1 Use of Metals in Our Society

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1.1 Introduction

"In truth, in all the works of agriculture, as in the other arts, implements are used which are made from metals, or which could not be made without the use of metals; for this reason, the metals are of the greatest necessity to man" [1].

Metals are essential to almost every aspect of our lives today—and they have been indispensable since the Bronze Age. We rely on metals for tools, food production, buildings, medical equipment, energy production, transport and communications. This chapter explores the properties and uses of metals which make them so valuable to society.

1.2 What Are Metals?

Metals are naturally occurring elements which are generally:

- Solid at room temperature (mercury is an exception)
- Opaque and lustrous
- Good conductors of heat and electricity
- Ductile (can be drawn into wire)
- Malleable (can be hammered into thin sheet)

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Melting points of pure metals range from mercury at −39 °C to tungsten at 3410 °C. Relative densities of pure metals (water is 1.0) range from lithium at 0.53 to osmium at 22.6.

Of the 90 naturally occurring elements on Earth, 66 are metals and another 7 have some of the characteristics of metals. However, from the Bronze Age until the seventeenth century, only a handful of those metallic elements were recognised and in common use: iron, copper, lead, gold, silver, tin and zinc. Most metals were still to be identified, purified and studied. Since then, there has been an explosion in identifying, understanding and using the unique characteristics of those 66 metals, with the result that aluminium, cadmium, chromium, cobalt, lithium, magnesium, nickel, platinum, silver, titanium, tungsten and others are now familiar names. The knowledge about these metals was key to the industrial revolution and the subsequent development of technologies which could hardly have been imagined 200 years ago—air travel and mobile phones, for instance. Up to 62 metals may be used in a smart phone, each with a unique function and with almost no possibility of substitution [2].

As civilisations have developed, so has our use of metals, which continue to be crucial for our economies and societies. The resulting socio-economic benefits of these changes have been huge: not just increased GDP, but improved production, storage and distribution of food; improved medical care; increased trade; easier and more efficient transport; and

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the whole field of computing, communications and access to knowledge. Of course, it cannot be claimed that metals alone were responsible for these developments, but they did play key enabling roles and continue to do so today, as discussed below.

1.3 Economic Impact of Metals

Table 1.1 lists the annual primary production tonnages for a selection of metals in 2014. This is a measure of the quantity of new metal being put into use each year. It shows that the use of iron mainly as steel is many times greater than the use of any other metals. The table also shows the approximate market value of that new production and illustrates both the scale and economic importance of the metals' industries. That is reinforced by the many applications for metals and alloys which are described in the rest of this chapter.

Table 1.1 The size and economic importance of the metal industries in 2014

Metal	Annual production, tonnes	Approximate value of production, US dollar millions
Aluminium	53,000,000	86,000
Beryllium	400	179
Chromium	11,690,000	23,100
Cobalt	91,400	2,350
Copper	22,600,000	104,000
Gold	3,020	128,000
Iron (as steel)	1,667,000,000	500,000
Lead	10,600,000	19,900
Mercury	2,900	49
Molybdenum	295,000	6,500
Nickel	1,947,000	19,000
Palladium	184	4,090
Platinum	146	5,050
Tin	374,000	7,070
Titanium (metal)	186,000	1,110
Zinc	13,600,000	31,100

British Geological Survey [3], LME [4], InfoMine [5], Chemicool [6]

1.4 Alloys

An important characteristic of metals is their ability to combine with each other to form "alloys". It is in the form of alloys that metals are mostly used, rather than as pure elements. The UN Global Harmonised System of Classification and Labelling of Chemicals (GHS) defines an alloy as:

> A metallic material, homogeneous on a macroscopic scale, consisting of two or more elements so combined that they cannot readily be separated by mechanical means.

Alloys are not simple mixtures and usually have properties which are not just a blend of the properties of the constituent elements. For example, steels—a well-known category of alloys—can have strengths many times that of their major constituent, pure iron. Even metals which look as if they are being used as pure elements may actually be alloys, for example, 18 carat yellow gold used for jewellery is an alloy containing 75% gold, the rest being silver, copper or other metals.

Alloys can be tailored to provide a combination of useful properties, for example, strong at very high temperatures, resistant to aggressive chemicals, magnetic or non-magnetic, not brittle at very low temperatures. As a result, metals are mostly used as alloys rather than as pure elements.

1.5 Corrosion

Corrosion is the gradual deterioration of a material as a result of chemical reaction with the environment, e.g. the familiar rusting of iron and steel. This can lead to change in appearance, reduced performance or even failure of components. It can also lead to interaction of the corrosion products with the human body if there is physical contact.

The corrosion rate of an alloy is not simply a linear function of the initial corrosion rate or of the corrosion rates of the constituent alloying elements. This is especially so when elements which can form a protective oxide layer are involved, like titanium in titanium alloys or chromium in stainless steel.

The cost to the world's economies of corrosion is enormous. The global cost has been estimated to be $2.5 trillion per year [7]. Corrosion can be reduced or prevented by using a coating to keep the corrosive medium away from the metal, by electrochemical methods or by using an inherently more corrosion-resistant material such as a stainless steel. The choice should be made after considering the whole life costs of possible solutions.

1.6 Origin, Occurrence, Extraction and Refining of Metals

All metals were created in stars and supernovae. They were incorporated in the Earth at the time of its formation 4.5 billion years ago. Their relative abundance on Earth is the result of those creation and formation processes. Most metals occur in nature as minerals: chemical compounds of the metals, such as oxides, sulphides, silicates and carbonates. Exceptions are the relatively unreactive, "noble" metals such as gold and platinum, which are found in the metallic form.

"Ores" contain minerals in a sufficient concentration to make it economically worthwhile to extract and refine the constituents. Those economic concentrations may cover a wide range: a high-grade iron ore might contain >65% iron, whereas a high-grade gold ore might contain as little as 0.002% (20 parts per million) gold. It is common for ores to contain not just the primary metal of interest but other metals, which can also be extracted as valuable by-products. It can take several years and major investment to develop an ore body from discovery to commercial production. Ultimately it is the economics of supply and demand which determine the viability of mining a particular ore body and determine the market prices of metals.

As a result of geological processes, minerals and ores are not distributed uniformly in the Earth's crust. Ores may occur at or near the surface, where they can be recovered by opencast mining techniques, or they may have to be mined underground—a more expensive process. Once extracted, the ores are processed to remove the waste rock and to concentrate the minerals of interest. This is normally done near the mine to minimise the transport of large quantities of waste rock. Then the concentrates are processed thermally and/or chemically to extract and refine the metals. The final product is usually the pure element but it may be an alloy or a chemical compound, depending on the intended use. These refining processes are tailored to the ores, the metals being extracted and the eventual use, and it may be more economic to site them away from the mining operations. All the extraction and refining processes use considerable amounts of energy [8].

1.7 Selecting a Material for a Product

Just as there have been great advances in understanding and developing the properties of metals, so there have been great advances in non-metals—polymers in particular. Faced with this large number of materials, how does a designer select the right one for an application? Many factors must be considered, including:

- Mechanical properties
- Resistance to the operating environment, e.g. corrosion resistance, resistance to extreme temperatures
- Special physical properties, e.g. magnetism, thermal conductivity
- Interaction with other materials
- Ease of manufacture and forming
- Appearance
- Maintenance and expected service life
- Recyclability
- Availability
- Initial material cost and whole life cost
- Impacts on the environment, health effects and their risk management

Sometimes this analysis may lead to several practical options with similar performance.

However, for some demanding applications, there is often only one clear choice of material, which provides the required performance at an acceptable cost. There may be pressure to find a substitute for a material—perhaps to improve performance or for reasons of cost or environmental impact—but the same factors used to select the original material need to be considered in selecting an appropriate substitute. These factors are powerful drivers for development of new and improved materials—metal alloys included. At the same time, materials which have been used for many years are not necessarily made obsolete by new developments but remain important because of their unique combination of properties. For example, stainless steel kitchen sinks are still being chosen alongside resin sinks for aesthetic, performance and cost considerations.

1.8 Manufacturing with Metals

Alloys are usually made by melting the constituents—including recycled material—in a furnace, where adjustments can be made to achieve the desired composition, before casting into ingots or slabs for further processing into semi-finished products, e.g. blocks, plates, sheet, foil, bars, wire, ingots or powder. Many processes are then available to make the final product assembly, whether a cooking pan or a jet engine—including cutting, hot forming, cold forming, machining, joining, heat treatment and surface coating as necessary. Considerable development effort continues to be put into all these manufacturing processes to enhance their efficiency and to produce materials with improved properties, greater consistency, less waste and at lower cost.

1.9 Recycling

Metals are naturally occurring elements and are "used" rather than "consumed". At the end of a product's useful life, the metals can be recovered and reprocessed. They are 100% recyclable without loss of their properties. In many cases, where there is no need to separate the individual elements, the metals will be reprocessed as alloys. For example, stainless steel collected at the end of a product's life—whether from a spoon or a railcar—can be added directly to furnaces making new stainless steel. In this way, the overall energy used in the manufacture of stainless steel—its embodied energy—can be minimised, contributing to sustainability and reduced environmental footprint [8]. For this reason, scrap metals are valuable raw materials, something which has been recognised right from the first use of metals, thousands of years ago. Today there are well-established scrap recovery and processing routes for metals, which make a positive contribution to their sustainability. Nevertheless, improving the recovery efficiency remains important [9].

1.10 Metals, Health and Allergies

Some metals are regarded as essential in trace amounts for human health, including chromium, cobalt, copper, iron, manganese, molybdenum, selenium and zinc. At the same time, some metals and chemical compounds of metals can be harmful to human health above certain levels.

The term "heavy metal" is sometimes encountered, which is an attempt to link the toxicity or ecotoxicity of a metal with its density or atomic weight. Yet there is no such correlation and the term is effectively meaningless.

It is recognised that people can develop allergies to some metals and that nickel is one of the most common causes of allergic contact dermatitis. However, brief skin contact with a metal cannot cause an allergic reaction. The metal must be in solubilised form, which can happen from corrosion of the metal or alloy. There must also be a sufficient amount of the solubilised form of an allergenic metal from corrosion by body fluids or exposure to a sufficient amount of an allergenic soluble metal compound. In the case of alloys, an allergy may be caused by one of the alloying elements or an impurity, rather than the alloy's majority constituent.

The corrosion rate, the nature and concentration of the solution, the skin contact duration and frequency, the amount of the solubilised allergenic metal ions, the threshold for an allergic reaction of these metal ions and the susceptibility of the exposed individual are all key factors in determining the extent of an allergic reaction. Understanding the clinical characteristics, incidence and mechanisms of metal allergies enables proportionate and effective risk management practices to be established which allow the continuing beneficial use of the metals concerned.

1.11 Applications of Metals Today

There is no space here to cover every metal and their applications. The metals described in this chapter have been selected to illustrate the major importance of metals to society today, the range of unique properties which metals show, the diversity of their uses and where skin contact is likely. This chapter includes metals which are recognised as allergens as well as those which typically do not cause allergies. Thus it provides a context for the detailed discussion of individual metals, their allergies and their risk management in the rest of the book.

Metals and their alloys remain indispensable and of major importance in many fields, from the manufacturing of products to key enabling technologies. Steel is by far the most widely used alloy, both by tonnage and by value, as illustrated in Table 1.1. Steel is all around us—in our homes, buildings, transport and factories. It is easy to see that the value to society is many times the intrinsic value of the steel. It is the same with other metals. Whilst some uses of metals have been superseded, in most cases innovation has led to new applications and sometimes new alloys and an overall growth in use of metals.

Security of supply of strategically important metals has long been a concern. Today the lists of critically important metals continue to grow [10]. One example is the "rare earth elements" (REEs) which are all metals. They are rare because their ores are widespread but low grade. They have become essential to the functioning of electronic devices as well as in the powerful magnets used in wind turbines. There are no effective substitutes.

Metals are also used in the form of chemical compounds. These may be raw materials for a further process, for example, the electroplating process in which a thin layer of a metal is deposited from a solution of a chemical compound of the metal: the compound is transformed in the process and none remains in the final metal product. In other uses, the compound itself may become part of the final article, such as pigments in ceramics or one of the active components in a battery—for example, nickel hydroxide in a nickel-metal hydride (NiMH) battery.

There is no doubt that in the past there were issues with the environmental and health impacts of metal mining, production and use—as there were for many other mining and manufacturing activities. Today, there is much more awareness of the need for ongoing actions to address these issues as part of a balanced approach to sustainability.

Whilst we cannot foresee the future for metals, we can expect that metal-based materials will continue to be developed and used in novel ways. New technologies such as nanoscale materials, smart materials and use of 3-D printing will open up even more opportunities.

1.11.1 Aluminium

Aluminium is the most widely occurring metal in the Earth's crust, 8% by weight. When first produced in the middle of the nineteenth century, it was more costly than gold, yet today it is one of the most widely used metals. It is characterised by its low density—only one third that of steel—good ductility and good thermal and electrical conductivity. It readily forms a protective oxide layer on the surface and so has good corrosion resistance.

Production of primary aluminium (i.e. from the ore) is an energy-intensive process. However, the durability of aluminium and the inherent recyclability of metals result in very much less energy being needed to recycle it than to produce it from its ore [8]. Its recyclability has been well recognised for many years.

Among many other applications, aluminium can be rolled to a very thin foil, which is widely used in food packaging.

Copper, magnesium, manganese, silicon, tin and zinc among other metals are used as alloying elements to strengthen aluminium. Aluminium itself is also an important alloying element in superalloys (see Sects. 11.11 and 11.4), which operate at temperatures hundreds of degrees higher than the melting point of pure aluminium.

The combination of low density and high strength makes aluminium alloys a first choice for many transport applications where light weight is important, for example, aircraft. It is not as stiff as steel, but this can sometimes be compensated for in the design. There is increasing use in the automotive industry to reduce weight, and the transport sector now uses 27% of aluminium production.

A further 25% of aluminium production is used as alloys in the construction industry because of its strength, light weight and corrosion resistance.

Aluminium is also used for electricity transmission lines because of the combination of high electrical conductivity, low density and corrosion resistance. It is sometimes combined with a steel core for additional strength. The energy sector uses 13% of aluminium production, and there are further applications in IT equipment.

1.11.2 Beryllium

Beryllium is one of the lightest and stiffest metals. It had few industrial applications until the 1930s when it started to be used in aerospace. Today it is listed as a strategically critical metal. Beryllium is mostly used in copper-beryllium alloys which have good corrosion resistance, high strength and elastic modulus and good electrical conductivity. That makes them valuable for springs, electrical contacts and collectors. Their non-sparking nature makes them suitable for tools in mining and other industries where explosions are a hazard.

The combination of stiffness, light weight and dimensional stability lies behind the choice of beryllium alloys for the mirrors of advanced space telescopes.

Beryllium is almost transparent to X-rays and so is used for windows on radiography equipment.

1.11.3 Chromium

Chromium is the element which makes stainless steels "stainless". When chromium is cut and exposed to water or moist air, it rapidly forms an adherent, protective "passive layer" of oxide on the cut surface. If damaged, the passive layer reforms quickly, so providing continuing protection to the underlying metal. Steels containing more than approximately 10.5% of chromium show this "stainless" characteristic. Without the protection provided by the passive layer, the steel would progressively rust away—something we are all too familiar with in ordinary steels.

Stainless steel is not just one alloy. The addition of other alloying elements, including nickel, molybdenum, manganese, tungsten and nitrogen has enabled a wide range of stainless steels to be developed, each with their own combination of corrosion resistance, mechanical properties and physical properties to suit a wide range of applications—from interior and exterior panelling for buildings to withstanding the very corrosive conditions in chemical plants.

Stainless steels account for the use of about 90% of the annual chromium production.

Chromium is also one of the key alloying elements in some low-alloy steels where it improves the ability to harden the steel by heat treatment.

Chromium-containing chemicals are used in chromium electroplating as well as in the production of cement and leather tanning.

1.11.4 Cobalt

Cobalt is a shiny, grey, brittle metal which is very rarely used as a structural material in its pure form but almost always as an alloy or as a component of another alloy system.

Nickel and cobalt are next to each other in the periodic table and are frequently found together in nature, as well as in alloys and chemical compounds, where it may be unnecessary to separate them for the intended use. Nickel-based and cobalt-based superalloys also have a lot in common, including their strengthening mechanisms and applications in the hot parts of jet engines.

Cobalt-chromium alloys have good wear and corrosion resistance, making them suitable for engineering and prosthetic applications.

Like nickel, cobalt is ferromagnetic at room temperature. The two elements combine with aluminium to form the Alnico™ permanent magnets. Magnet performance improved with the development first of samarium-cobalt magnets and then with neodymium-iron-boron, which contains a small amount of cobalt. These are important in today's high-performance electric motors. There is also a range of soft magnetic materials based on iron-cobalt.

Cobalt additions can be made to the iron-nickel alloys to control the thermal expansion coefficient.

Cobalt is an excellent binder for tungsten carbide and other cemented carbides for cutting tools, and other applications where hardness and wear resistance are needed.

Historically, metallurgical applications were the most important for cobalt. However, cobalt-containing chemicals now account for almost 70% of end uses and are particularly important in modern rechargeable battery technologies. Other uses include as catalysts[1] in the oil and gas and plastics industries, in bio-pharmaceutical applications and in dyes. Familiar to artists, cobalt pigments (e.g. cobalt blue) have been used in paint, glass and ceramics for millennia.

1.11.5 Copper

Copper's unmatched combination of high electrical and thermal conductivity, mechanical properties, corrosion resistance, workability and ready availability makes it one of the most widely used—and widely recognised—metals. Some 60% is used in electrical cables, a further 25% in roofing and plumbing systems and 15% in engineering machinery.

Alloying copper with tin to increase the strength and hardness of copper was discovered in prehistoric times and was a sufficiently important technological advance, particularly for tools and weapons, that it is recognised in the eponymous Bronze Age. Bronzes with small amounts of other alloying elements are still used for bearings, seawater handling equipment and bells.

Brass, an alloy of copper and zinc, has also been used since ancient times. It is easily worked and machined, which has made it widely used for small engineering parts, taps and other water fittings, cartridge cases and decorative parts. Brass is used for trumpets and other musical instruments—the "brass" instruments—as a result of its malleability and acoustic properties. The properties can be improved by small alloying additions, such as lead to improve machinability.

Copper and copper alloy surfaces resist fouling by marine organisms. Fouling which does occur is relatively easily removed. The antifouling properties of copper were recognised hundreds of years ago. Copper cladding of wooden ships in the eighteenth century also protected the timbers from attack by marine organisms, hence the expression "to give a copper-bottomed guarantee".

Similarly, copper and copper alloy surfaces can be antimicrobial. This property can assist in controlling transfer of bacteria via touch surfaces.

Copper alloys readily with nickel to form the copper-nickel alloys. Their resistance to corrosion, good thermal conductivity and workability make them suitable for applications as diverse as marine heat exchangers and coins. Closely related are the nickel-silver alloys, which, in spite of their name, do not contain any silver! These copper alloys are whitened by adding nickel and zinc. They have been used for many years as the substrate for silver plating on cutlery and tableware—the familiar "EPNS", electroplated nickel-silver.

[1] A catalyst is a substance which increases the yield and speed of a chemical reaction but without being consumed itself.

1.11.6 Gold

Gold's unique combination of distinctive appearance, tarnish resistance, malleability and scarcity has made it a highly prized metal for thousands of years for jewellery, coins and bullion. The purity of gold is measured in carats, 24 carat being 100% pure gold. Twenty-four carat is too soft for some applications so it is alloyed with metals including silver, copper, palladium, zinc and sometimes nickel. Jewellery is commonly made from 9, 14 and 18 carat gold. Almost 80% of gold used each year goes into jewellery.

The number of new applications for gold has increased considerably in recent decades so that they now account for around 12% of gold use. Most notable is its use in electronics and computers. The high electrical conductivity and tarnish resistance make for consistent performance and excellent reliability of contacts and connectors.

Often gold is deposited as a thin layer onto a less expensive metal substrate. Nickel plating is frequently used as a substrate for gold plating because it gives a very smooth finish. Thin gold layers are being used as a lubricant in space equipment because of their low tendency to seize.

A thin layer of gold on the windows of buildings can reduce the infrared transmission both ways, so increasing energy efficiency.

Because of its biocompatibility, gold is used in dentistry and also plays an important part in medical diagnostics, implants and treatments.

1.11.7 Iron and Steel

Iron and particularly its alloy, steel (iron alloyed with carbon and other elements), are today the metal and alloys with the greatest usage both by tonnage and by value (see Table 1.1). About 50% of steel production is used by the construction industry, where there is no suitable substitute for the frameworks of high-rise buildings. The transport industry (road, rail, sea and air) uses 25% of steel production, machinery 14% and metal goods a further 14%.

The use of chromium, manganese, molybdenum, nickel and vanadium as alloying elements with carefully controlled heat treatments has enabled a wide range of high-performance steels to be developed which combine high strength-to-weight ratio with stiffness. These developments continue in, for example, the automotive industry where there is continuing pressure to reduce weight and increase performance. This has led to the development of a range of high-strength steels whose properties are tailored by careful control of composition and microstructure.

Many structural and engineering steels corrode (rust) in damp and aggressive environments. This corrosion can be controlled by the use of paint or other protective coatings on these materials, for example, zinc (see Sect. 11.16). Alternatively, stainless steels can be used which contain at least 10.5% of chromium with other additions, including nickel, molybdenum, manganese and nitrogen which enhance corrosion resistance, strength and magnetic properties. Their corrosion resistance and the resulting low levels of metal release make stainless steels very suitable for equipment where cleanability and hygiene are important, such as in food handling, pharmaceutical production, medical applications, water treatment, chemical plant and building cladding. As a result, the use of stainless steel has grown faster than the use of other alloys.

The appearance and durability of stainless steels are evident not just in iconic buildings such as the Chrysler Building (New York), Lloyds Building (London) and Jin Mao Tower (Shanghai) but also in many smaller structures, architectural details, building services, home appliances and other items in everyday use.

1.11.8 Lead

Lead has been used for thousands of years. The Romans used it extensively for water pipes—long before any health impacts were recognised. Pewter—a tin alloy sometimes containing lead—was used for tableware for many years.

Lead-tin alloys have a low melting point which makes them suitable for joining other metals by soldering. Recently, concerns about the health and environmental effects of lead have led to restrictions on its use and to the development of lead-free solders (see Sect. 11.14).

The lead-acid battery came into and remains in widespread use for automotive starting. In spite of the battery's weight, it provides the necessary high current and cold weather performance. It continues to be used widely to provide standby power systems for hospitals, communication systems and other essential services. Batteries now account for 85% of the growing use of lead.

Lead chemicals were used in ceramic glazes, glass "crystal" and paint pigments. However, during the twentieth century, health and environmental concerns related to the use of lead and its chemicals resulted in a reduction in permitted uses and consequent reduction of emissions and exposure.

Other uses include radiation shielding, where its high density, high atomic weight and ready availability make it an economic choice.

Nearly 95% of lead is collected and recycled at end of life, making it one of the most recycled metals today.

1.11.9 Mercury

Mercury is the only metal which is liquid at normal room temperature, making it useful in thermometers and electrical switches. Amalgams (alloys of mercury) were used for dental fillings and for extraction of gold from its ore. Mercury compounds were used for antiseptic and antifungal treatments. However, many of those uses have been or are being phased out because of their impact on health and the environment. There is still some, but declining, use in thermometers and electrical switches.

1.11.10 Molybdenum

Molybdenum is an example of a metal which is not widely known but has a combination of properties which play a vital role in a wide range of applications—including medical—and emerging technologies. Many alloy steels achieve their high strengths as a result of comparatively small alloying additions of molybdenum—typically less than 1% having a major effect. These steels are used widely for engineering components throughout the transport, oil and gas, power generation and chemical industries. Consequently, 41% of the molybdenum produced is used in these steels.

Molybdenum is also added in small amounts to many stainless steels to improve their corrosion resistance, for example, in marine applications. This is another example of how a few percent of an alloying addition can have a very marked effect on properties. Modern alloy production methods allow the composition to be controlled within fine limits to ensure the effective and efficient use of the alloying additions. Stainless steel uses 22% of annual molybdenum production.

Molybdenum has a very high melting point but its density is significantly less than other "refractory" metals (e.g. tungsten). It is used for tools which operate at high temperatures and for handling molten metal and glass. It is an important component in superalloys (see Sect. 11.11).

The coefficient of thermal expansion of molybdenum metal is close to that of silicon, and it also has good electrical conductivity, making it a suitable substrate for silicon electronic devices. It also plays a key role in improving the performance of photovoltaic cells for solar electricity generation.

Of the molybdenum-containing chemical compounds, the best known is molybdenum disulphide which is used as a lubricant additive. The chemicals are used as pigments for paints and ceramics, corrosion inhibitors and versatile catalysts, accounting for 13% of molybdenum production.

1.11.11 Nickel

Nickel-containing alloys are indispensable and widely used today—a far cry from the days when German miners saw nickel as an unwelcome impurity in the copper ores they were seeking. Today nickel is a good illustration of the versatility of metals and their alloys.

About two thirds of the nickel produced is used in stainless steels (see also Sect. 11.7). Whilst it is chromium which makes stainless steels stainless, nickel improves strength, ductility, toughness (not brittle) and corrosion resistance. As a result, approximately two thirds of the stainless steel produced today is alloyed with nickel.

Corrosion resistance, formability, ease of cleaning and the ability to be sterilised have ensured that the stainless steels are used extensively in food processing, catering, water treatment, wine production, pharmaceutical plants and medical equipment. The use of stainless steels continues to grow faster than many other alloys.

Alloys based on 80% nickel with 20% chromium have been used for many years as heating elements—from domestic cookers to industrial furnaces. The addition of aluminium and titanium in particular, but also cobalt, molybdenum and tungsten, produces a further family of alloys often called "superalloys" because of their exceptional strength at temperatures over 1000 °C. They are stronger at these high temperatures than many materials are at room temperature. They are used in the hottest parts of the gas turbines (jet engines), which are widely used for power generation and aircraft propulsion. Without these alloys, modern, fuel-efficient air travel would not be possible.

At the other extreme of temperature, nickel-containing stainless steels remain tough (not brittle) to very low temperatures making them candidates for liquid natural gas (LNG) transport and storage, along with aluminium and iron-36% nickel alloy.

The iron-36% nickel alloy is remarkable in that it has nearly zero thermal expansion from low temperatures up to around 200 °C. For his discovery of this alloy, Guillaume was awarded the Nobel Prize for physics in 1920. Known as "Invar™", the alloy was originally used for pendulums for high-precision clocks. More recently, it was used extensively in colour television tubes—until display technology progressed. Today the alloy is used in the electronics industry as well as for linings in some designs of liquid natural gas (LNG) storage tanks. Other alloy compositions, including cobalt, have expansion coefficients tailored to match those of the plastics used for integrated circuit encapsulation—important for the external connections.

Nickel is one of only four elements which are ferromagnetic (strongly magnetic) at room temperature. The other three are the metals iron, cobalt and gadolinium. Alloys of iron and nickel are easily magnetised (soft magnets) and are particularly suitable for shielding sensitive electronic equipment from electromagnetic interference (EMI). Alloys of aluminium, nickel and cobalt give rise to the Alnico™ family of permanent magnets—the first mass-produced permanent magnets. Used for many years in motors and loudspeakers, these magnets are being superseded for many applications by stronger magnets using the rare earth elements (see Sect. 11.4).

Electrodeposition of nickel—electroplating—was one of the first commercial uses of nickel 150 years ago and produced an attractive, corrosion-resistant coating. It also provided a suitable substrate for other decorative coatings, especially chromium but also gold and other metals. Nickel-chromium plating has become very widely used for decorative and corrosion-resistant coatings. It is familiar in automobile trim, plumbing fittings and office furniture. Today electroplating accounts for about 10% of the annual use of nickel. Nickel plating reproduces the surface detail on the substrate very accurately. This is the basis of the electroforming process to produce screens for rotary screen printing of fabrics and the moulds for pressing CDs, DVDs and security holograms.

Nickel can also be deposited chemically. This "electroless" nickel plating can produce coatings for wear and corrosion resistance as well as providing a smooth substrate, for example, for the magnetic medium on discs of computer hard drives.

Nickel plays an important role in the structure and chemistry of several rechargeable battery technologies. Stand-by power, portable devices and electric/hybrid vehicles all depend on nickel.

Nickel has a long history of being used for coins. The Canadian five-cent piece or "nickel" was struck in pure nickel at times in its history, but since 2000 it has been struck in nickel-plated steel for cost reasons. An alloy of copper with 25% nickel has been and continues to be used widely for coins because of its silvery colour, corrosion resistance, ease of striking and durability.

Normally metals which have been deformed have no memory of their previous shape, but there are alloys which do have a memory and can reform to a previous shape when heated. An alloy of nickel and titanium in equal proportions is the best known of these "shape-memory alloys": formed at one temperature and then deformed at a lower temperature, it will return to its original shape when reheated. This property is exploited in medical devices and implants, for example, in stents which can be squashed and put into a blood vessel where they will re-expand at body temperature to open up the blood vessel. These alloys also exhibit "superelasticity", reversible elastic deformation many times greater than other metals, making them suitable for dental braces and spectacle frames.

Nickel-based catalysts are important in the production of hydrogenated vegetable fats, reforming hydrocarbons and the production of chemicals.

1.11.12 Palladium

Palladium is one of the platinum group metals (PGMs; see platinum). Like platinum, palladium is very resistant to corrosion at low and high temperatures and has strong catalytic properties. It is used in similar applications to platinum, vehicle catalytic converters being a major use.

Some palladium jewellery is made, but more frequently palladium is used as one constituent of white gold (see Sect. 11.6). It is also used in dentistry.

A unique property of palladium is its ability to absorb 900 times its own volume of hydrogen at room temperature and pressure. This property enables palladium to be utilised in purifying and storing hydrogen.

1.11.13 Platinum

Platinum is a dense, very unreactive (so very corrosion resistant), malleable, silvery, scarce and valuable metal. It is a potent catalyst. As a result, 45% of platinum goes into catalytic converters to control vehicle emissions and a further 10% is used in the chemical industry. The other major use for platinum is for jewellery because of its appearance, corrosion and wear resistance and value.

Platinum metal is biocompatible because of its corrosion resistance and low reactivity and so has many uses in medical applications. It has many niche applications in engineering which depend on its corrosion resistance, particularly at high temperature, for example, spinning molten glass. It is often used in conjunction with its neighbouring elements in the periodic table (ruthenium, rhodium, palladium, osmium and iridium), which are known collectively as the platinum group metals (PGMs).

A platinum 10% iridium alloy cylinder made in 1879 is the international prototype kilogram which remains to this day the world standard of mass. The alloy was chosen because of its high density, wear resistance and tarnish resistance.

1.11.14 Tin

Around 3000 B.C. the Bronze Age started with the discovery of the hardening effect of alloying copper with tin. Pewter—tin alloys containing small amounts of copper, antimony, bismuth, sometimes lead and silver—became widely used by the fifteenth century for domestic tableware. Tin alloys are still extensively used—as bronze, in wine capsules and, more recently, in lead-acid battery grids.

Lead-tin solders have been phased out of plumbing, electronic and other applications. They have largely been replaced by tin-based solders which can also be tailored to have precise melting ranges. Solder represents 47% of tin use today.

A thin tin plating on the interior of steel cans provides the corrosion resistance necessary for the success of canning as a means of food preservation, which accounts for 15% of tin use. In some products, tin is in direct contact with food to provide anti-oxidant action, which preserves colour and taste.

Extensive use of glass is a feature of many buildings today. The glass must be flat, of uniform thickness and flawless. This has been possible by using the “float” process where the molten glass floats on a bath of molten tin during solidification. Tin is also coated onto glass for radiation insulation, conductivity and scratch protection.

Niobium alloyed with tin is the key constituent of the high field strength superconducting magnets used in medical scanners and in the Large Hadron Collider particle accelerator in CERN (the European Organisation for Nuclear Research in Geneva).

Tin compounds are used as catalysts, in ceramics and in plating baths, and to prevent the degradation of PVC building products by heat and sunlight. It is likely to continue being used in a wide variety of energy-saving materials.

1.11.15 Titanium

Titanium has the highest strength-to-density ratio of any of the pure metals. Its density is about half that of steel. It also forms a very adherent surface oxide film which makes it very corrosion resistant in many media, including seawater. It can be further strengthened by alloying, particularly with aluminium and vanadium. This combination makes it well suited to applications which require high strength with light weight, particularly in aerospace. It is used in compressor blades of jet engines and, more visibly, for the fan blades at the front of turbofan engines in which the fan generates most of the thrust.

About 44% of titanium metal production goes into aerospace applications, but it is perhaps not surprising that the same properties—particularly light weight—are exploited in some high-performance items of sports equipment, for example, in cycling, mountain climbing and golf.

Industrial uses of titanium are found in the energy, chemical, marine and desalination industries for heat exchangers, pipework and vessels. One high-profile architectural application is the titanium external cladding of the Guggenheim Museum in Bilbao, Spain.

Its biocompatibility, along with its other characteristics, makes titanium suitable for surgical implants and medical tools.

The above uses illustrate the versatility of titanium metal, but uses of the metal itself account for only 5% of the annual titanium production. The remaining 95% is used to produce titanium dioxide. This is a very white, stable powder which is unaffected by ultraviolet light and so is used as a pigment in paint, as a whitener in plastics, paper, food and toothpaste.

1.11.16 Zinc

The major use of zinc is for corrosion protection. When steel is in contact with zinc in a situation where the steel would rust, the zinc corrodes preferentially, protecting the steel from corrosion. The zinc can be applied as a coating on the steel—galvanising—either by an electrolytic process or by dipping the components into molten zinc. Galvanised steel handrails and fences are a familiar sight. Blocks of zinc (“anodes”) can be fastened in contact with immersed structures and buried pipelines to provide cathodic protection.

Zinc has been used for many years in battery construction. Today zinc powder is used for alkaline dry cell batteries.

Brass, an alloy of copper and zinc, was being made in the first millennium BC from zinc ore and copper although it was not as easy to make as bronze because of the low melting point of zinc. With the production of elemental zinc metal in the fifteenth century AD, brass then became an important engineering material in the industrial revolution. It has an attractive combination of mechanical properties, corrosion resistance, ease of machining and fabrication, appearance and cost.

In addition to brass, zinc is also used as an alloying element in the nickel-silver alloys (see Sect. 11.11). Zinc alloys—often with aluminium—are used to produce small, intricate components by die casting, the injection of the molten alloy into a die under pressure where it sets quickly because of the relatively low melting point.

Around 25% of zinc is used as chemicals in diverse applications.

1.12 Summary

- Metals have been important to society since the Bronze Age and their use is still increasing.
- Metals are frequently critical to the success of new technologies.
- The specific and unique properties of some metals mean that they have very specific but important uses and cannot readily be substituted.
- Metals are used but not consumed and are therefore theoretically infinitely recyclable. However, improving the efficiency of recovering metals from products at end of life continues to be important.
- Exposure to an allergenic metal is not in itself sufficient to cause an allergic reaction. The metal must be in a solubilised form, and the exposure must be in sufficient amounts to provoke an allergic response.
- As the examples have shown, the opportunities for direct skin contact in most applications of metals, and hence the opportunities for an allergic reaction, are specific but limited.
- Understanding the science associated with metal allergies and where those metals are used is key to managing the risks of metal allergies and allowing safe use of metals and alloys in appropriate applications.
- Agricola's view of metals in 1556 still holds today, and metals remain indispensable for developing and maintaining a sustainable society. There are no signs of that changing in the foreseeable future.

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