high *melting temperature*, but when hot undergo relatively little *thermal expansion*. The Forth Road Bridge in Scotland is painted continuously because steel rusts, but aluminium window frames corrode only very slowly even if unpainted: they have high *corrosion resistance*. Electrical cables as we've seen are a major application of aluminium because it has a low *electrical resistance*. Hercule Poirot's metal snuff box could be formed from a flat sheet of either steel or aluminium without any joints, and indeed the whole plethora of goods made from sheets of these two metals can be manufactured, because both metals are *ductile*: they can be made to change shape without cracking. And we'll finish off by noting that both metals are easily *available*: the earth has vast reserves of bauxite and iron ore with which to make them, and we can produce them *cheaply*.

The Eiffel tower made from stiff wrought iron

Rust forming on painted steel

We've listed the properties of stiffness, strength, density, toughness, melting temperature, thermal expansion, corrosion resistance, electrical resistance, ductility, availability and cost, and could add a few more if we kept going, and it is the combination of all these properties that make steel and aluminium so extraordinarily useful, and hence widely used. In the next section we'll explore whether we have any viable alternatives, for now we'll explore just two of the properties in more detail: strength and ductility. We want to look at those two in detail because, so far, we're referred to steel and aluminium as metals, but actually they're both families of metals. The members of the families vary because of *alloying*—adding other elements such as chromium, manganese or magnesium to our vats of liquid iron or aluminium to change their composition. They also vary due to *processing*—even with the same composition, we can create different properties for particular family members, by changing what we do to them after we've poured them from liquid. Surprisingly, many of the properties we've mentioned are virtually unaffected by alloying and processing. For example stiffness, density and electrical conductivity are virtually constant within the two families. However, in just over 100 years since Henry Bessemer, Charles Hall and Paul Héroult opened the door to cheap mass production of these two metals, we've discovered that we can create an amazing variety of strength and ductility in the two metals. In fact the aim of a vast swathe of ongoing metals research and development has been to increase both: increased strength allows us to use less metal for applications limited by strength, while increased ductility leads to easier manufacturing and often improves toughness also. So for the rest of this section, we'll explore where those properties come from, and how we can influence them.

Figure 3.5—**A piston which has been cast then machined**

Armed with a camera, an optical microscope (invented in Holland around 1590 by Zaccharias and Hans Janssen), a scanning electron microscope (invented by Max Knoll in Germany in 1931, but developed up to commercialisation in 1965 by Charles Oatley, in our department in Cambridge), and a good computer drawing package (Adobe, ~1982) the pictures in Figures 3.5 to 3.9 show us what metal looks like as we keep hitting the zoom-in button. Our zooming is pretty impressive: the piston in the first picture is about 300 mm tall, and the atoms in the last picture are spaced at around a tenth of a nanometre: there are a million nanometres in a millimetre.

Figure 3.6—**The surface finish on the piston (above)**

Figure 3.5 shows the piston, which has been cast and machined, and Figure 3.6 shows its surface as seen with the naked eye. The product has a precise geometry, with a surface that looks and feels smooth, but on closer inspection you might see traces of the manufacturing route: abrasions from machining or pinholes from casting. You won't be able to tell by eye, but the surface of aluminium parts is actually an oxide layer, the prettier equivalent of rust on steel parts. In contrast to rust on steel, this oxide layer doesn't grow upon continued exposure to air, as the aluminium oxide forms an impenetrable barrier to air and so prevents further oxidation. Steel parts can rust away, which is why they must be coated with paint or other protection.

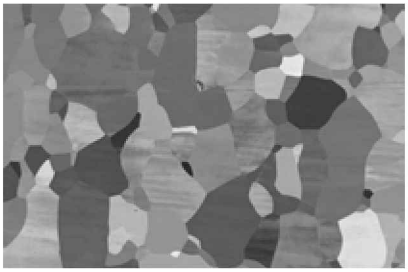


Figure 3.7—**The grain structure within the metal**

Figure 3.7 has zoomed in further, and with the benefit of polishing and etching, has revealed the grain structure of the metal. At school we hung a thread with a knot into a glass of concentrated salt solution, and watched as a crystal of salt grew on the knot. The crystal was roughly cubic, and every grain of salt in our salt cellar is a single crystal. Metals similarly form crystals as they solidify. However, unlike the school experiment, many crystals—called grains in metals—begin to grow at the same time, but in different directions. So, the picture shows us the final form when all the metal has solidified and formed grains, and we can imagine that at the boundaries between the grains, the material is locally much less ordered than within a single grain.

Figure 3.8—**The structure within a grain**

Figure 3.8 is an image of the material within a grain. Things aren't as uniform as we might expect, and this is because the metals we're looking at aren't pure iron or aluminium, but have alloying elements mixed in. We can see that two different types of crystal have formed in the one grain: a dominant formation, in which the main metal has a small concentration of one of the alloying elements (light areas); a secondary formation, with a much higher concentration of the alloying elements, and relatively less of the base metal (dark areas). The secondary formation occurs in smaller volumes, because we have much more of the basic metal element (iron or aluminium) than the alloying elements. But you can imagine how many interesting small secondary grains you can create if you mix up several small quantities of other elements in one alloy. We can see several different formations in this image, and that's what metallurgists dream about at night!

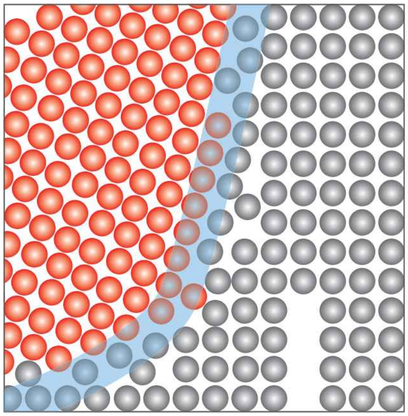


Figure 3.9—**The boundary between two grains**

Figure 3.9 (in the absence of a suitable microscope, we've turned here to a drawing package) shows the material within a grain and at a boundary between two grains. The atoms mostly form a regular lattice pattern within a grain, but in some places discontinuities form as 'dislocations' in the lattice. These dislocations are important when the grains change shape under load.

Figure 3.10 shows our most detailed zoom in and we can see how the atoms of the previous picture link together. The balls represent atoms, nature's building blocks, and the lines are a convenient way of showing how they relate to each other. This picture represents a 'unit cell' which replicates and tessellates thousands or

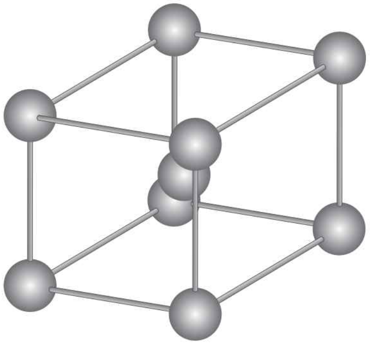


Figure 3.10—**The arrangement of atoms in a typical 'unit cell'**

millions of times to form each grain. When we referred to grains 'growing in different directions' you can now see exactly what that means: the direction of the lines joining the outer atoms in the cell are the same for all the unit cells replicated in a single grain.

These pictures have shown us everything we need to know about the two metal families to understand the properties of strength and ductility. But before we look at how composition affects them, we need to address one more question: how do metals deform? For ceramics, which also form in crystal like structures, when we stretch them with sufficient force we will eventually separate the bonds between the atoms in the material, at which point it will fracture. If the microstructure of the ceramic is imperfect, which in reality is always the case, there will be small cracks in the initial structure, so a tear starts at an existing crack, and then propagates rapidly across the piece we're pulling. The strength of ceramics is therefore usually determined by the largest pre-existing crack in the material. Metals however are quite different: they can deform before they fracture, and this requires a different mechanism.

Let's imagine a tug of war between one team on a level platform attempting to pull a second team, which has formed up as a Chinese Dragon, up a long set of steps. If the people in the dragon were on adjacent steps, they would all be able to pull with full strength, but in fact they've made a mistake, and left one step empty in the middle. This means that the person just below the empty step is greatly disadvantaged—he can't brace himself as well, so is pulled forwards to the point that he can't avoid stepping up onto the empty step. He can now brace properly and take up the full load, but the person immediately behind him is disadvantaged, and is now under tremendous pressure so he too, eventually steps up to the newly empty step in front of him. Over time the empty step appears to move downwards, as each member of the Chinese Dragon in turn, steps up, until the whole dragon has moved one step upwards. Rather than having to pull against all the people in the dragon at the same time, the team on the level have a great advantage, and need provide only enough force to de-stabilise the one behind the empty step.

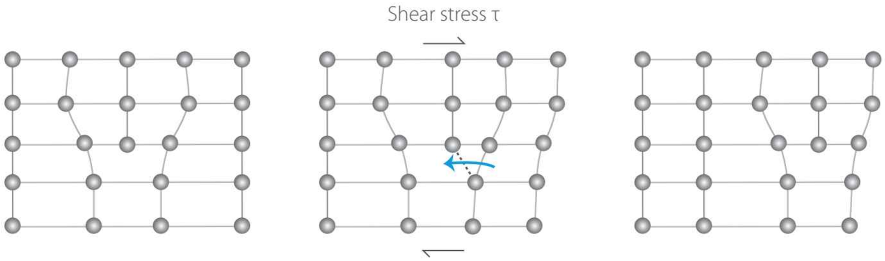


Figure 3.11—**A dislocation moving under an applied force**

Figure 3.11 shows this story being played out in a metal grain. The empty step is called a dislocation, and as a force is applied across the grain, the atom just ahead of the dislocation is under extra pressure, so jumps into the gap of the dislocation, the gap moves backwards, and slowly the metal deforms forwards. The strength of the metal is the force required to cause the dislocation to move. Its ductility is the amount of movement (shape change) that can occur before the metal eventually fractures.

In reality, the dislocation is a line, going straight into the page, so what happens when the line meets with one of the secondary particles, we saw in Figure 3.8? If these small particles are stronger than the surrounding metal, in effect they provide an extra brace point, the force required to move the dislocation to the next step increases and the strength of the metal has increased. Metallurgically, alloying has therefore increased the strength of the metal and this increase depends on the size of the secondary particles, their distribution and relative strength. A similar strengthening happens when two dislocations intersect, which is more likely as more deformation occurs. This is known as work hardening and explains why metals get stronger as they are deformed more, up to the limit when they fracture. Finally, we noticed earlier that the grain boundaries disrupt the regular structure of the metal grains or crystals and of course, it is difficult for dislocations to cross these boundaries. More boundaries makes stronger metal so small grains imply greater strength. We can also now see that strength and ductility are in conflict with each other: strength is increased when it is more difficult for dislocations to move, but dislocation movement is what we need for ductility.

So if this is how composition affects strength and ductility, we also need to work out what's the effect of processing. And we can do so with just one more piece of information. So far the atoms in the metal grains were fixed in their initial positions on solidification, and have moved in the lattice only when an applied force has caused dislocations to move. However, if the metal is heated up, the bonds between atoms become weaker, so some internal reorganisation of atoms occurs, driven by energy stored in dislocations and grain boundaries.

On solidifying from liquid to solid, grains grow in the metal. Slow cooling leads to big grains of more uniform composition, faster cooling to smaller ones with more variety. Once cool, deforming the metal tends to increase its strength by work hardening. However, if it is re-heated to above one third of the melting temperature, internal reorganisation can occur, which may involve growing new larger grains and allowing smaller secondary particles to coalesce into fewer bigger ones.

For our purposes in this book, that's all we need to know about the formation of properties. Obviously there are libraries worth of further detail, but our purpose is to understand enough about how properties arise that as we start to look at recycling, or different processes, we can deduce the consequences. Let's pose a couple of questions to test that:

- What happens if I recycle a skip of aluminium scrap containing a mixture of different alloys? The composition when I melt the scrap will be different from any previous alloy, and rather difficult to predict. Therefore I will tend to have a wider variety of secondary particles forming in my recycled material, and while these may or may not increase strength, it's very likely that they will reduce ductility so the material will be brittle and therefore probably less useful;

- Could we save a lot of energy by casting steel and aluminium components directly into their final shape? If we do so, it will be difficult to control the cooling rate, so we will get a mixture of grain sizes, an uneven distribution of the secondary particles, and without any deformation to break up the grains or induce work hardening, it's likely that the final product won't be very strong. Worse, the casting process may leave imperfections in the metal and we won't have a chance to remove them with further processing. These defects can be sources of failure that mean the product also won't be tough.

Armed with what we now know about strength and ductility, we can do a quick survey of the different branches of the steel and aluminium families. Our table at the end of the chapter summarises the main groups within the two families, and describe the main features of their composition, processing and resulting properties. The two graphs summarise this information, by showing for the two metal families how strength and ductility play off against each other.

This section was motivated by the question "why do we find these two metals so useful?" The answer is that the ores required to make both metals are widely available at low cost, and we have efficient routes to process the ores into liquid metal. The two metals are both families, and by adjusting their composition and processing we can create a very wide range of strength and ductility to suit particular applications. We can't directly mould liquid metal into final products, because the resulting properties would be poor. But we can select our composition with great precision, to allow a range of deformation and heating stages, at the end of which we'll have components of the required shape and with the required properties.

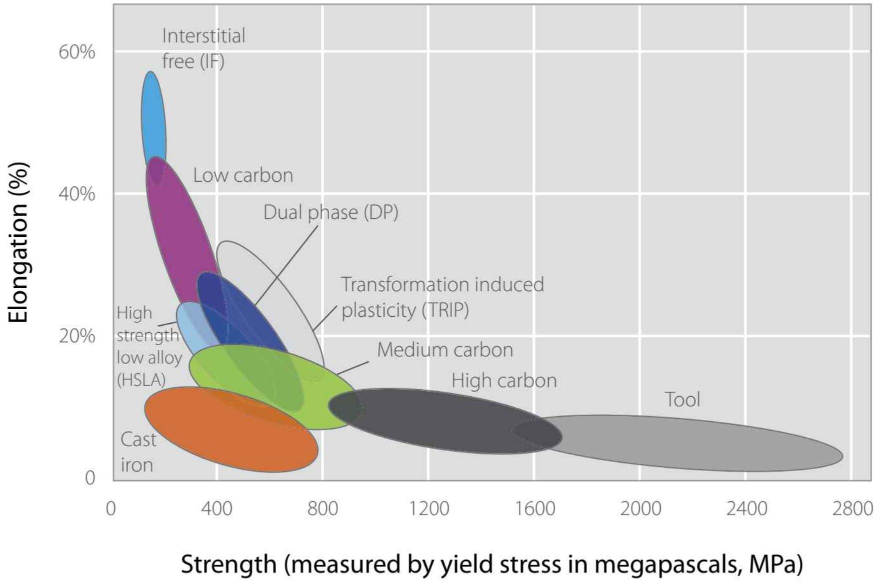


Figure 3.12—**Typical properties for groups of steels**

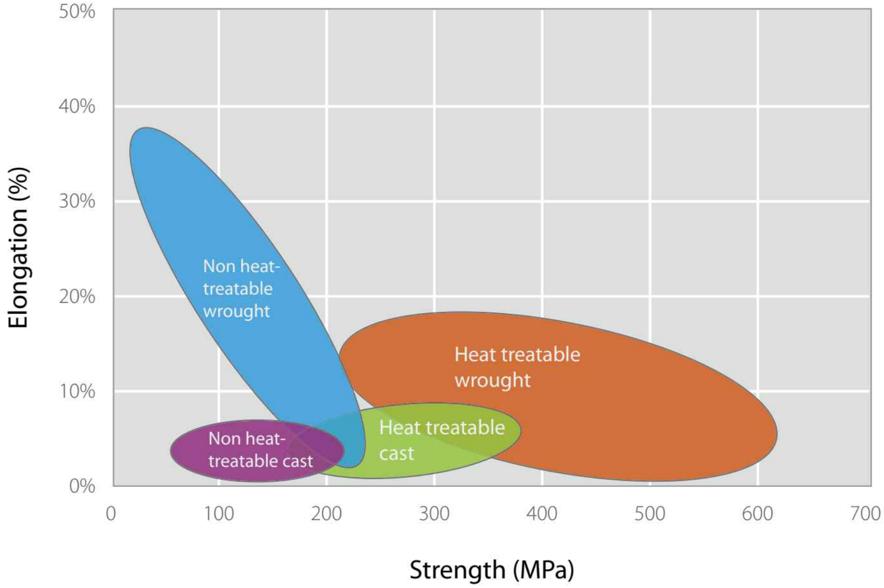


Figure 3.13—**Typical properties for groups of aluminium alloys ('wrought' alloys can be deformed)**

To end this chapter, we need to find out whether any other materials could replace these two key metals.

Could we use other materials instead of steel and aluminium?

We decided that making the Eiffel Tower in rubber didn't look too promising. What else could we use? Marble? Expensive, and probably the blocks at the bottom would crumble. Clay? Not strong enough? Glass? Too fragile. Concrete? Yes—we could and the wasteful and pointless world of 'my tower's taller than yours' is currently headed by the horrible and concrete Burj Khalifa in Dubai. 2.5 times taller than the Eiffel Tower, it has 300,000 m^2 of floor space made from 1 Mt of concrete and 55,000 tonnes of steel re-bar, giving an average embodied emissions of around 4 tonnes of CO_2 per square metre. This is eight times the average office block, and at least 10 times the typical traditional and beautiful homes of Dubai.

The Burj Khalifa in Dubai, the world's tallest building, has ten times the embodied emissions square metre...

... of a beautiful traditional home in Dubai

If not steel and aluminium what else? The US Geological Survey regularly reports estimates of mineral availability in the earth's crusts, and we aren't going to run out of iron, aluminium, limestone, trees, magnesium, titanium or any of the other structural materials in the next hundred years or more[3]. So purely by volume, we have a lot of possible substitute materials, but of course the energy requirements for extracting the different materials vary considerably, as does their cost: Figures 3.14 and 3.15 show an estimate of the current cost per tonne of each key material and the energy of converting it to a useful form[4]. At first glance, concrete, stone and wood appear to be interesting alternatives to steel and aluminium. However, the bar charts do not tell the full story, as in reality we would not replace one tonne of steel with one tonne of wood. Different families of materials have radically different properties (strength, stiffness, ductility and many others as just discussed) so to compare the energy used when making the same products, we must delve deeper. Professor Mike Ashby in our department has initiated a huge effort to map materials by their various properties, to help designers make good choices, and particularly recently his concern has been to account for the environmental impact of their choices[5]. His maps of materials show an enormous span of material choices and as we'd anticipated, wood, stone and concrete stand out as the three viable candidates to substitute for steel and aluminium. Members of the family of composite materials, glass/carbon fibre reinforced epoxies mainly, can meet the strength criterion, but their embodied energy is higher than the two metals, and they can't be recycled. So, although they often come up in conversation about substitutes, they're not a great choice if we're after reduced emissions. They're also used much less: today's use of composite materials is around 8 Mt per year[6], compared to 1040 Mt of steel and 45 Mt of aluminium.

So now we're down to concrete, stone and wood. What were the two dominant materials before the industrial revolution? Stone and wood, the predecessors of cement and steel/aluminium. Stone and concrete have similar properties, but concrete is much easier to use: you can pour it into moulds to create any shape, and while pouring you can include rebar within the mould to make up for the problem that both stone and concrete are rather weak in tension. Wood has excellent properties, and other versions of Professor Ashby's charts show that it performs extremely well on the axes of strength or stiffness against density, so the Wright brothers choice to build the first aeroplane with a wooden frame was inspired. However wood also has disadvantages compared to steel and aluminium: it is less stable, more easily damaged by fire, and although it has a good strength to weight ratio, you still need a lot of wood if you want a lot of strength.

That leaves concrete as the competing material and it is the material of choice for construction in many countries. However, it has to be reinforced by rebar before use, and has few applications outside of construction: we don't make vehicles or equipment from concrete.

To summarize, we don't have any real substitutes for steel and aluminium. They can substitute each other, and that's the subject of a lengthy marketing campaign by both trade associations so not our business here, but there aren't any other materials with such a good range of properties, available cheaply and in abundance.

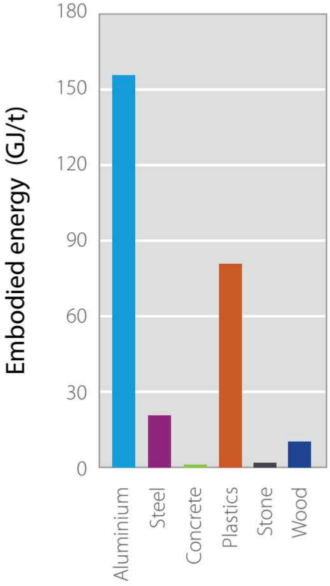


Figure 3.14—**Embodied energy in conversion for key materials**

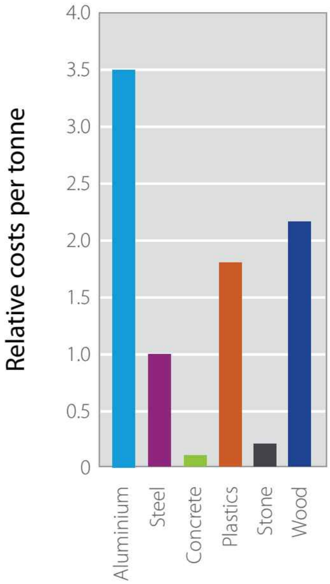


Figure 3.15—**Relative costs per tonne for conversion of key materials to useful forms**

Outlook

We've seen in this chapter that steel and aluminium are used across a very broad range of applications, because of their excellent combination of properties. We've looked into the link between two of those properties, strength and ductility, and seen how they arise from selection of composition and processing. And finally, we've seen that there aren't really any substitute materials available in sufficient quantity, with guaranteed supply, and comparable performance. That sets us up for chapter 12 when we'll be looking for new options to use less metal. But we're not ready for that yet. Instead we need to find out how the uses of the two metals in our catalogue of applications adds up to global demand for metal, and by looking at past and present production data, we can begin to forecast future requirements.

Notes

1. In case you are not fully briefed on British crime writing, all these characters are famous fictional detectives. Miss Marple is an elderly spinster and Hercule Poirot a suave Belgian, both of whom were created by author, Agatha Christie, to solve crimes in 1920s and 30s Britain. Dr Watson is the companion of Sir Author Conan Doyle's famous creation, Sherlock Holmes.
2. There are not so many companies operating in the steel and aluminium industries, and most of them belong to the two key organisations, the World Steel Association or the International Aluminium Institute. These two organisations publish detailed data on annual production of stock products which gets us half way to solving the mystery of the uses of metals.

Could we use other materials instead of steel and aluminium?

3. Based on data collected and published in USGS (2011).
4. Embodied energies for a range of building materials have been collated by Hammond and Jones (2011) in their 'Inventory of Carbon and Energy'. Costs have been obtained from a range of sources including Steel Business Briefing (2009), UNCTAD (2011) and IDES (2011)
5. Examples of Professor Ashby's charts appear in his book (Ashby, 2009) and are available as a software package through Granta Design (2011)
6. According to a Pudaily (2007), global composites production was 8 million tonnes in 2010 with 40 % of this occurring in the Asia-Pacific region.

Images

We would like to thank Novelis for their image of aluminium grain structure in Figure 3.7.

	Alloy Group	**Composition**	**Processing**	**Typical Properties**	**Examples of applications**
Carbon steels	Low-carbon	<0.25wt% C	Hot rolled and allowed to cool in air	Low to medium strength and moderate ductility	Structural beams for buildings, plates
	Med-carbon	<0.25–0.5wt% C	Heat treatment through quenching and tempering	High strength and moderate toughness	Forgings
	High-carbon	<0.5–1wt% C	Heat treatment through quenching and tempering	Very high strength	Rail, wire
	Cast iron	>2wt% C	Cast to shape directly, possibly with heat treatment	Low strength and ductility	Large equipment and transport parts
Alloy steels	High strength low alloy (HSLA)	<0.25wt% C plus Nb, Ti, V	Hot rolling with controlled temperature	Higher strength than plain carbon steels through grain refinement	Line pipe
	Stainless	>12wt% Cr, plus Ni	Hot and cold worked	Corrosion resistant	Food handling equipment
	Tool	>0.5wt% C with combination of Mn, Cr, V, W, Mo	Hardened through heat treatments of surface or entire part	High strength and toughness	Machining tools, dies
	Interstitial free (IP)	Very low C and N content	Vacuum degassing and casting control to avoid carbon, nitrogen and oxygen pickup	Very high ductility and formability, low strength	Outer automotive panels
	Dual phase (DP)	<0.25wt% C plus Mn, Si, V	Heat treatment through intercritical annealing and controlled cooling	Lower yield strength and similar tensile strength to HSLA steels with increased ductility	Automotive sheet
	Transformation induced plasticity (TRIP)	<0.25wt% C plus Si, Mn	Heat treatment through intercritical annealing and holding at temperature	Higher ductility than DP steels at high strengths	Automotive sheet

Table 3.1—**The world of steel**

	Alloy Group	Composition	Processing	Typical Properties	Examples of applications
Wrought	Heat-treatable (AA2xxx,6xxx,7xxx)	Cu, Si, Mg-Si, Zn	Heat treated to increase strength by solutionising, quenching and then age hardening	Medium to high strength	Aircraft and automotive structures
	Non heat-treatable (AA1xxx,3xxx,5xxx)	Mg, Mn	Cold worked to give strength by strain hardening	Lower strength	Foil, cans, electrical conductors
Cast	Heat-treatable (2xx.x,3xx.x,5xx.x,7xx.x)	Mg	Casting followed by heat treatment (solutionised, quench, age harden)	Low-medium strength, low ductility	Engines, housings
	Non heat-treatable (1xx.x, 4xx.x)	Si, Si-Mg, Si-Cu	Cast directly to product shape	Lowest strength aluminium alloys, low ductility	Pipe fittings

Table 3.2—**The world of aluminium**