Conference Paper

Prospects for the Ferronickel Production Development from the Urals Oxidized Nickel Ores

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Received: 5 February 2019
Accepted: 6 March 2019
Published: 17 March 2019

Publishing services provided by Knowledge E

Selection and Peer-review under the responsibility of the NIOKR-2018 Conference Committee.

Abstract

The analysis of state of processing technologies for oxidized nickel ores, volumes of their extraction and processing, range of obtained products was carried out. Methods of ore processing are divided into hydro- and pyrometallurgical. The last of them are more common. The main product in demand is ferronickel, which is produced by the method of reducing electric smelting of previously calcined ore. The main factors determining the prospects of selected technology are composition and quality of obtained products. Ferronickel of the standard ISO 6501:1988, containing at least 15 % Ni, is in demand on the international market. Processing technologies for poor oxidized nickel ores to ferronickel, which provide solutions to environmental problems, reduce energy consumption, fluxes and increase the recovery of valuable metals, are highly relevant for industry development. The processing technology of serpentinite ores, which includes the following main stages: ore preparation (averaging, crushing and screening, drying); roasting a mixture of dried ore and crushed dolomite (flux) in tubular rotary kilns; melting of hot cinder with the addition of a reducing agent in an ore-smelting direct-current electric furnace to produce a rough ferronickel; refining ferronickel from impurities of carbon, silicon, sulfur, phosphorus, chromium was substantiated. In the course of industrial testing of electric smelting of calcined ores of the Ural deposits, ferronickel, containing (in wt. %) 8.9-15.5 Ni, 1.1 Cr, 0.17 Co, 0.1 S, 0.1 C was produced. Nickel extraction in ferronickel was 96.1 %, cobalt – 89.1 %.

Keywords: ore, nickel, production, heating, roasting and reduction, phase transitions

1. Introduction

According to the US Geological Survey data, the world nickel resources comprise more than 130 million tons, ~ 60% of which are concentrated in oxidized and 40% in sulfide ores. Nickel ores are mined in 20 countries, and metallurgical facilities for the production of this metal are available in 25 countries. The largest producers of nickel [1] are China (742 thousand tons), Russia (234 thousand tons), Japan (178 thousand tons), Australia (139 thousand tons) and Canada (132 thousand tons). China increased its production at an

How to cite this article: Selivanov E.N. and Sergeeva S.V., (2019), “Prospects for the Ferronickel Production Development from the Urals Oxidized Nickel Ores” in *Theoretical and practical conference with international participation and School for young scientists «FERROALLOYS: Development prospects of metallurgy and machine building based on completed Research and Development»*, KnE Materials Science, pages 77–91. DOI 10.18502/kms.v5i1.3954

accelerated pace: 1994 - 30 thousand tons, 2004 - 75 and 2015 - 550 thousand tons, out of them 390 thousand tons - Nickel Pig Iron and 150 thousand tons - cathode nickel. As of 2015, Valo Inco Ltd. is one of the five most important nickel producers. (291 thousand tons), MMC "Norilsk Nickel" (266 thousand tons), Junchuan Group Co. Ltd (150 thousand tons) [2]. In 2017, the volume of nickel production at MMC Norilsk Nickel was reduced to 217 thousand tons, which is due to the diversification of production. In general, China (38.1%) is a leader in melting of nickel and nickel products that are measured in terms of nickel. It climbed to the first place in 2010, increasing nickel production tenfold. Russia is in second place (12%).

The scale of nickel production (Table 1) is characterized by constant growth. For the years 2001 - 2011 the annual increase amounted to 3.1%, for 2011–2015 - 5.1%. In recent years, the production volume has been stabilized at about 2 million tons. The price of nickel fluctuates [3] within very wide limits on an annual basis from 10.7 to 17.5, and monthly - 8.5 (February 2003) - $ 52 thousand dollars/t (May 2007). Price changes are influenced by both economic and political factors.

Table 1: Nickel production and metal prices.

Year	2010	2011	2012	2013	2014	2015	2016	2017
Mass, million tons	1.442	1.602	1.74	1.852	1.98	2.005	1.995	2.052
Price, USD/kg	21.92	23.12	17.54	15	16.9	11.8	10.69	12.24

Price changes are influenced by both economic and political factors. Among the economic ones, the balance of production and consumption (stocks or shortages in the metal market), the phases of economic growth and crisis, the fall in domestic demand, for example, during the disintegration for the alliance of the Eastern Bloc countries in the 1990s should be noted. Political bans include the export and import of ores, metals, and equipment. For instance, the introduction of quotas for the ores export in Indonesia (Table 2), in 2014 contributed to a slight increase in metal prices. The price of nickel in the first half of 2017 had high volatility [4]. Initial expectations for the closure of almost half of the nickel mines in the Philippines as part of the 2016 environmental audit led to an increase in metal prices in February above $ 11,000/ton. After a weakening of the embargo on the export of raw ores from Indonesia and with weak demand for the metal in China for the production of stainless steel, in the second quarter, the price of nickel dropped to $ 8,800 per ton in June of this year. At the same time, the average price of LME in the first half of 2017 amounted to US $ 9761 per ton, which is 10% higher than the same period of the last year.

TABLE 2: Nickel ore mining by the largest exporters, mln. tons.

Year	2012	2013	2014	2016	2017	2018
Indonesia	622	811	146	173	[262]*)	[340]
Philippines	318	316	411	311	[333]	[360]
Note: *) – hereafter, predicted values are given in parentheses.						

The main areas of primary nickel consumption are the production of [5]: stainless steel (73.0%), alloys (8.1%), special steels (7.2%), electroplating (6.9%), batteries (5.1%) and others (1.0%). The main end consumers by industry: machines and mechanisms (24.6%), transport (21.6%), electrical machines and mechanisms (13.9%), metal goods (15.3%), construction industry (10.3%), chemicals (4.9%) and other (9.4%). The main consumer countries (in 2017) are China (55% of world demand), other Asia (20%), Europe and Africa (17%), America (8%). Due to the characteristics of the properties, nickel is used in more than 300 thousand products, in the military sphere, transport, shipbuilding, construction, space equipment, etc. Nickel consumption in the battery industry is growing at a high rate, primarily due to an increase in the output of electric and hybrid cars by 38%, as well as the introduction of more nickel-capacitive technological solutions for the production of cathode material for batteries. Top 5 world leaders in the nickel market, billion dollars [6]:

Country	2016 y.	2017 y.
Canada	3110.6	2843.7
Russia	2018.8	2058.3
USA	1881.8	2006.5
Great Britain	1085.6	1207
Germany	958.4	1202.2

The main amount of nickel goes to the production of stainless steel. This steel is produced in a wide range of compositions (200, 300 and 400 series) by AISI. By 2016, stainless steel smelting had risen to 44.5 million tons, 1.4 million tons of primary nickel were used for its production. Over 75% of stainless steel is austenitic 300 series with 8-20% Ni and the 200th series with lower nickel content, where it is replaced by manganese. The increased share of nickel in steel enhances its corrosion resistance and strength in a wide temperature range, provides ductility and stability in aggressive environments, changes magnetic properties. The transition to the 200 series reduces these characteristics somewhat - surficial pitting corrosion appears on the steel, it has less heat resistance and resistance in aggressive environments. However, the lower cost of such a metal determines the use in household appliances. About 90% of the production of steel series 200 is concentrated in China and India, in countries specializing in the production of consumer goods.

Stainless austenitic-ferritic steel, in addition to nickel, contains 18–25% Cr, 1–4 Mo, its production is 1–2%, at the statistics data it is combined with the 300 series. Ferritic and martensitic grades of stainless steel (400 series) are mostly nickel free, similar to low carbon steel with increased corrosion resistance, used for household appliances (dishes, razor blades, washing machine drums, etc.). In Europe, the production of stainless steel will increase by 2%, thanks to the participation in the EU anti-dumping measures, against Chinese cold-rolled coils [7]. In the United States, there is an expansion (3%) of stainless steel consumption in construction and consumer electronic equipment. In India, a 7% increase in stainless steel production is due to government efforts to improve the country's infrastructure. Similar events are held in the Philippines. The produced primary nickel is divided into two groups: high-grade (cathodes, briquettes, carbonyl, compounds) and low-grade (ferronickel, rough ferronickel, and nickel oxide). Production [1] of the first in the years 2015/2016 is - 1.108/1.040, the second - 0.897/0.95 million tons. Production of rough ferronickel or NPI (Nickel Pig Iron) is concentrated in China and Indonesia, its output amounts to, thousand.t:

Years	2013	2014	2015	2016	2017
China	508	489	386	366	388
Indonesia	-	-	29	87	173

Based on the fact that China is the world leader in steel production and seeks to improve product quality, it seems natural to continuously increase the production of stainless steel, in million tons:

2007	2008	2009	2012	2013	2014	2015	2016	2017	2018
1.4	1.4	1.3	16.1	19	21.7	21.6	24.9	25.5	[29,3]

According to experts, 4.4 to 4.6 million tons of nickel-containing waste, or 350 thousand tons in terms of nickel, are collected and processed annually. Most of the waste is a dormant scrap from stainless steel. Nickel extracted from scrap is reused to produce stainless steels. In 2017, total stainless steel production increased by 6% to a record 48 million tons.

The ferronickel and ferronickel chromium market is determined by the volumes of domestic production and export [8]. Domestic production of ferronickel and ferronickel chromium according to the Discovery Research Group in Russia in physical terms in 2017 amounted to 69884 tons, which is 9.9% lower than in 2016. The leading producers of ferronickel and ferronickel chromium in physical terms in Russia in 2017 were: Svetlinsky Ferronickel Plant (formerly the Buruktal'sky Nickel Plant), Serov Plant of Small Metallurgy, Interprom, etc.

The leaders among the producers of ferronickel, imported in Russia, are the producers of Kazakhstan and ZTS - KABEL. The export of ferronickel and ferronickel chromium from Russia in 2017 amounted to $ 243.3 thousand, which is 26% less than the previous year. In the export volume of ferronickel and ferronickel chromium from Russia, export of ferronickel chromium prevails (94.8%). In 2017, the leading exporter was the Svetlinsky ferronickel plant, with a share of 57.7% of the total exports of ferronickel chromium, Serov Plant of Small Metallurgy (17.4%) and Interprom (5.5%). Among the producers of ferronickel, exported from Russia, NPK " FerroSpetsSplavy " became the leader in physical terms in 2017, with a share in the export volume of 85.4%.

2. Results and Discussion

The methods of oxidized nickel ores processing, from which the major share of ferronickel is produced, can be divided into hydro- and pyrometallurgical. Oxidized nickel ores are processed mainly by pyrometallurgical methods. Almost the entire world volume of ferronickel is produced by the method of reducing electric smelting for preliminarily calcined ore [9–11]. The process does not require agglomeration of the charge; it is applicable for ores with different contents of refractory slag-forming oxides, it allows to obtain high-quality refined metal. Ferronickel is smelted in ore-smelting alternating current (AC) electric furnaces with a capacity of 20–100 MVA with graphitized electrodes and a power consumption of 800–850 kWh per ton of dry ore and specific melt of 3.5–14 t/m^2 per day [12, 13]. The profitability of ferronickel production is primarily determined by the nickel content in the ore. Improvement of the technology is carried out in the directions of increasing the size of electric furnaces, increasing their power and turnaround time, switching to a direct current. Attention is paid to the averaging of ores and the mechanical benefication due to the screening of the nickel-poor large classes of ore. Modern concepts of ore processing technology involve the use of pyrometallurgical processes that ensure the production of ferronickel of the required quality, the processing of slags to crushed stone, sand or additives in cement production, as well as the utilization of slag heat and gas to minimize energy consumption [14, 15].

The following pyrometallurgical methods are currently used to process nickel oxide ores: blast reduction - sulfidation matte smelting (Russia), blast-furnace smelting to Nickel Pig Iron (China), electric smelting to ferronickel (China, Japan, Canada, Ukraine, Macedonia, New Caledonia, Philippines, Greece, etc.), electric smelting to matte (Indonesia) (Figure 1). Oxidized nickel ores have features that affect the choice of technology, preparation for smelting and subsequent processing of intermediates [16].

Pyrometallurgical processing of oxidized nickel ores is essentially the smelting to slag, regardless of the chosen method, since their number reaches 75–110% of the mass of raw material loaded into the metallurgical aggregate, while the mass of the collector phase (matte, ferronickel) is only 3 - 10%. The results of ore processing depend both on the metallurgical properties of the slag - its melting point, viscosity, basicity, chemical composition, and the characteristics of the metallurgical unit - thermal efficiency, design, specific power (kW/m^2), as well as efficient use of smelting products. Ural plants (Rezhnikel, Ufaleynickel, Yuzhuralnikel) processed ores according to blast smelting technology for matte with further converting, calcination of the nis material and smelting of nickel oxide to metal of the N-3 grade. The technology is associated with high coke consumption, low nickel content in the original ore and emissions of large amounts of sulfurous anhydride into the atmosphere. Therefore, at present, all the plants, operating on this technology, have been shut down.

The processing of ores by the bloomery process was previously performed at the plants in Frankenstein (Germany), Larimna (Greece), Shklyary (Poland), Nana, Itavaki (Japan), and others. At the Orsk-Khalilovsky Metallurgical Combine, a pilot production unit was installed at which were carried out tests on the processing of ores from a number of deposits. Unfortunately, the work of the bloomery process ovens required fairly precise control of the charge composition for slag-forming oxides and was accompanied by the formation of the scaffold, the fight against which is very difficult.

The processing technology of oxidized nickel ores in a Vanukov furnace (VF) has been developed for a bubbling unit widely used for smelting of sulfide materials. Repeatedly conducted tests on the smelting of oxidized nickel ores on matte in the Vanyukov furnace at JSC Yuzhuralnickel. Tests on the ore smelting at the Buruktalsky deposit were conducted with the supply of natural gas, smelting of the charge during the tests reached 40 t/m^2 per day, during the beneficiation of the blast with oxygen it reached up to 96%. In the reduction zone, natural gas was burned with an excess of oxidizer equal to 0.7, while the beneficiation of the blast with oxygen up to 60%. In this mode, matte is obtained with 30% of nickel and 0.15% of cobalt. At the same time, energy consumption remained at the level of blast smelting, due to the high temperature of the exhaust gases.

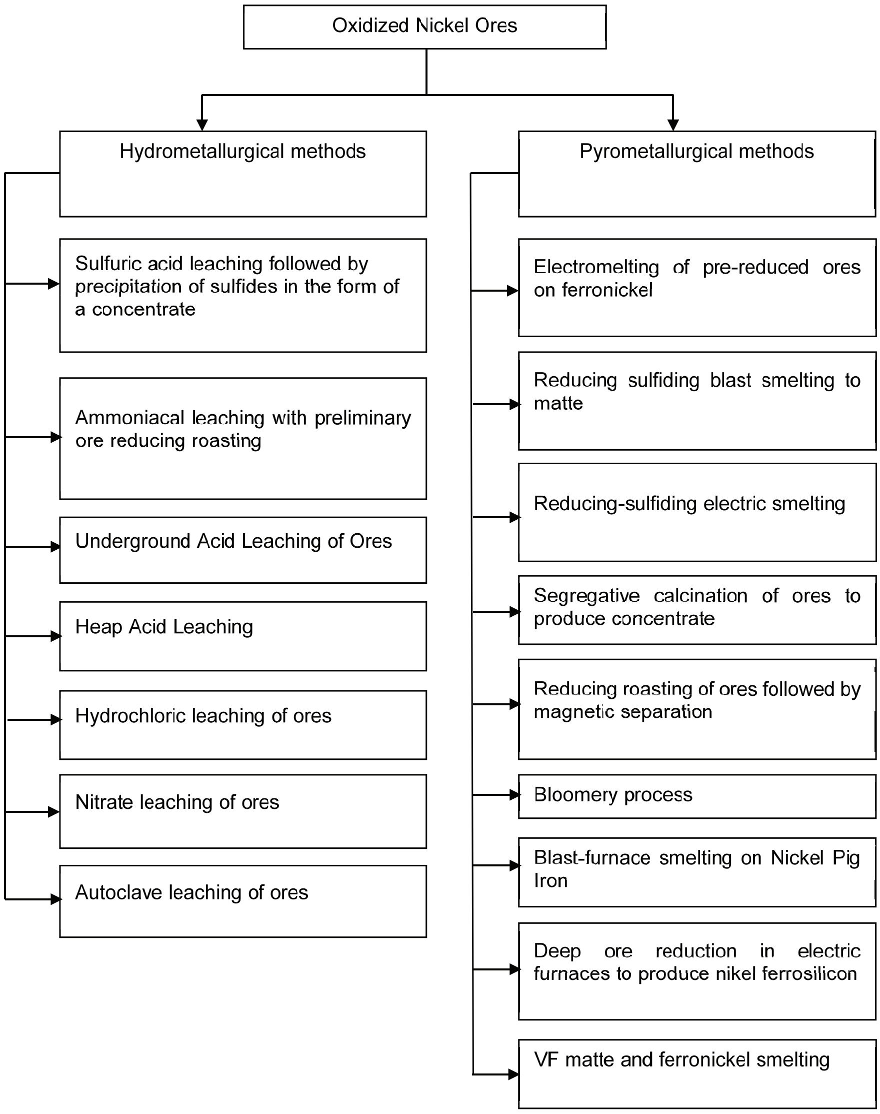

Figure 1: Basic technologies for the processing of oxidized nickel ores.

Currently, there are 8 plants in the nickel industry that use hydrometallurgical methods to extract nickel. In connection with the stricter regulations towards reducing emissions of industrial enterprises and the degree of environmental pollution, as well as the need to increase labor productivity, reduce energy intensity of production, prospects for the further development of hydrometallurgical processes are opening up. The use of solvent extraction for the processing of oxide ores ensures the extraction of both nickel and cobalt into independent types of commercial products. Before the ammonia-carbonate leaching, the ore is roasted with a reducing agent. The ability of ammonia solutions to form soluble nickel complex compounds, their low aggressiveness and ease of ammonia regeneration ensured the spread of the method. Most of the impurities (iron, aluminum, manganese, and others) remain in the insoluble residue.

The process of autoclave sulfuric acid leaching is based on the reaction of goethite recrystallization $2FeOOH \rightarrow Fe_2O_3 + H_2O$, which at a noticeable rate (even at a temperature of 270 ° C) proceeds only when free acid is present, which indicates its staging. Nickel oxides, as well as other oxide compounds of metals (cobalt, magnesium, aluminum, etc.) interact with sulfuric acid. The conditions (temperature, pressure, oxygen and sulfuric acid consumption) were determined for various types of ores, ensuring high recovery of nickel and cobalt in the solution. During sulfuric acid leaching, the transition to a solution of iron and aluminum is minimized by carrying out the process at temperatures above 220 ° C.

Mechanical benefication methods for oxidized nickel ores are inefficient since it is difficult to concentrate a metal that practically does not form separate grains of its own minerals. Therefore, for the processing of oxidized nickel ores from the Urals deposits, it is recommended a pyrochemical benefication scheme by segregation roasting followed by concentration of reduced metals (Ni, Co) by flotation or magnetic separation of roasted product.

For the ores benefication, it was proposed to use selective crushing and milling, taking into account one of the features for the ores - nickel localization mainly in soft magnesian silicates and its low content in vein and enclosing rocks. The practice of flotation for nickel sulfide raw materials is evidence of the mechanical benefication of high-Mg ores. As is known, during the benefication of non-ferrous metal sulfide ores, magnesium-containing silicates are easily floated together with sulfides, reducing the quality of the concentrates. The undesirable process is suppressed by the introduction of depressants or by preliminary flotation with one blowing agent. It is noticed that iron-free oxidized minerals float much better. Solving the problem of reducing energy consumption and the use of cheap types of energy sources is possible by carrying out the stage of pyrometallurgical benefication of ores by their reductive roasting and magnetic separation of the roasted product followed by melting of the enriched product into ferronickel.

If in 2009, nickel production in ferronickel was 23% of its total world output and 67.5% from the volume of nickel oxide ore processing, now, due to the development of Chinese enterprises, 40% and 80%, respectively. It should be noted that melting on ferronickel requires a high consumption of reducing agent and electricity and does not provide the extraction of cobalt into an independent product. Therefore, hydrometallurgical and mixed pyro-hydrometallurgical processes are promising for the processing of nickel oxide ores in a number of deposits, which ensure the extraction of not only nickel but also other valuable components of the raw material, such as cobalt, iron and magnesium oxide.

In pyrometallurgical technologies, heating of the entire mass of ore to melting temperatures is required, which is associated with one-time high energy costs. However, in hydrometallurgical technologies, it is necessary to heat, albeit to lower temperatures, and not only ore but also solutions (Liquid: Solid = 4: 1), which makes the energy costs on technological processes comparable. The local conditions related to the cost of energy, labor, infrastructure, as well as the payment of railway tariffs, fines for environmental pollution, etc., have a great importance on the efficiency of enterprises.

An important factor of the technology prospects is the quality of the products. According to literary data, the marketable product of most nickel plants is ferronickel, containing at least 15% Ni. In the international market, the composition of ferronickel must comply with ISO 6501: 1988. The standard provides 5 grades of ferroalloy with 20, 30, 40, 50 and 70% of nickel divided into 5 groups (Table 3). When using the well-known pyrometallurgical technologies for processing the poor Urals oxidized nickel ores, then the possibility of achieving the presented compositions is very problematic.

Table 3: Ferronickel compositions in groups according to ISO 6501: 1988.

Ferronickel grade	Content in ferronickel, % wt.						
	C		Si	P	S	Cu	Cr
	More than	Up to	Less than	Less than	Less than	Less than	Less than
LC – low carbon	-	0.03	0.2	0.03	0.03	0.2	0.1
LCLP – low carbon, low phosphorous	-	0.03	0.2	0.02	0.03	0.2	0.1
MC – medium carbon	0.03	1	1	0.03	0.1	0.2	0.5
MCLP - medium carbon, low phosphorous	0.03	1	1	0.02	0.1	0.2	0.5
HC – high carbon	1	2.5	4	0.03	0.4	0.2	2

Thus, we can conclude that the processing of poor oxidized nickel ores into ferronickel with a demanded nickel content (10–20%) is highly relevant for Ural enterprises, since it solves environmental problems, reduces energy consumption (by reducing the amount of coke), fluxes and increases the extraction of valuable metals.

It is advisable to consider as one of the options for the reconstruction of the Ural enterprises a scheme (Figure 2), including pyro- and hydrometallurgical processing, in which:

- the volume of ore, processed by the hydrometallurgical method, should not exceed the volume of associated products demanded by the market (SiO_2, MgO, FeO_x);
- pyrometallurgical processing should ensure the winning of ferroalloy with a nickel content of 10 - 20% - as the minimum required for the wide marketing of products for the production of stainless steel.

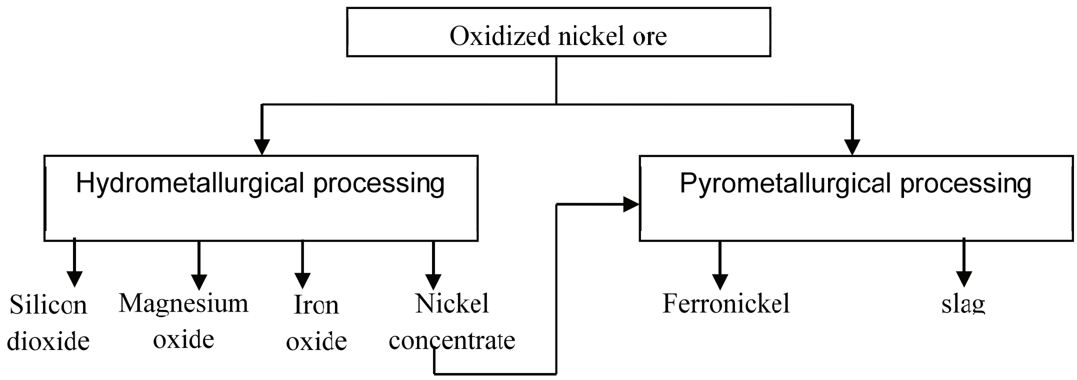

Figure 2: Processing scheme of oxidized nickel ores.

It should be noted that the choice of the technological scheme for ore processing is influenced not only by the nickel content in the ore but also by the ratios Ni/Fe, Ni/Co, Ni/Cu, as well as the concentration of impurity elements (P, S, As, etc.). The first of these parameters determine the nickel content in the resulting ferroalloy. It is advisable to process ores with a high content of Cu and Co, the presence of which in ferronickel is undesirable, according to "sulfide" technology, including the formation of matte (nis material). Currently, only by the method of matte and nis material processing copper and cobalt can be separated in economically viable ways. In addition, Cu and Co can be isolated as a separate product.

Oxidized nickel ores from the Ural deposits are represented by clinochlore, talc, lizardite, palygorskite, sepiolite, clintonite, annite, saponite, smectite, vermiculite, glauconite, thomsonite, quartz, dolomite, nickel hexahydride, and others. Goethite and serpentines, in which up to 90% nickel is concentrated are the main ones out of listed above. The difference in the structure of the ores of Serovskiy, Buruktalskoye, Kulikovskiy, Sakharinskiy and other deposits of the Urals consists mainly in the ratio of these two groups of minerals, differing by the contrast of thermal properties in the reducing environment.

During the evaluation of the ores thermal properties in a reduction environment (CO - Ar), the initial course of the processes, characteristic for heating in an inert (Ar) environment, was established [17]. If in an inert environment the reactions, which are coupled with a change in the mass of the sample, are completed at about 800 ° C, in a reducing environment, mass loss occurs over the entire studied temperature range (up to 1250 ° C). This is due to the initial development of the reduction reactions for iron and nickel oxides:

$$NiFe_2O_4 + CO \rightarrow Ni + Fe_2O_3 + CO_2, \quad (1)$$

$$Fe_2O_3 + CO \rightarrow 2Fe_3O_4 + CO_2, \quad (2)$$

$$Fe_3O_4 + CO \rightarrow 3FeO + CO_2, \quad (3)$$

$$FeO + CO \rightarrow Fe + CO_2, \quad (4)$$

$$Fe_3O_4 + 4CO \rightarrow 3Fe + 4CO_2. \quad (5)$$

The reduction of nickel and iron from magnesium silicates occurs in the region of elevated temperatures:

$$\begin{aligned}(Mg_{1-x-y}Fe_xNi_y)_2SiO_3 + 2(x+y)CO \rightarrow\ & 2xFe + 2yNi + 2(x+y)SiO_2 \\ & + Mg_{2-2x-2y}Si_{1-2x-2y}O_{4-2x-2y} \\ & + 2(x+y)CO_2,\end{aligned} \quad (6)$$

$$(Mg_{1-x-y}Fe_xNi_y)SiO_3 + (x+y)CO \rightarrow xFe+yNi + (x+y)SiO_2 + (1\text{-}x\text{-}y)MgSiO_3 + xCO_2, \quad (7)$$

$$Ni_xFe_{2-x}O_3 + 3C(CO) \rightarrow Ni_xFe_{2-x} + 3C(CO_2), \quad (8)$$

$$(Mg_{1-x-y}Fe_xNi_y)_2SiO_4 + C(CO) \xrightarrow{\geq 1200} 2yNi + 2xFe + Mg_{2-2x-2y}SiO_4 + C(CO_2). \quad (9)$$

Iron and nickel formed at elevated temperatures have unlimited mutual solubility, the composition of the Fe – Ni alloy (ferronickel) depends on the Ni/Fe ratios in the ore and the proportion of metals reduced from oxides.

Since the product must be a 20% ferronickel, produced in accordance with ISO 6501: 1988, electric smelting in a DC (direct current) furnace was proposed as the main process. Technological scheme (Figure 3) of ore processing from one of the Urals deposits includes the following main stages [18]:

- preparation of ore (ore blending, ore breaking and screen separation, drying);
- roasting of a mixture of dried ore and crushed dolomite in tubular rotary kilns;

- melting of a hot roasted product with the addition of a reducing agent in an ore-smelting direct-current electric furnace to produce a rough ferronickel;
- refining of rough ferronickel from impurities of carbon, silicon, sulfur, phosphorus, chromium.

Factors that ensure the growth for the nickel extraction degree, the composition of ferronickel and increase of the electric furnace performance are the preparation of the mixture for the required chemical and granulometric compositions, regulation of the carbon proportion in the mixture and the temperature regime at the processing stages. The optimal chemical composition of the mixture is achieved by mixing raw materials, repetition and main materials. As a melting unit for the processing of the hot roasted product and the reducing agent, a closed ore-smelting DC electric furnace is proposed. The fuel elements in an electric furnace are open electric arcs formed between dual upper graphite electrodes (cathode) and melts of slag and ferronickel. Supply of electricity to the slag and ferronickel (anode) can be carried out through the hearth bottom metal sectional electrode passing through the lining of the furnace bottom. Supply of the hot roasted product and the reducing agent is made by feeding units into the space between the cathode electrodes. Under the influence of plasma heat with a temperature above 4000, a roasted product is continuously melted and recovered on the surface of the melt. In an electric furnace bath, the smelting products are separated by density, forming layers of slag and metal melts. When the solid charge is heated in an electric arc and on the surface of the slag melt, the processes of reduction and slag formation proceed. The selected melting technological parameters are: the gas temperature under the roof is 1000–1100 ° C, the vacuum is 0.5–1.5 Pa. Liquid smelting products (slag and metal melt) as they accumulate are removed from the furnace bath, respectively, through the tap-hole and blast hole. Slag of electric smelting was proposed to be subjected to water granulation. Dust and process gases are sent to the recuperator, then to the cyclone cell system, electrostatic precipitator and used for heating of the drum dryers. Heated air in the recuperator is also used to dry the ore.

3. Conclusions

In the course of the study, new data on the structure of ores from the Ural deposits were obtained. The main phase components of nickel ores are serpentines, talc, clinochlore, and silicon dioxide. Nickel is concentrated mainly in serpentines, while in talc its content is significantly lower. Aqueous magnesium silicates (talc, antigorite), when heated to 600-700 ° C, decompose into anhydrous forsterite and enstatite. During the

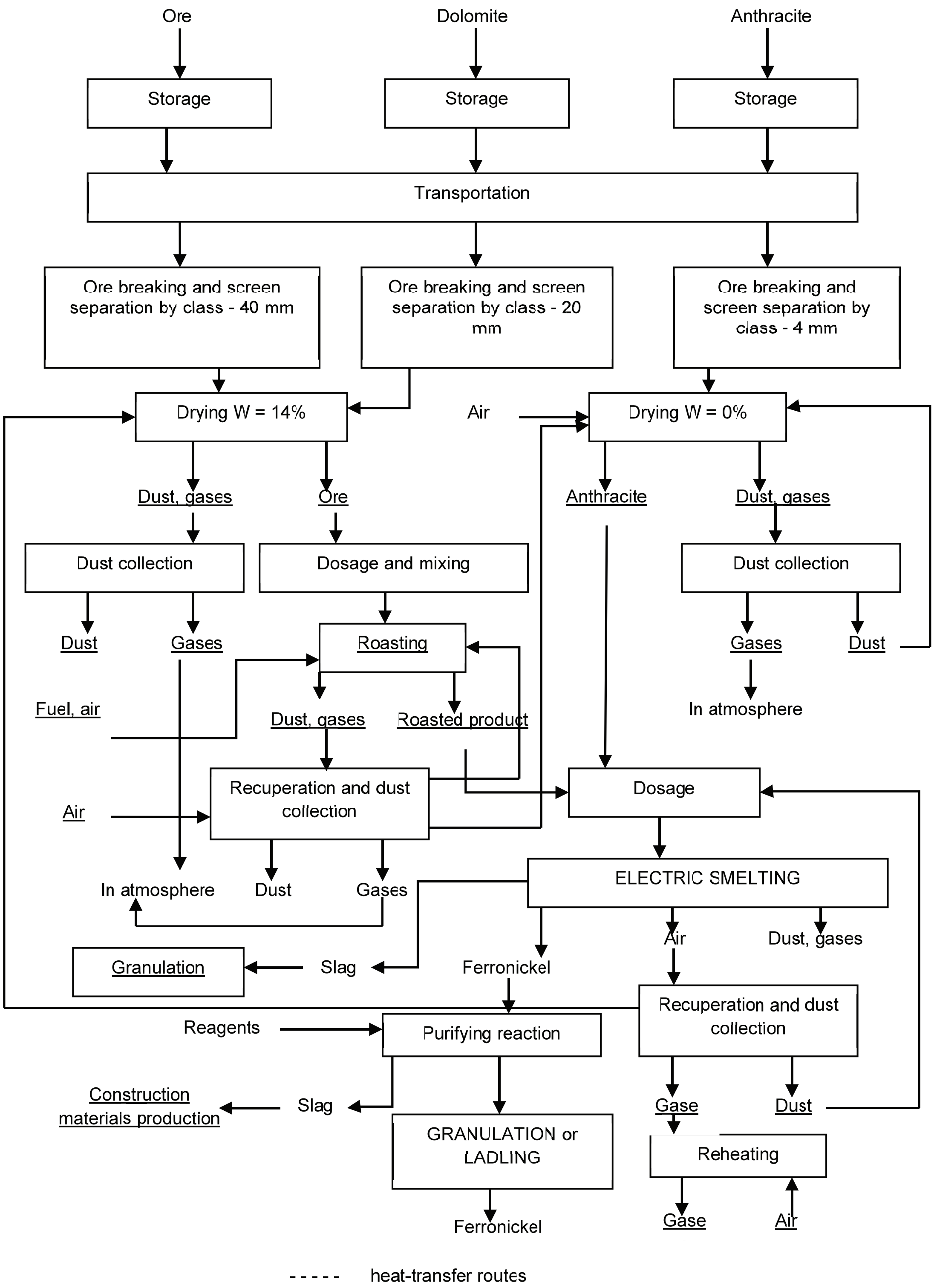

Figure 3: Technological scheme of processing for oxidized nickel ore [18].

heat treatment of ores, in addition to the decomposition of hydrates and carbonates, the formation of magnesium silicates, stable at elevated temperatures, occurs. The thermal properties and phase transformations of ores are determined when heated in a reducing environment. Heating the ore with a reducing agent above 1200°C leads to the formation of ferronickel.

In the course of industrial testing of electric smelting for calcined oxidized nickel ores (Serovskoe and Kulikovskoye deposits), obtained ferronickel with a content of 8.9% Ni, 1.16% Cr, 0.17% Co, 0.1% S, 0.067% P, and also 15.5% Ni, 0.17% Co, 0.1% S, 0.067% P, 1.09% Cr, 0.1% C. Melting of the ore from the Kulikovskoe deposit is possible in a flux-free mode, which improves melting rates. Nickel extraction to ferronickel is 96.1%, cobalt - 89.1%.

This work was performed according to the State task of the IMET UB RAS within the Program of fundamental research for state academies.

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