3. Cobalt

Cobalt is shiny, grey, brittle metal with a close packed hexagonal (CPH) crystal structure at room temperature but which changes at 421 °C to a face centred cubic form. It has a high melting point (1493 °C) and boiling point (3100 ºC) and it maintains its strength and integrity at extremely high temperatures. In addition, cobalt, as well as nickel and iron, is ferromagnetic and retains this property up to 1100 °C, a higher temperature (Curie point) than any other material. Hence, one of its key uses is in magnets for high-temperature applications.

Cobalt is rarely used as a structural material in its pure form but rather is employed as an alloying element. The first use of cobalt was as a pigment in conjunction with silica to produce intense blue colours. This remained as the main use of cobalt until the 20th century. However, cobalt is a very versatile metal and over the 20th century it started to be employed for a wide array of applications such as metallurgical uses (e.g. superalloys), magnets, batteries, pigments, catalysts, etc.

In addition to its industrial uses and relevance, cobalt is one of the around 20 elements which are essential to humans. Cobalt is contained in vitamin B12, which is important in protein formation and DNA regulation.

Cobalt is recovered both as a main metal from dedicated cobalt mines (minor source) and as a by-product (major source), especially of nickel and copper mining.[1,2] It is only extracted alone from Moroccan and Canadian arsenide ores. The main producer of cobalt worldwide is the Democratic Republic of Congo. Historical price data are shown in Figure 2. The average price in 2011 was 8.18 US$/kg[*].[3] When looking at the price of cobalt in more detail, the large scale fluctuation seen in Figure 2 continues. The price decreased in the beginning of 2013, rose up in the middle of the year and felt down after this peak recently.[4]

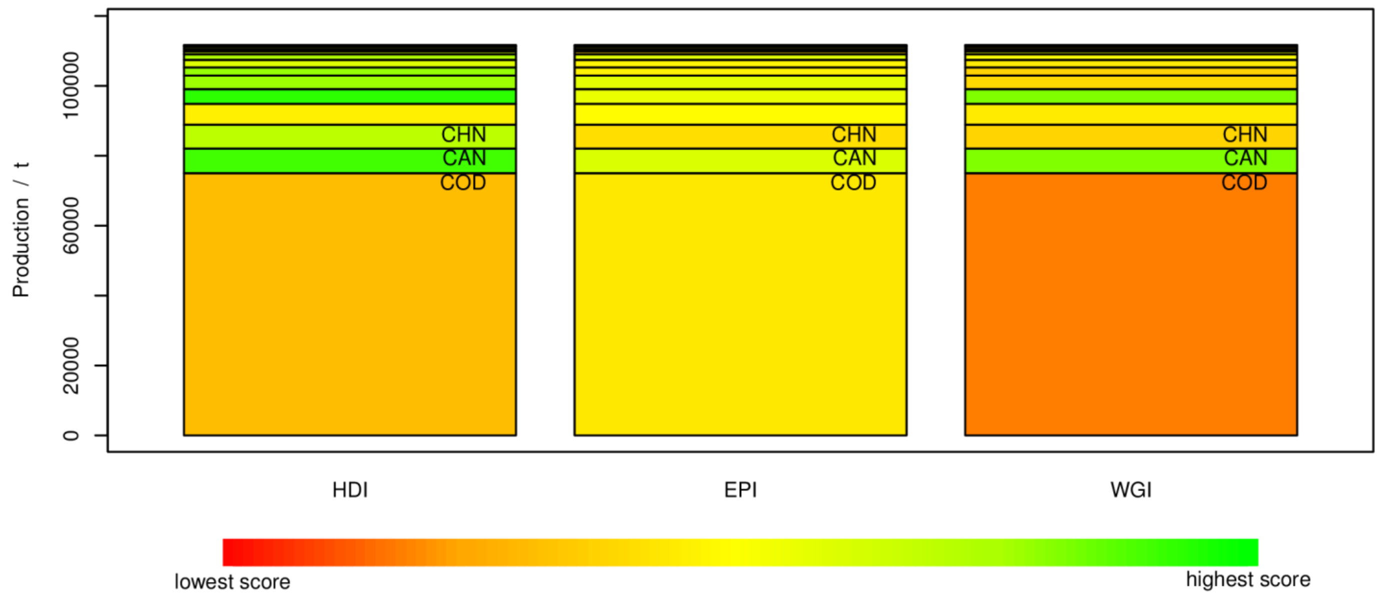

Figure 1: Distribution of cobalt production[5] and corresponding scores of the producing countries in the Human Development Index (HDI)[6], Environmental Performance Index (EPI)[7], and World Governance

[*] Spot, cathode: As reported by Platts Metals Week

Indicators (WGI)[8]. Both the EPI and WGI are used to assess supply risks with the EU methodology for determining critical raw materials [9]. COD = D. R. Congo; CAN = Canada; CHN = China.

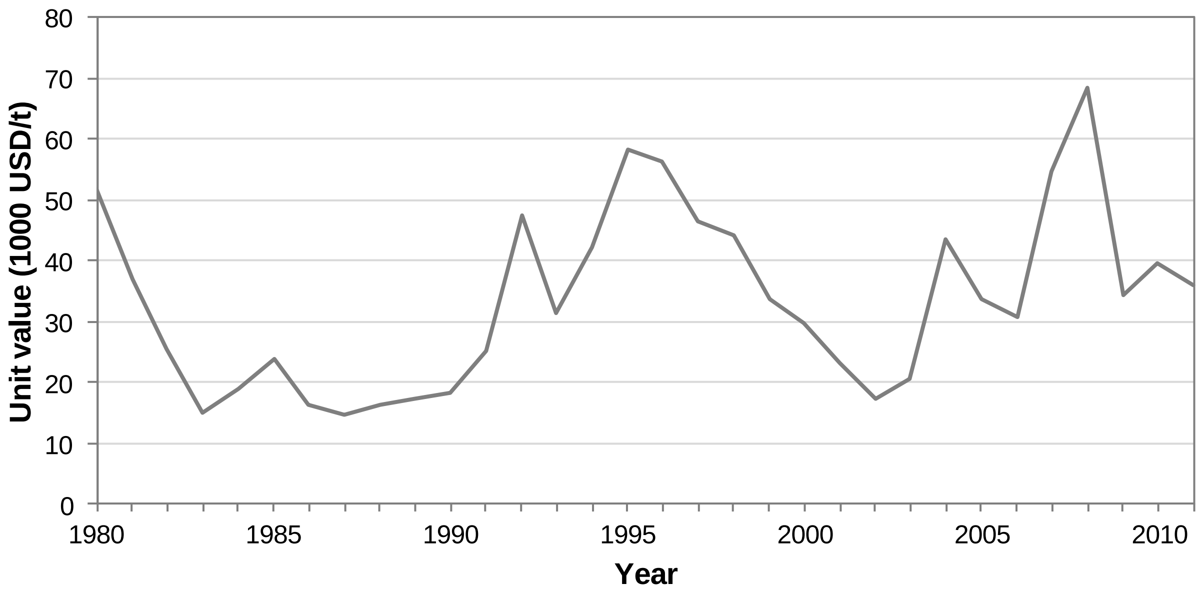

Figure 2: Cobalt price development during 1980 – 2011. The unit value is defined as the value of 1 t of cobalt apparent consumption (estimated).[10].

Uses and substitutability

Batteries

The increase in demand for portable electronic devices since the 1980s boosted the demand for high capacity rechargeable batteries. In this context, rechargeable batteries containing cobalt display a high energy density, along with the capability of quick charging and low stand-by energy losses. For this reason, one of the preferred uses of cobalt is in batteries of portable devices, such as cell phones, laptops, smartphones, tablets, etc. Lithium-ion (Li-ion) batteries containing cobalt-based cathodes contain the most cobalt with a market share of 30%, but nickel metal hydride (Ni-MH) and nickel cadmium (NiCd) batteries also use cobalt. Overall, close to 30% of cobalt demand is attributed to its use in batteries.

A continued increase in demand for Li-ion is expected in the electronics sectors correlating to the surge in demand for portable devices (especially telephones) in emerging economies. Moreover, emerging use of cobalt in some rechargeable batteries for electric vehicle applications is expected to increase cobalt demand over the next ten years.

Substitution of cobalt in Li-Ion batteries is potentially possible. Although $LiCoO_2$ is the preferred material for portable battery applications[11], both $LiNiO_2$ and $LiMn_2O_4$ can also be used for the same purpose. In addition, latest industry predictions indicate that many of the disadvantages of alternative materials have been overcome and although rechargeable battery demand is expected to increase rapidly in the next few years, cobalt demand in this application could remain stable or even decrease slightly.

In addition, the recycling and recovery rates of cobalt from end-of-life batteries are promising. Recent research [12,13] shows that new recycling strategies are being implemented to increase the recovery valuable materials, especially cobalt, from batteries. In this regard, it should be noted that high recycling rates of end-of-life cobalt are reported[14]. Finally, it is worth mentioning the industrial scale end of life rechargeable batteries recycling facility set up by Umicore in Belgium in 2011[15].

Superalloys and magnets

Cobalt-based super-alloys are one of the largest markets for cobalt [16]. They have their origins in the Stellite alloys patented in the early 1990's by Elwood Haynes. Cobalt-based super-alloys have higher melting points than nickel-based ones and retain their strength at higher temperatures. They also show superior weldability, hot corrosion and thermal fatigue resistance than nickel-based alloys.[17] These properties make them suitable for use in turbine blades for gas turbines and jet aircraft engines.[18]

Fiber-reinforced metal matrix composites (MMC), ceramic-ceramic and carbon-carbon composites, titanium aluminides, nickel-based single crystal alloys or iron-based super-alloys may substitute cobalt-based ones in these applications to some extent. Loss of performance at high temperatures (due to the unique physical properties of Co) can, however, be expected in some cases.[19] Therefore, substitution for cobalt in jet engine castings will probably not occur and cannot be considered as a meaningful solution to the cobalt supply problem.

Cobalt is also used in samarium-cobalt and aluminium-nickel-cobalt permanent magnets. These are widely used in electric motors, electric guitar pickups, microphones, sensors, loudspeakers, traveling-wave tubes, and cow magnets.[20] They have comparable strength but much higher temperature ratings and higher coercivity than neodymium magnets.[21]

There is some potential for substitution of cobalt-alloyed magnets by nickel-iron or neodymium-iron-boron ones. The substitution seems to be difficult though in high temperature applications since cobalt-alloyed magnets have significantly higher Curie temperatures and are the only magnets that have useful magnetism even when heated red-hot.[22]

Hard metal and surface treatment

Around 12% of the final cobalt consumed is destined to hard metal and surface treatment. Cobalt is used in cemented carbides as a binder phase. The carbides are usually Tungsten-Carbides although sometimes also Titanium-Carbo-Nitrides or Tantalum-Carbides are used. The binder phase is typically between 5 and 30 vol% of the component. The more hard carbide particles are within the material, the harder it is but the less tough it behaves during loading; and, vice versa, significant increases in toughness are achieved by a higher amount of metallic binder at the expense of hardness.

The high solubility of tungsten carbide (WC) in the solid and liquid cobalt binder at high temperatures provides a very good wetting of WC and results in an excellent densification during liquid phase sintering and in a pore-free structure.[23] There is potential for substitution of cobalt-iron-copper or iron-copper in diamond tools. Research and development in this field is very active and most of the competing matrix materials have a lower cost.[24–26] However, there is a certain loss of performance.

Pigments

Pigments account for 9% of cobalt use. The unique colouring properties of cobalt produce light blue to black pigmentation for ceramics, glass, porcelain, enamel, paint and inks [2], whereby the amount of cobalt oxide added to the final product depends on the required colour. As cobalt(II) acetate it is used in the production of drying agents for inks and pigments. Cerium, iron, lead, manganese, and vanadium can all be used as substitutes for cobalt for this application, unfortunately not necessarily with the same results.[3]

Catalysts

Cobalt is widely used in the oil and gas sector. It is used in hydrodesulfurization (a catalytic chemical process widely used to remove sulfur from natural gas and from refined petroleum products such as gasoline or petrol), where the catalyst must be sulfur resistant. [27] Catalysts account for 6% of cobalt use.

Cobalt catalysts also play an important role bulk chemical production of PTA (a monomeric precursor to polyester) and a process called hydroformylation which generates aldehydes and alcohols used in the plastics and detergent markets.[27]

In addition, it is also used in the catalysis of gas to liquid processes. [28] The application of this technology is expected to result in a major new demand for cobalt. [29]

Finally, a potential emerging use (and subsequent increase in demand) of cobalt is as catalyst in hydrogen fuel cells.[30]

With regard to its application for hydrodesulfurization, ruthenium, molybdenum, nickel and tungsten can be used depending on nature of the feed, instead of cobalt.[3,31–33] Also alternative ultrasonic process can dispense with the use of cobalt, and rhodium can serve as a substitute for hydroformylation catalysts.[3]

Others

There is still a remaining 8% of cobalt that is used for various other applications. Cobalt powders are used for their high melting point, high-temperature strength and for the fact that they can be produced as a very fine powder in binders for the diamond tool industry. For this application, cobalt can be substituted by cobalt-iron-copper or iron-copper.[1]

Cobalt salts are used in agriculture as a supplement to animal feeds, as cobalt is an essential element in the human and animal metabolism.[2]

The cobalt isotope Co^{60} is a strong gamma-ray emitter, which is used in the medical field for radiation therapy. Other medical applications for cobalt include the use of cobalt-chromium alloys for cast denture bases, complex partial dentures, and some types of bridgework for dental applications due to cobalt's high strength and tension properties. The good castability, resistance to tarnish, compatibility with mouth tissues, high strength and stiffness, and low density makes cobalt suitable for these applications. Similar cobalt-chromium alloys are also used for surgical implants and bone replacement (e.g. hip joint replacement) and repair because of cobalt's resistance to corrosion and high fatigue strength of the cobalt-chromium-alloy.[1]

Other applications include the manufacture of Elgiloy, a spring alloy containing 40% cobalt, 20% chromium, 15% nickel, 7% molybdenum, and 2% manganese, alloys composed of cobalt-nickel or cobalt-iron-magnesium-carbon used as magnetic recording materials and cobalt silicate, which is applied for electrical connectors and integrated circuits. A material with a very low coefficient of thermal expansion results from alloying cobalt in low-expansion iron–nickel alloys of the Invar type.[1]

Summary

Substitution of cobalt in Li-Ion batteries—the single largest application—is possible, although this is not the preferred option. Moreover, in this field, recycling and recovery hold some promising potential. Similarly, substitution comes at the expense of performance due to the unique properties of cobalt in superalloys, magnets, hard metals and surface treatment. Cobalt substitution in pigments by acetate, cerium, iron, etc. is possible but also leads to a decrease in performance. Finally, cobalt as a catalyst may be substituted to some extent for hydrodesulfurization and hydroformylation proceses.

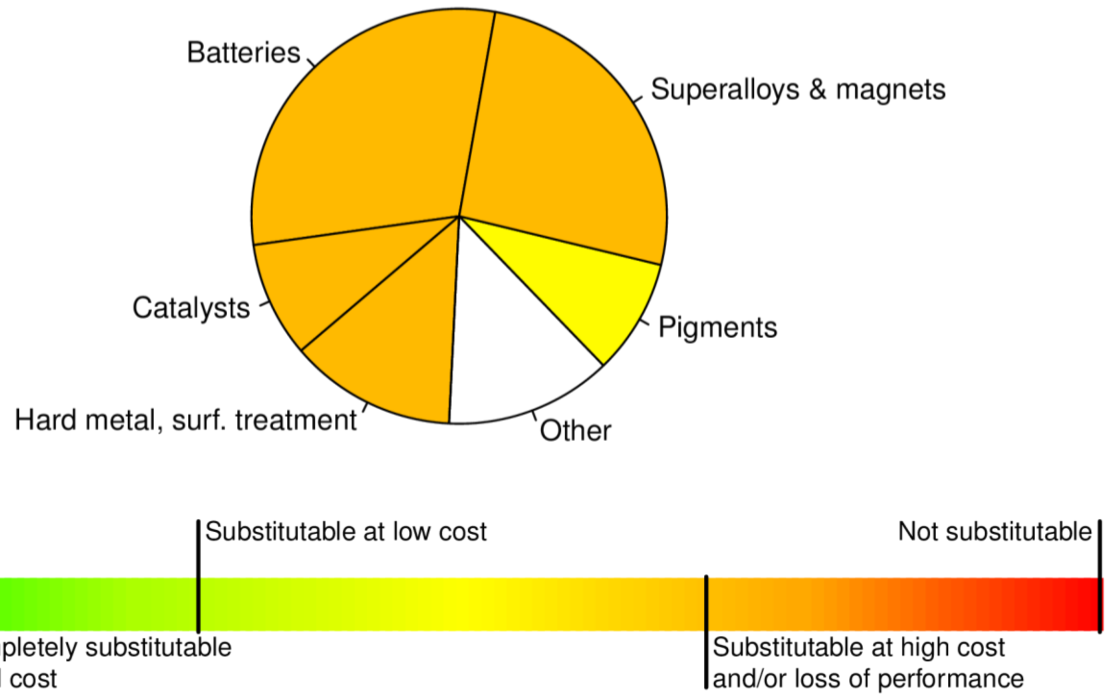

Figure 3: Distribution of end-uses and corresponding substitutability assessment for cobalt. The manner and scaling of the assessment is compatible with the work of the Ad-hoc Working Group on Defining Critical Raw Materials (2010).

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