Trends in the development of cobalt production

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Cobalt, as one of the "critical" and "strategically important" metals, plays a key role in the contemporary development of the world's industry. Cobalt has specialized applications where it is currently impossible to replace it with other alternative materials. It finds application in the rechargeable batteries of portable devices (mobile phones, laptops, tablets) and electric and hybrid vehicles, integrated circuits, semiconductors, magnetic tunnel contact transistors, magnetic recording devices, catalysts, various alloys and super alloys, pigments, healthcare (prosthetics, diagnosis, radiotherapy), etc. A study is conducted, data and information on trends in global cobalt resource, reserves and production development has been analyzed and summarized. The modern technologies and methods for processing cobalt raw materials, by obtaining concentrates, intermediates or metal are presented. As a final step in the production of high purity metal, the vacuum electrometallurgy technologies - vacuum electro arc and electron beam melting methods are applied, that makes it possible to obtain metal with high purity and cobalt alloys and semi-finished products with new or improved chemical composition, structure and properties.

Keywords – cobalt, primary raw materials, primary and refining production, electron beam melting

Тенденции в развитието на кобалтовото производство (Валерия Ковачева-Нинова, Георги Савов, Ваня Василева, Катя Вутова, Евгени Петров, Добрин Петров) *Кобалтът, като един от „критичните" и „стратегически" важни метали, заема ключова роля в съвременното развитие на световната индустрия и има специализирани приложения, в които понастоящем е невъзможна замяната му с други алтернативни материали. Намира приложение в акумулаторните батерии на портативните устройства (мобилни телефони, лаптопи, таблети), електрическите и хибридните превозни средства, интегралните схеми, полупроводниците, магнитните тунелни контактни транзистори, магнитните записващи устройства, катализаторите, различните сплави и суперсплави, оцветителите, здравеопазването (протезиране, диагностициране и радиолечение) и др. Направено е проучване и са анализирани и обобщени данни и информация относно тенденциите в развитието на световните ресурси, запаси и производство на кобалт. Представени са съвременните технологии и методи за извличане на кобалт и получаване на концентрати, междинни продукти или метал. Като краен етап при получаване на метал с висока чистота се прилагат методите на вакуумната електрометалургия - вакуумно електродъгово и електроннолъчево топене, което дава възможност за получаване на метал с висока чистота и кобалтови сплави и полуфабрикати с нови или подобрени химичен състав, структура и свойства.*

Introduction

The physical and chemical properties of cobalt and its alloys and compounds determine their specialized applications where it is difficult to replace them with other alternative materials. Consequently, the current development of the industry and technologies is strongly dependent on the global trends in the insurance of cobalt supply. Historically, until the 1970s, the major suppliers of cobalt were Norway, Sweden, Hungary and Germany (Saxony). In recent years, those have been mainly displaced by the Democratic Republic of Congo (DRC) and other countries. About 50% of the global cobalt reserves are concentrated in the DRC and the country produces about 50% of the world's cobalt production. At the same time, the state is identified as highly risky [1], which may affect global cobalt supply and prices. Such example is the "Cobalt Crisis" in 1978 when the situation in the DRC (then Zaire), a world leader in mining and the production of refined cobalt, had an impact on the price of cobalt: from $18 kg it rose to $99 kg. The uncertainty in the raw material base for the production of cobalt from Cu-Co ores has led to the expansion of its production from sources like the increasing quantities of Ni-Co ores, the recycling of cobalt-containing scrap, and intermediates. Metal cobalt, as well as its alloys, are recyclable and this favors the creation of a circular economy.

Despite the expansion of raw material sources, the uneven distribution of the exploited quantities mainly concentrated in a few countries (DRC, China, Canada, Cuba, Australia and Russia), and the potential risk of imbalance between supply and demand define cobalt as a "critical and strategically" important metal [2, 3].

Cobalt applications

Cobalt is a silverfish-gray metal with various uses determined by its key properties - ferromagnetism, hardness, corrosion- and wear-resistance when alloyed with other metals, low thermal and electrical conductivity, high melting point, multi-valence and coloring in intensive blue colors. Cobalt and its compounds are used in relatively small amounts in each application. However, many of the innovative processes and products that each of us takes for granted in modern life are the result of their uses in the modern production and technologies. The main cobalt and its compounds applications are in [4]:

✓*Rechargeable batteries* – on a global scale, around 50% of the produced cobalt are used in the batteries of portable devices (mobile phones, laptops, tablets, cutting tools), electric and hybrid electric vehicles, electric trains, electric bikes, renewable energy power stations, ancillary services to the electrical grid [5]. Cobalt prevents the occurrence of dendrites in Li-ion batteries. It extends their service life and that of cylindrical alkaline batteries;

✓*Integrated circuits* - the unique physico-chemical cobalt properties, as well as its wear and electrical resistance make it applicable to various components of the integrated circuits (contacts, metal cables and circuit boards). The resistant materials used are Co-Sb, Co-B, Co-In, Co-Mo, Co-P, Co-Re, Co-Ru, Co-W, Co-V, and Co-Ge;

✓*Semi-conductors and magnet tunnel junction transistors* - the cobalt's ability to increase the power and electrical current and to prevent electro-migration in copper wires is used. Optical electrical devices use Co-Si-Ge to improve the contact interface. In 2015, the latest generation of 11 nm semiconductor technology was developed, with the addition of Co with innovative deposition methods: physical vapour deposition (PVD) using an ion beam for evaporation and subsequent deposition of Co onto a target surface; chemical vapour deposition (CVD) using chemical reactants to apply Co on a target surface; atomic layer deposition, with the deposition of Co on alternating atomic layers; metal plating using an electric current to deposit Co onto a target surface;

✓*Magnetic recording devices* - cobalt is an essential metal for the process of magnetic recording, a technology used in data recording devices, such as hard disk drives. Digital storage of information is vital to everyday life and allows photos, documents and media to be accessed and reproduced;

✓*Catalysts* - cobalt acts as a catalyst in natural gas and refined petroleum products (gasoline, diesel, kerosene) desulphurisation reactions. Each tonne of cobalt applied as a catalyst mixture reduces the emissions of sulfur oxides by 25,000 tons and of nitrogen oxides by 750 t. It is also used in the synthesis of polyester precursors and the production of aldehydes from alkenes in the OXO reaction. Cobalt catalysts are used to synthesise terephthalic acid (TPA) and di-methylterephthalate (DMT) which are predominantly used as precursors in the formation of polyester (PET). 60% of PET is used for textile production and 31% for the production of recyclable plastic bottles;

✓*Colourant* - cobalt oxides and other complex cobalt compounds have a unique combination of color, solubility and stability and are therefore used as coloring agents in glass, ceramic products, paints, inks, and enamel paints. Apart from the famous "cobalt blue" color, the metal is also used to create other colors - purple, violet, green, turquoise, pink, brown, and yellow;

✓*Alloys* - cobalt is used as an alloying element in a number of alloys to create materials with specific applications. Alloys containing cobalt can be divided into super alloys, magnetic alloys, prosthetic alloys, and alloys resistant to elevated temperatures, wear and corrosion. The super alloys containing cobalt are used in gas turbines, space vehicles and rocket motors, nuclear reactors, power plant turbines, and chemical equipment. Usually, vacuum melting is used to provide strict control over the elemental make-up of the superalloy. The high wear-resistant alloys containing cobalt are Stellite, Tristelle and Tribaloy. Because of their high biocompatibility, Co-Cr alloys (Vitallium) are often used in combination with titanium alloys [6], in the manufacture of prosthetic and orthopedic implants. Cobalt is mainly used in hard magnetic alloys, but also in some soft magnetic alloys to achieve a high saturation point, magnetoconductivity, and a high Curie Point (950 - 990 °C). The hard magnetic alloys Al-Ni-Co, Sm-Co and Nd-Fe-B (1 - 16% Co) are used in permanent magnets, sensors, motors, and in electronics. In Japan, Nd-Fe-B magnets are used in the Maglev high-speed magnetic train systems. Sm-Co and Nd-Fe-B magnets are also used in headphones, voice telephones, and speakers. Another key use of the metal is as a binder in cemented carbide for solid metals. Adding it to the carbide makes it possible to achieve the essential qualities of cutting tools, hot rolled metal rollers and engine components such as wear resistance, durability, and hardness;

✓*Healthcare* – cobalt is used in the form of metal, cobalamin and cobalt isotopes (^{60}Co, ^{58}Co, ^{57}Co and ^{55}Co) for the diagnosis and radiotherapy of tumors, cancer, Hodgkin's disease, retinoblastoma and Graves ophthalmology, for making orthopedic and dental implants, for the creation of biomolecules, for measurement and diagnosis of the adsorption and vitamin B12 deficiency, and for the sterilization of medical equipment.

According to data from the Cobalt Development Institute for 2012, the main uses of cobalt in [%] of its world consumption are presented in Table 1.

As a result of the widespread use of cobalt, especially in rechargeable batteries, by 2025 the global consumption is expected to increase by 65% compared to that in 2015 [7].

Table 1

Main cobalt applications by end use (2012)

Application	Share, %
Batteries	30
Super alloys	19
Cemented carbides and diamond tools	13
Catalysts	9
Pigments and ceramic products	9
Magnetic alloys	7
Steels, alloys and hardfacing	5
Drying agents for paints and other chemical uses	8

Global cobalt reserves, production and consumption

A. Global cobalt resources and reserves

Global cobalt resources [8] are estimated to about 147 million tons of Co. They cover different types of terrestrial and ocean floor deposits: sediment-hosted stratiform Cu-Co (7%), magmatic Ni-Cu (-Co-Pt group elements) sulfide (3%), Ni-Co laterite (6%), seafloor Fe-Mn (-Ni-Cu-Co-Mo) nodules (4%), seafloor Fe-Mn (-Co-Mo-REE) crusts (38%), and other terrestrial deposits (1%). Terrestrial resources contain about 25.5 million tons of Co, distributed in the following types of deposits shown in Table 2. According to another source [9], the continental cobalt resources are 26.1 million t Co.

Table 2

Types of terrestrial cobalt deposits

Deposit	Share, %
Sediment-hosted stratiform Cu-Co	41
Ni-Co laterite	36
Magmatic Ni-Cu (-Co-Pt group elements) sulphide	15
Other terrestrial types	8

Mineral concentrations of Co in terms of economic interest are mainly found in the deposits types presented in Table 3.

Table 3

Summary of main cobalt deposit type

Deposit type	Co, %	Example deposit
Sediment-hosted stratiform Cu-Co	0.1-0.4	Kamoto, KOV and Tenke Fungurume, DRK [10]; Nkana, Zambia [11]; Mt Isa, Australia
Hydrothermal/ volcanogenic	0.1	Bou Azzer, Morocco [12]; Keretti, Finland
Magmatic Ni-Cu (-Co-Pt group elements) sulphide	0.1	Norilsk, Russia [13]; Sudbury, Ontario, [14]; Voysey's Bay, Newfoudland and Labrador, Canada [15]; Kambalda, Australia
Ni-Co laterite	0.05 – 0.15	Koniambo Massif, Goro deposit, New Caledonia [16]; Nkamouna, Cameroon [17]
Manganese nodules and Co rich crusts	up to 2.5	None currently economic

Apart from those shown in Table 3, the continental cobalt deposits with economic or potentially economic significance are of the type: black-shale-hosted Ni-Cu-Zn-Co (Talvivaara, Finland, [18]); iron oxide-Cu-Au (-Ag-U-REE-Co-Ni) (Olympic Dam, Ernst Henry, Australia, [19, 20]; Sogesso, Brazil, [21]); metasedimentary-rock-hosted Co-Cu-Au (Kuusamo belt, Finland [22]; NICO, Canada, [23]); volcanogenic

Cu (-Zn-Co-Ag-Au) massive sulfides (Outukumu, Finland [24]; Windy Craggy, Canada [25]; Deerni, China [26]); Mississippi Valley type Zn-Pb (-Co-Ni); Fe-Cu-Co skarn and replacement (Mount Elliott, Australia, [27]); polymetallic (Ag-Ni-Co-As-Bi) and other cobalt rich veins (Bou Azzer, Morroco [12]).

The common cobalt-bearing minerals distributed in economic deposits are presented in Table 4.

Table 4

Cobalt minerals of economic importance

Mineral	Group	Formula	Content, %		Example deposit
			Ni	Co	
Linnaeite	Sulphide	Co_3S_4	-	45-53	Bou Azzer, Morocco; Norilsk, Russia
Carrollite	Sulphide	$Cu(Co,Ni)_2S_4$	0.3-7	35-38	Chambishi, Copperbelt, Zambia; Carroll County MD, USA
Skutteru-dite	Arsenide	$(Co,Ni)As_3$	0-9	11-20	Skutterud mines, Norway; Bou Azzer, Morocco
Cobaltite	Sulph-arsenide	CoAsS	0.5-2	26-35	Sudbury, Canada; Broken Hill, New South Wales, Australia
Erythrite	Arsenate	$Co_3(AsO_4)_2.8H_2O$	0-6	20-30	Daniel Mine, Germany; Bou Azzer, Morocco
Asbolite (Asbolane)	Oxide	$m(Co,Ni,)O.MnO_2.nH_2O$	0.8-20	0.8-32	Koniambo Massif, Goro deposit, New Caledonia

The world's cobalt reserves are distributed as follows: around 50% are in sediment-hosted stratiform Cu-Co deposits, 34% are in laterite Ni-Co deposits, 14% are in magmatic Ni-Cu (-Co-Pt group elements) sulphide deposits, and 2% are in other terrestrial deposits. The world cobalt reserves presented in Fig. 1 (1996-2016) [28] show that over a period of twenty years they rose by about 1.8 times and are estimated to around 7 100 000 t Co. It is clear that after a drop in reserves quantity levels to around 3 165 000 tonnes in 2000, they have been maintained at around 7 000 000 tonnes in recent years. According to the classification which is used to determine the rate of depletion of the mining reserves, the cobalt reserves are characterized by a high rate of depletion [29]. Within a twenty-year period, the index of usage of reserves (IUR, %) increased from 0.7% to 1.7 - 1.8%, i.e. more than twice.

Table 5 shows the variation in distribution of the world’s cobalt reserves for 1996 and 2016. For the whole period presented, the largest share of global reserves are concentrated in the DRC and they increased 1.8 times. This period has also seen the appearance of new countries in the distribution of reserves. The reserves in Cuba decreased 2 times, in Zambia 1.3 times, while in Australia, Russia and Canada they increased 4.4, 1.8 and 5.5 times, respectively.

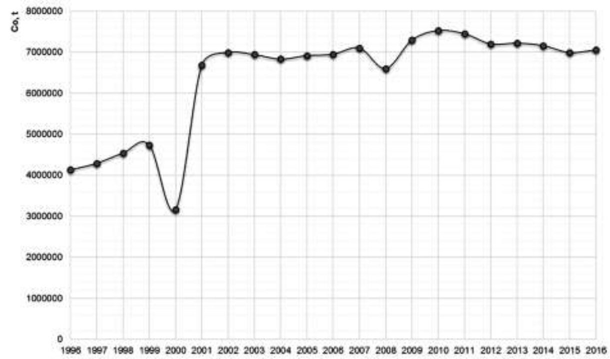

Fig. 1. Global cobalt reserves (Co, t), 1996-2016 г.

Table 5

Distribution and changes of the word’s cobalt reserves for 1996 and 2012

Country	1996	2016	Changes
	Share, %	Share, %	
Kongo (Kinshasa)	48.4	49.6	Increased 1.8 times
Cuba	24.2	7.1	Decreased 2.0 times
Zambia	8.7	3.8	Decreased 1.3 times
Australia	6.5	17.0	Increased 4.4 times
New Caledonia	5.6	-	
Russia	3.4	3.6	Increased 1.8 times
Canada	1.1	3.5	Increased 5.5 times
Philippines	-	4.0	
Madagascar	-	2.1	
Papua New Guinea	-	0.7	
South Africa	-	0.4	
United State	-	0.3	
Other countries	2.1	7.9	Increased 6.2 times
Total	100.0	100.0	

There is a great potential for covering much of the metal needed in the recycling (reuse) of the scrap. For countries like Bulgaria that do not produce cobalt due to the lack of primary raw sources, it is especially important to use the most of all available its waste. A study and analysis has been carried out and they show that there is a stock of waste materials containing cobalt alloys in Bulgaria. They are mainly in the form of used Co-Mo catalysts from the petroleum and chemical industry (over 100 t per year from Lukoil Neftohim Burgas, Neohim Dimitrovgrad, Solvay Sodi Devnya, etc.), scrap from the military industry, wastes from used tools, parts of dentures and implants for medicine and dentistry containing cobalt-chromiummolybdenum alloys, spent solid-alloy plates containing cobalt, together with tungsten carbide and molybdenum - metal scrap from industry, electronic components containing cobalt and cobalt alloys (Co-Mo, Co-W) - waste from the electronics and electrical engineering, etc. The recycling of technogenic materials containing metals by melting into electro arc and electron beam vacuum installations is a considerably more environmentally friendly and economically viable solution (the available resource will not be dissipated) compared to the practice of landfilling waste in landfills.

B. Global cobalt production and consumption

The world‘s cobalt mine production is carried out by various types of deposits. The basic deposits for cobalt production with economic importance are shown in Table 6 [8].

The world production of refined cobalt, depending on the type of ore, the metallurgical methods and processing technologies, the requirements of the market for the products obtained, the protection of the environment is done in the form of metal, oxides, carbonates, hydroxides, sulphates and others compounds.

Table 6

Mine production by type of deposit

Type of deposit	Share, %
Sediment stratiform Cu-Co	60
Magmatic Ni-Cu (-Co-Pt group elements)	23
Ni-Co laterite	15
Other terrestrial	2

The quantitative data for the world mine production, the production of refined cobalt, and its consumption for the period 2006-2016 are presented in Fig. 2 [28, 30].

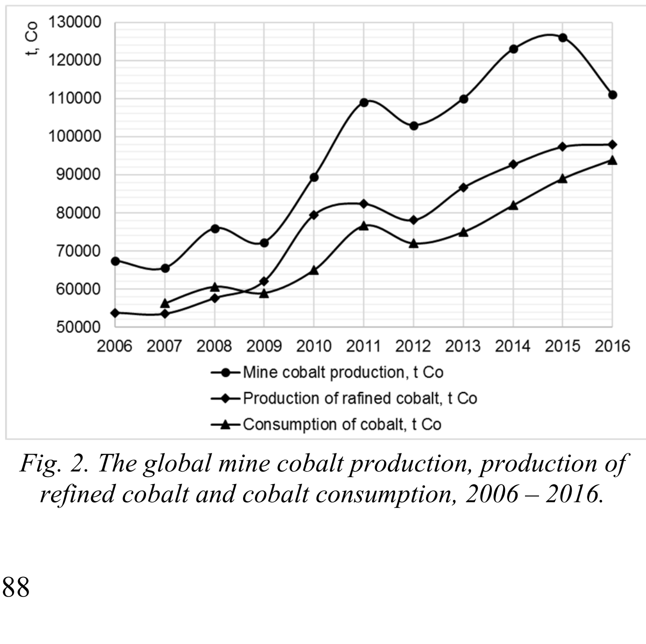

Fig. 2. The global mine cobalt production, production of refined cobalt and cobalt consumption, 2006 – 2016.

Within a period of ten years, mine production has risen 1.6 times, refined cobalt production - 1.8 times, and cobalt consumption - 1.7 times. Table 7 presents the distribution of global cobalt mine production and world refined cobalt production for 2016 [31].

Table 7

Global mine and refined cobalt production (2016)

Mine Production of Co		Refined Co production	
Country	Share, %	Country	Share,%
DRK	54.0	China	46.0
China	8.2	Finland	12.6
Canada	5.4	Canada	6.5
Australia	4.7	Belgium	6.5
Zambia	3.7	Zambia	4.8
New Caledonia	3.4	Japan	4.4
Cuba	3.0	Norway	3.6
Brazil	2.8	Madagascar	3.3
Madagascar	2.6	Australia	3.3
Philippines	2.0	New Caledonia	2.6
Finland	1.8	Russia	2.1
Papua New Guinea	1.7	Morocco	2.1
Russia	1.6	South Africa	1.1
Morocco	1.6	DRC	0.4
Other	3.5	Other	0.7

China is a world leader in the production of refined cobalt and is a major global supplier of cobalt. The production of refined cobalt in the country is mainly from partly refined cobalt imported from Congo (Kinshasa), scrap and, various commodity cobalt products. Over 80% of the global cobalt consumption is distributed in China, USA, Japan, and the EU. China is the world's leading consumer of cobalt, with nearly 80% of the domestic consumption associated with the production of rechargeable batteries [28].

Primary cobalt production

The primary production of cobalt is carried out by several types of ores: Ni-Co sulphides, Cu-Co sulphides, Cu-Co oxides, Ni-Co laterites (oxides) [32] and Co arsenides [33, 34]. Cobalt is extracted and concentrated as by-product after the primary processing of the other basic metals, usually Cu and Ni. Depending on the type cobalt-containing ores/concentrates, they are processed by applying the following processes: leaching, roasting and leaching or smelting and leaching. Leaching is performed at various temperatures and pressures using acids or ammonium, chlorine or nitrate solutions. Purified and refined cobalt is obtained by the application of hydrometallurgical and/or electrometallurgical methods such as chemical precipitation, electrowinning, hydrogen reduction, ion exchange, and solvent extraction [35].

Fig. 3 presents the summarized flowsheet for the processing of cobalt-containing ores/concentrates [36]. Cobalt is usually a by-product in the production of copper and/or nickel. The primary raw material is subjected to leaching by first removing copper from the production solutions. After removing the impurities, the cobalt and finally the nickel are extracted. The cobalt production section is usually fed with an acidic or neutralized cobalt-bearing solution containing impurities and sometimes a significant amount of nickel. Before the cobalt production, some of the following impurity removal processes are used: impurity precipitation with $CaCo_3$ or $Ca(OH)_2$; solvent extraction (SX) for the removal of Cu, Zn, Mn and others impurities as well as for Co-Ni separation; ion exchange (IX) for the removal/polishing of Cu, Zn and Ni. When solvent extraction is applied, reagent combinations of the so-called SSX (synergistic SX) and DSX (synergistic direct SX) are used to rationalize the extraction of Co and Ni from impurity solutions without the need for intermediate precipitation and re-leaching. CSIRO (Australia) have developed synergic systems for various specific applications. For example, in the Boleo project (Baja Mining, Mexico), selective Co-Zn co-extraction with Versatic 10 / LIX63 is going to be used to separate them from Mn. Also, with relatively low pH, the Cyanex® 301 and 302 extragents are used to collectively extract Co and Ni and separate them from the Mg, Mn and Ca impurities. The development in conventional ion-exchange processes (IX) is the so-called Molecular Recognition Technology (MRT) using specially produced SuperLig® resins to remove Fe, Ni, Cu, Cd, Pb and Zn impurities [37]. For the production of copper and nickel, the SX-EW are applied.

Cobalt can be produced in various forms: concentrate, intermediates, metal(s), and salts of high purity. Depending on the processing scheme adopted in the cobalt section, the following final products may be obtained: cobalt sulphide or mixed Ni-Co sulphide precipitate (MSP), low/high grade cobalt hydroxide or mixed Ni-Co hydroxide (MHP), cobalt carbonate, cobalt oxide or oxy-hydroxide, cobalt sulphate, cobalt electrowon cathode HG 99.8% or LG 99.3% and cobalt powder/briquettes via hydrogen reduction.

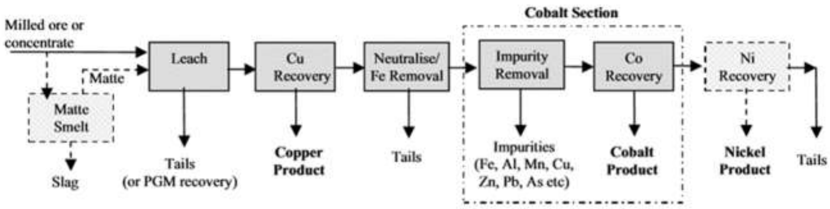

Fig. 3. Generic Cu/Co/Ni recovery flowsheet (Fisher, 2011).

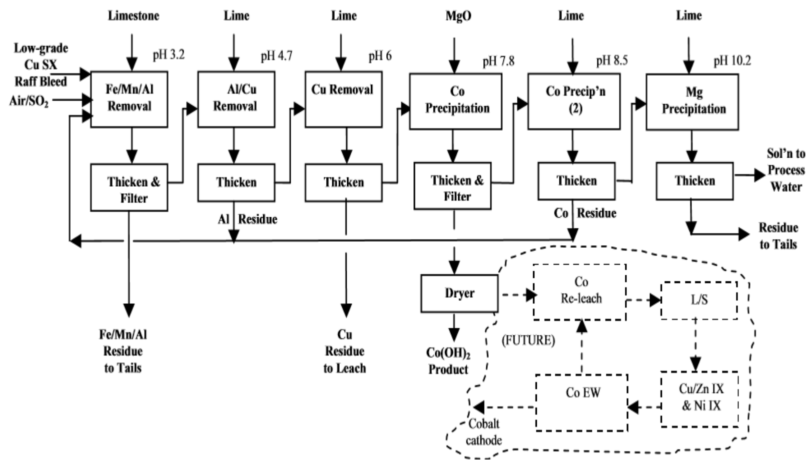

Fig. 4. A typical flowsheet of a cobalt section (Fisher, 2011).

The choice of processing scheme for obtaining a final cobalt product depends on a number of business, technical, technological and other factors. The basic of those are: capital and operating costs, location, logistics, electricity price, availability of qualified personnel, the environment, state policy, etc. Regardless of the choice, the processing schemes are complex, and the management of technological processes is connected with difficulties and risks. As an illustration, Fig. 4 shows a flowsheet of the cobalt production in the DRC [36].

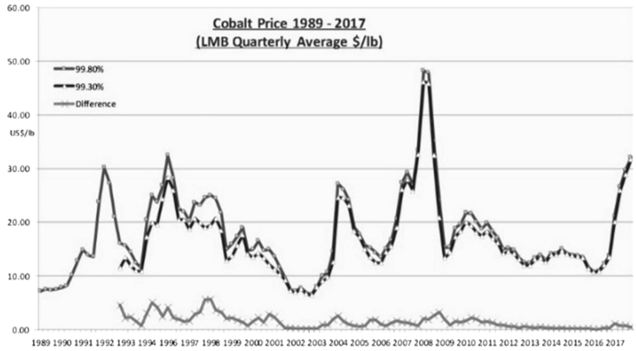

Fig. 5. Cobalt price (1989 – 2017).

Table 8

Chemical composition of cathode cobalt

	Canada INCO	Norway Falcon-bridge	Zambia ZCCM	Japan Sumitomo Metal mining	USA
Co	99.9	99.95	99.65	99.8	99.9
Ni	0.04	0.03	0.35	0.12	0.04
Cu	0.0005	0.0005	0.0015	0.0016	0.0015
Fe	0.0025	0.0010	0.005	0.002	0.004
Al			0.0025		
Bi	0.0001		0.0001		0.0001
Cd			0.0001		
Si			0.0025	0.01	0.001
Mg	0.0004				
Mn	0.04	0.005	0.0005		0.00007
As	0.0001	0.0001	0.0001		0.001
Sn			0.0005		0.001
Pb	0.0014	0.0002	0.001	0.0005	0.0003
Se	0.0001		0.0001	0.0005	0.0005
S	0.0015	0.0002	0.0025	0.0008	0.001
Sb			0.0005		0.0001
C	0.005	0.002	0.008	0.001	0.005
P			0.001	0.001	0.0005
Zn	0.0003	0.0002	0.0001	0.0019	

Worldwide, most enterprises prefer to produce a high-quality cobalt product in the form of hydroxide, carbonate and others. The attractive and relatively high cost of cobalt is a prerequisite for the introduction of electrolytic production in some enterprises by producing high purity cathode metal, despite the complexity and consumption of capitals involved. The price of HG (99.8%) or LG (99.3%) cobalt for a thirty-year period is shown in Fig. 5. The difference in the price of HG and LG cobalt in recent years is not so large, as is seen in Fig. 5.

Most of the world's producers of electrowinning cobalt achieve high-quality metal (HG). Table 8 gives the chemical composition of cathode cobalt [38] produced by leading companies and producer countries.

Methods for obtaining cobalt with high purity and cobalt super alloys

Electrolyte cobalt can be subjected to further treatment to obtain a high-purity metal that is needed to produce the latest generation super alloys.

Due to the exceptional demand and increasing need for high purity cobalt, ways to improve the technologies and equipment are continuously looking for that will ensure increase in the cobalt production and in the level of its extraction from the raw materials, a production losses reduction and the full using of technogenic materials obtained during the whole processing. Good results are obtained by application of only one method or by combining application of different methods of special electrometallurgy such as plasma melting, vacuum induction melting (VIM) and electron beam melting (EBM).

EBM technology is environmentally friendly and no waste products are produced. The method provides high level of impurity refinement (gases, metals, and non-metals impurities), as well as fine microstructure of the obtained ingots, without defects and with uniformly distributed components and with improved characteristics, magnetic and resistance properties. This is a strategic method in R&D and it is used in more applications in the industry in the industrial-developed countries and the research in this area still becomes one of the most important nowadays research [39-45]. The use of the method as a final stage in material processing for obtaining high purity metals would eliminated many intermediate technological processes some of them harmful and dangerous for the nature and for the health. The method provides obtaining metals and alloys processing both natural raw materials and technogenic materials containing these metals or their alloys in the case of lack of such natural raw sources.

At combined application of both technologies VIT and ELT, simultaneous metal refining and casting of the product are carried out [44]. The technology includes three stages in which the following steps are performed: (i) partial melting of the material and starting of the formation of a liquid pool in the crucible by induction heating, (ii) complete melting of the material and forming a liquid pool by electron beam heating the material with a gradual increase of the electron beam power to maximum values and electromagnetic stirring of the molten metal, (iii) homogenizing the liquid pool, alloying if necessary and overheating to a temperature for casting in stationary metal moulds of the required sizes.

The main and most extensive applications of cobalt in different areas of life are mainly through its alloys. Additive manufacturing (AM) is growing faster and the last several years have seen many advances towards realizing its goal for medical and aerospace applications. The efforts of this industry has focused on producing 'higher end' metals including medical grade stainless steels, cobalt-chrome alloys, titanium and titanium alloys [39,40,45]. EBM is one of these industry-leading methods that is a powder based additive metal manufacturing process. With this method, it is possible to manufacture high-density metal parts with complex topology such as orthopaedic devices in several materials, including Co-Cr-Mo alloy. The surface finish is one of the problems concerning this method and some finishing operations are needed to improve the surface quality [43].

Conclusions

A study is conducted, data and information on world experience and trends in global cobalt resource and reserves has been analyzed and summarized, modern technologies and methods for processing cobalt raw materials by obtaining concentrates, intermediates or metal are also presented.

At the current consumption rates and proven quantities, the world has been reliably secured with cobalt for more than 75 years. At the same time, it should not be overlooked that this provision has decreased almost twice (1.7 times, precisely) within a period of just 10 years. Ocean floor deposits are potential great resources for Co. For these resources, ore mining and processing technologies are needed.

Significant technical and technological developments have been achieved in the processing of Cu-Co and Ni-Co ores with which the growing demand for cobalt on a global scale is satisfied. The largest Co sources in the world at present are the Cu-Co ores in the DRC and those will remain such in the near future.

Exceptional demand and increasing need for high purity cobalt require continuous improvement in technologies and equipment. It is seen that the production of cobalt has increased significantly based on the achievements in this area. The applied processing technological schemes are improved in the direction of increasing the level of metal extraction from the natural raw sources, reducing the production losses and the full utilization of the technogenic materials obtained throughout the whole production process.

Various technologies have been developed for the extraction of cobalt from primary raw materials and for processing technogenic materials to various end products, including hydro-, pyrometallurgical and vacuum processes. The technological processing schemes are mainly determined by the choice of the type of the final product, its quality and, last but not least, the requirements for the environmental protection, logistics, and risks.

For obtaining high purity metal the vacuum electrometallurgy technologies - vacuum electro arc and electron beam melting methods are applied as a final step in the production. The electron beam melting method successfully competes and is superior to the conventional methods for metal refining and the produced metals are with very high purity. The use of the method makes it possible to obtain metal with high purity and cobalt alloys and semi-finished products with new or improved chemical composition, structure and properties.

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