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Shevchenko D.V., Ovcharuk A.M., Nadtochii A.A., Prikhodko S.V., Shutov V.Yu.

Research on the properties of ferronickel production slags and development of technological schemes for their enrichment

Шевченко Д.В., Овчарук А.М., Надточій А.А., Пріходько С.В., Шутов В.Ю.

Дослідження властивостей шлаків феронікелевого виробництва та розробка технологічних схем їх збагачення

Abstract. Objective. *Determination of the physicochemical properties of slags, phase composition, and forms of nickel presence in them, development of enrichment modes and equipment parameters.* ***Research Methods and Equipment.*** *X-ray spectral microanalysis (RSMA) on the SELMI REM-106I installation was used to determine the distribution of nickel between the metallic and oxide phases in the presented slag samples. Dry and wet gravity and magnetic separation using modernized magnetic separators established the possibility of slag enrichment and the distribution of nickel between the enrichment products.* ***Research Results.*** *This work has conducted research on the gravitational-magnetic separation of electro-furnace and refining slags of ferronickel production in the conditions of the Pobuzhsky ferronickel plant. The efficiency of implementing the developed technological schemes in production was shown, providing additional extraction in the amount of 119 tons or 9.8% of the total annual nickel production at the plant. Slag samples were ground in experimental ball mills to fractions of –0.16; 0.16÷1.6 and +1.6 mm and subjected to enrichment by gravity and magnetic separators with a magnetic induction on the drum surface of 0.3-0.6 T (Tesla) of the MBS-300 and MS-500 types with a total metal phase yield of up to 30%.* ***Scientific Novelty.*** *RSMA established that nickel, both in electric furnace granulated slags and in refining slags, is in the metallic phase and is represented by metal nuggets in combination with iron of various shapes and sizes. Enrichment of electric furnace and refining slags by a combined method using a high-intensity magnetic field will allow obtaining a metal concentrate containing 0.9-38% nickel. The combined enrichment method using high-intensity magnetic separators is one of the most promising for enriching both primary mineral raw materials and secondary materials of ferrous and non-ferrous metal production.* ***Practical Significance.*** *The developed and proposed for implementation technological schemes for enrichment of electric furnace slags using the “wet” technology and refining slags using the “dry” technology allow for the utilization of about 1200 tons of nickel per year or the extraction of 31.6% and 94.65% of nickel from slags, respectively.*
Keywords: *nickel, electric furnace and refining slags, X-ray spectral microanalysis, gravity and magnetic separators, enrichment, metal concentrate, extraction.*

Анотація. Мета. *Визначення фізико-хімічних властивостей шлаків, фазового складу та форм присутності в них нікелю, розробка режимів збагачення та параметрів обладнання.* ***Методи та обладнання дослідження.*** *Для визначення розподілу нікелю між металевою та оксидною фазами в представлених зразках шлаку використовувався рентгеноспектральний мікроаналіз (RSMA) на установці SELMI REM-106I. Суха та мокра гравітаційна і магнітна сепарація з використанням модернізованих магнітних сепараторів встановила можливість збагачення шлаку та розподіл нікелю між продуктами збагачення.* ***Результати дослідження.*** *У цій роботі проведено дослідження гравітаційно-магнітної сепарації електропечних та рафінувальних шлаків феронікелевого виробництва в умовах Побузького феронікелевого заводу. Показана ефективність впровадження розроблених технологічних схем у виробництво, що забезпечує додаткове вилучення у кількості 119 тон або 9,8% від загального річного виробництва нікелю на заводі. Зразки шлаку подрібнювалися в експериментальних кульових млинах до фракцій –0,16; 0,16÷1,6 та +1.6 мм і піддавалися збагаченню гравітаційними та магнітними сепараторами з магнітною індукцією на поверхні барабана 0,3-0,6 Т (Тесла) типів МБС-300 та МС-500 із загальним виходом металевої фази до 30%.* ***Наукова новизна.*** *RSMA встановлено, що нікель, як у електропечних гранульованих шлаках, так і в рафінувальних шлаках, знаходиться в металевій фазі і представлений металевими самородками в поєднанні із залізом різної форми та розміру. Збагачення електропічних та рафінувальних шлаків комбінованим методом із застосуванням високоінтенсивного магнітного поля дозволить отримувати металевий концентрат, що містить 0.9-38% нікелю. Комбінований метод збагачення із застосуванням високоінтенсивних магнітних сепараторів є одним з найперспективніших для збагачення як первинної мінеральної сировини, так і вторинних матеріалів виробництва чорних та кольорових металів.* ***Практичне значення.*** *Розроблені та запропоновані до впровадження технологічні схеми збагачення електропечних шлаків за "мокрою" технологією та рафінувальних шлаків за "сухою" технологією дозволяють утилізувати близько 1200 тон нікелю на рік або вилучати 31,6% та 94,65% нікелю зі шлаків відповідно.*
Ключові слова: *нікель, електропічні та рафінувальні шлаки, рентгеноспектральний мікроаналіз, гравітаційні та магнітні сепаратори, збагачення, металевий концентрат, вилучення.*

© Shevchenko D.V. – Postgraduate student, Ukrainian State University of Science and Technologies;
Ovcharuk A.M., Doctor of Technical Sciences, Professor, Ukrainian State University of Science and Technologies;
Nadtochii A.A., candidate of technical sciences, associate, Ukrainian State University of Science and Technologies;
Prikhodko S.V., Postgraduate student, Ukrainian State University of Science and Technologies;
Shutov V.Yu. – Candidate of Technical Sciences, Associate professor, Dnipro University of Technology.

Introduction. At the current stage of global industrial production development, special attention is paid to the issues of comprehensive rational use of mineral resources, utilization of secondary material and energy resources, and environmental protection. The production of ferronickel from oxidized nickel ores by the electric thermal method is one of the most material- and energy-intensive processes, due to the low content of the main element - nickel, whose concentration in ores from various deposits is only 1-2.5% [1,2].

With such a nickel content in the raw material, the slag ratio ranges from 6-10 and determines various specific energy consumption values per ton of calcine and finished product, which amounts to 30-55 thousand kWh/ton of nickel, despite the fact that it is an easily reducible element [3]. Therefore, the utilization of the metallic phase of ferronickel allows for the reduction of energy and material costs. The main amount of metal granules is concentrated in both refining and electric furnace slags. The most important aspect in the utilization of slags from ferroalloy production is the separation of their metallic and oxide components to obtain metal concentrate and slag. Currently, various methods are used worldwide to separate the metallic and oxide components of slags, ranging from manual selection to modern X-ray radiometric separation, although technologies based on gravitational and magnetic methods are the most widespread [4,5].

Research Goals and Objectives. Rational and comprehensive use of mineral raw materials in metallurgical production, one of the most material-intensive industries, is an important and urgent problem, the solution of which allows for increased production efficiency, improved economic indicators, and addressing environmental protection issues.

Theoretical and Experimental Research. To conduct research on the physical and chemical properties of electric furnace and refining slags, determine the phase composition and forms of nickel in it, and develop enrichment modes and equipment parameters, 5 slag samples (Table 1) from ferronickel production were studied at the Pobuzhsky Ferronickel Plant.

Table 1. Chemical Composition of Slag Samples*.

Sample	Chemical Composition, %					
	Ni	Fe	MgO	SiO_2	CaO	Al_2O_3
1	0,28	13,02	34,69	47,24	0,297	2,248
2	0,26	12,45	31,48	43,80	0,285	2,056
3	10,95	17,60	7,29	16,30	42,66	6,590
4	9,90	17,75	7,26	16,32	42,68	6,62
5	9,33	17,14	7,34	16,42	42,65	6,61

*Samples 1-2 – granulated electric furnace slag
Samples 3-5 – refining slags

A distinctive feature of the technological scheme for ferronickel production at PRONICO S.A. is that the refining process of crude ferronickel is carried out in a modern unit - a ladle furnace, while at PFK this process is conducted in oxygen converters. The research on the distribution of nickel in slags was conducted using the RSMA (SELMI REM-106I) setup at the National Technical University of Ukraine (Igor Sikorsky Kyiv Polytechnic Institute) in Kyiv. Based on the results of studies of five slag samples on the SELMI REM-106I installation using the X-ray spectral microanalysis method, it was found that nickel, both in electric furnace (Figures 1-2) and refining (Figures 3-10) slags, is present in compounds with iron in the metallic phase, while no nickel was found in the oxide phase.

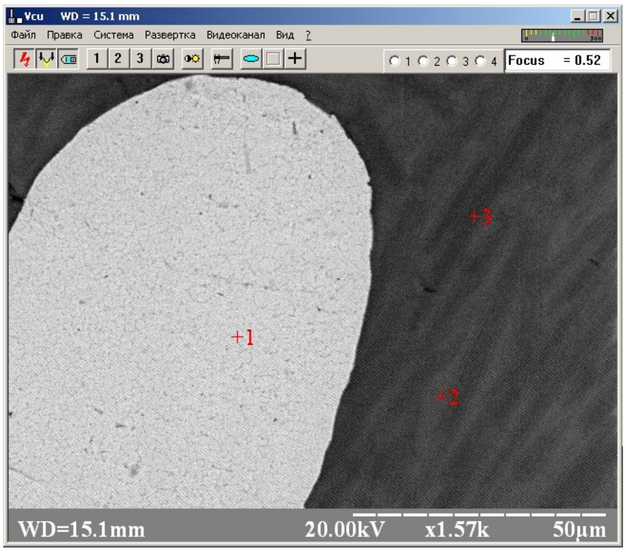
Sulfur in electric furnace slags is concentrated in metal granules in compounds with nickel and iron, while in refining slags, it is mainly in compounds with CaO. Metal granules are mostly spherical or represented by aggregates of various shapes and sizes. In some areas of the samples, their significant amount reaches up to 47% (see Figure 1), and the nickel content in some granules reaches ~72%.

In Figure 1, the light spots (point 1) have a high content of nickel and iron (approximately 70 and 25%), while the dark spots (points 2 and 3) contain silicon and iron oxides (35 and 40%).

In Figure 2, point 1 contains a large amount of iron and nickel (67% and 30%), while points 2 and 3 mainly contain iron and silicon (40% and 40%) and a small amount of magnesium (11%).Research on samples of electric furnace and refining slags from ferronickel production using nickel-containing ore from the Guatemala deposit by X-ray spectral microanalysis (RSMA) has shown that metal granules are composed of 95-99% iron and nickel in various ratios. The nickel content in some granules of granulated electric furnace slag reaches 72%, which provides some insight into the mechanism of reduction processes occurring in the ore-thermal furnace, indicating the primary reduction of nickel followed by its dilution with iron. The metallic phase also contains the main amount of sulfur, while in refining slags, sulfur is concentrated in compounds with calcium oxide and is inversely related to the content of iron oxides in them.

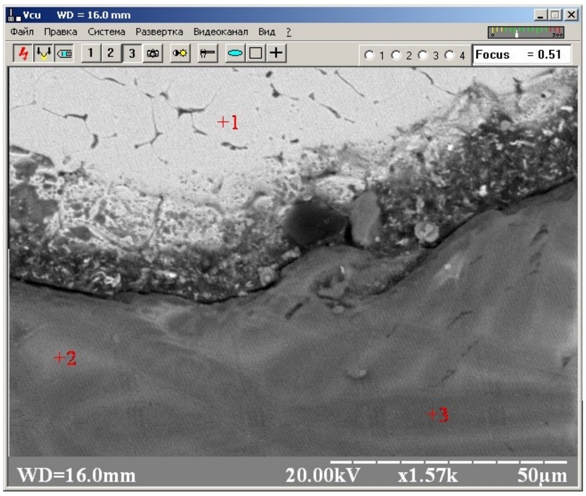
Currently, various enrichment technologies have been developed and implemented – mechanical, hydrometallurgical, electrolytic, and others, using modern equipment, taking into account the physicochemical and mechanical properties of secondary materials [6-10]. The research conducted in this work is aimed at developing a technological scheme for enriching granulated electric furnace and refining slags from ferronickel production using a high-intensity magnetic field [11-17].

The same five slag samples (Table 1) from ferronickel production were studied. To more fully disclose the slags and extract metal from them, they were crushed from the initial fraction (Table 2) to size classes –0.16 mm; 0.16-0.4 mm; 0.4-1.6 mm and +1.6 mm.



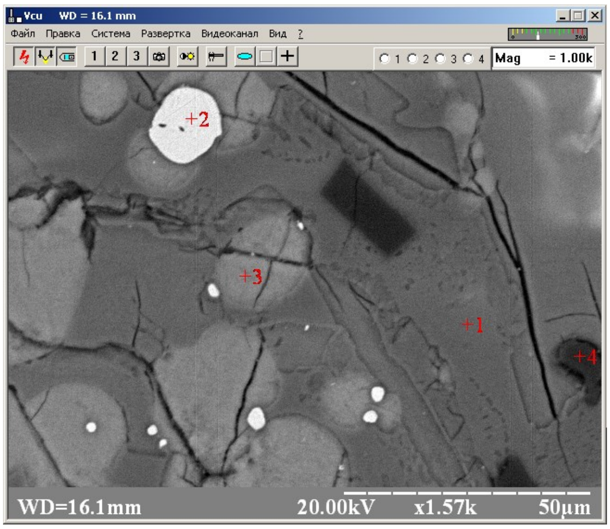
No.	Chemical Composition, %					
	Ni	Fe	S	Ca	Si	Mg
1	71,80	25,88	0,18	0,19	1,29	0,00
2	3,08	45,19	0,00	1,16	39,86	7,11
3	1,25	36,74	0,00	1,58	40,92	15,25

Figure 1. RSMA Results of Electric Furnace Slag (Sample No. 1).



No.	Chemical Composition, %					
	Ni	Fe	S	Ca	Si	Mg
1	31,46	67,21	0,00	0,15	0,29	0,00
2	1,88	51,68	0,00	0,92	36,53	5,01
3	2,34	42,04	0,00	0,34	43,07	10,92

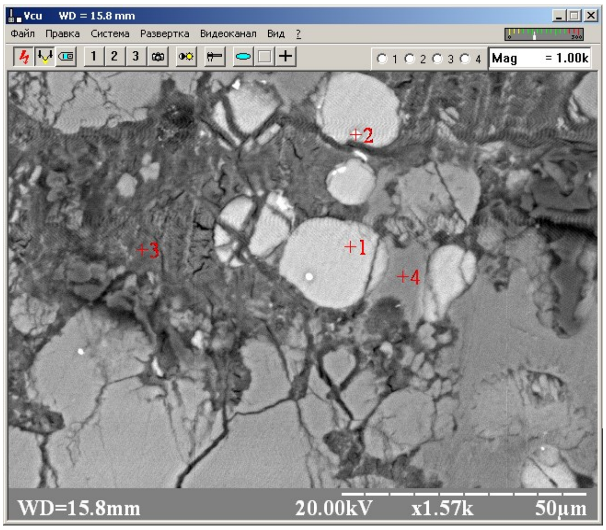
Figure 2. RSMA Results of Electric Furnace Slag (Sample No. 2).

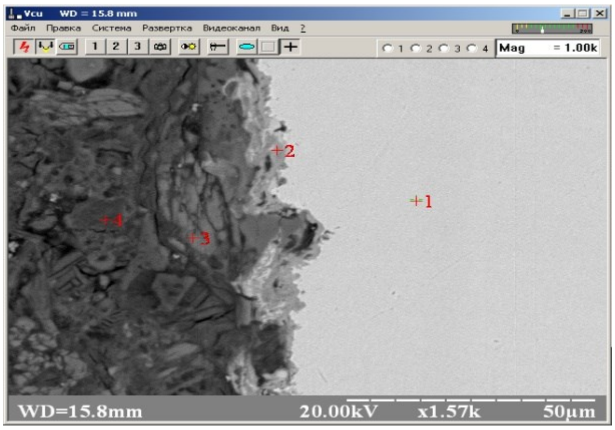


No.	Chemical Composition, %					
	Ni	Fe	S	Ca	Si	Mg
1	0,00	0,00	0,00	88,61	1,49	0,00
2	42,61	56,80	0,11	0,49	0,00	0,00
3	0,00	0,13	34,39	65,29	0,08	0,00

No.	Chemical Composition, %					
	Ni	Fe	S	Ca	Si	Mg
1	0,14	78,46	0,00	1,85	2,28	0,58
2	0,00	88,98	0,19	4,53	4,86	0,00

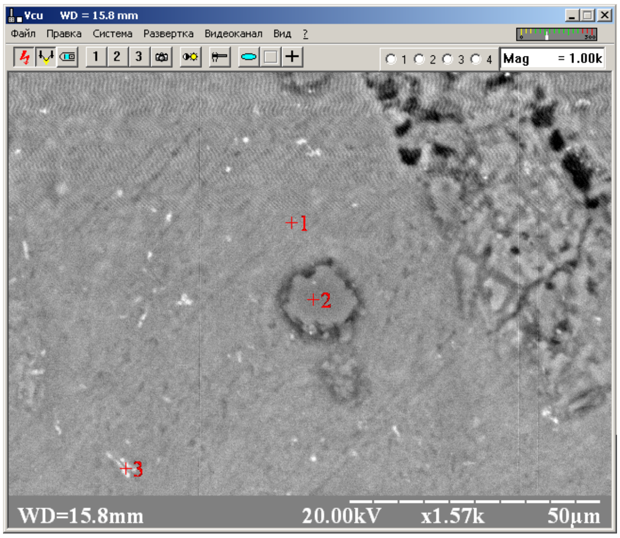
Figure 3. RSMA Results of Electric Furnace Slag (Sample No. 3).





No.	Chemical Composition, %					
	Ni	Fe	S	Ca	Si	Mg
1	0,33	0,23	34,68	63,89	0,19	0,00
2	25,04	30,42	14,11	29,63	0,07	0,00
3	0,00	3,16	13,07	74,28	4,96	0,00
4	0,45	2,44	3,25	77,44	2,98	0,00

No.	Chemical Composition, %					
	Ni	Fe	S	Ca	Si	Mg
1	30,84	68,00	0,11	0,54	0,00	0,00
2	6,38	83,31	1,17	3,10	0,02	0,00
3	2,31	5,48	1,19	78,60	11,70	0,00
4	4,38	7,88	3,19	70,28	11,46	0,00



No.	Chemical Composition, %					
	Ni	Fe	S	Ca	Si	Mg
1	2,05	3,72	1,25	55,28	31,14	0,00
2	1,24	1,08	0,40	8,73	86,61	0,00
3	1,05	5,98	2,37	45,21	25,30	0,00

Figure 4. RSMA Results of Electric Furnace Slag (Sample No. 4).

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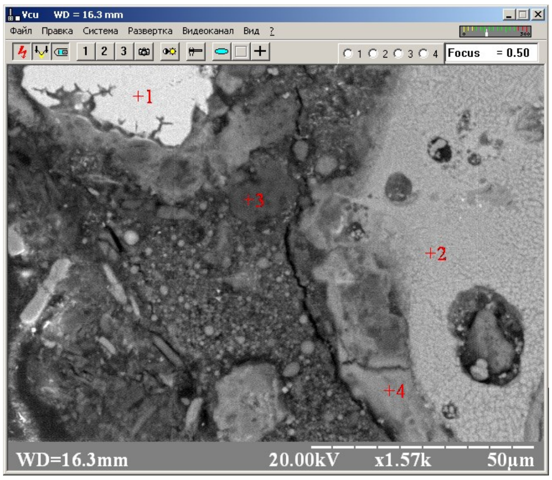
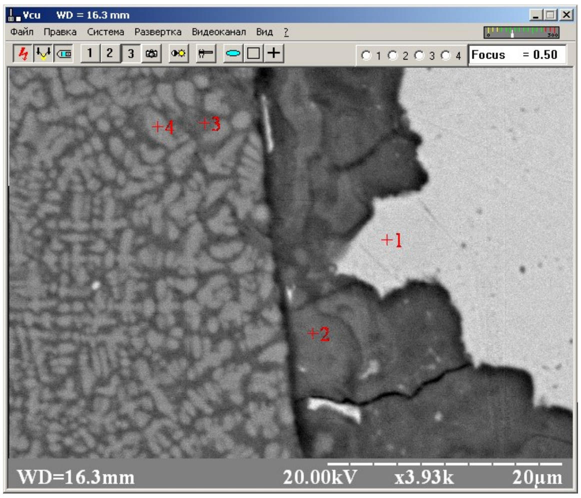
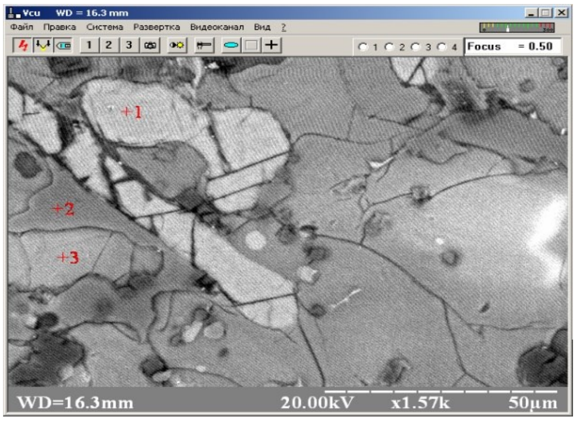


No.	Chemical Composition, %					
	Ni	Fe	S	Ca	Si	Mg
1	23,73	75,69	0,00	0,33	0,25	0,00
2	0,48	96,71	0,00	0,36	2,23	0,00
3	2,83	8,29	0,00	4,26	57,04	0,50
4	21,06	65,42	2,72	7,03	3,19	0,11



No.	Chemical Composition, %					
	Ni	Fe	S	Ca	Si	Mg
1	46,10	53,26	0,34	0,21	0,02	0,00
2	24,29	70,66	1,69	3,02	0,34	0,00
3	2,26	91,57	0,00	0,59	5,02	0,00
4	0,85	97,95	0,38	0,20	0,45	0,00



No.	Chemical Composition, %					
	Ni	Fe	S	Ca	Si	Mg
1	0,00	0,08	36,65	63,26	0,00	0,00
2	0,00	0,97	2,07	78,11	1,26	0,00
3	0,41	0,06	3,61	88,60	7,01	0,04

Figure 5. RSMA Results of Electric Furnace Slag (Sample No. 5).

Table 2. Granulometric Composition of Electric Furnace and Refining Slag Samples.

Size Class, mm	Yield, %	
	Electric Furnace	Refining Slag
+ 5	3,68	3,17
3 – 5	11,58	11,61
1 – 3	73,55	40,22
0,5 – 1	6,36	6,25
0,25 – 0,5	4,4	18,34
0,16 – 0,25	0,3	2,82
– 0,16	0,13	17,59
	100	100

The results of determining the granulometric composition of the samples show that the yield of classes +1 mm for electric furnace slags is more than 88%, and for refining slags – about 55%. It should be noted that in these size classes, there is not enough disclosure of the initial products, and therefore, preparation operations (crushing, grinding) are necessary for the subsequent enrichment processes of the presented samples.

In the process of developing the technological scheme for preparing the initial materials and their enrichment, more than 50 experiments were conducted, and more than 70 chemical analyses of enrichment products – metal concentrate, slags, and sludges – were performed.

The slag preparation schemes include: crushing the initial materials on a roll crusher, classification, grinding in a ball mill with subsequent classification – for electric furnace slags, and classification and double grinding for refining slags.

Analyzing the +1.6 mm size class in refining slag samples, it was found that there are metal granules and a non-metallic light product (practically slag fraction). Chemical analysis showed that in this size class, the nickel content in the metal phase is within 26-33%, and in the slag phase, the nickel content is about 0.5%. The +1.6 mm fraction was sent for re-crushing to isolate a purer metal phase. Chemical analysis of the purified metal product showed an increase in nickel content to 38%. The yield of these size fractions for samples No. 3, 4, and 5 is about 10-4.5%.

For the 0.16-0.4 mm size fraction, a metal product with a nickel content of about 9.7% was obtained in the magnetic separation process, with a yield of this product of 15.34%.

For the 0.4-1.6 mm size fraction, a metal product with a nickel content of about 25% was obtained by magnetic separation, with a yield of 18.27%.

Thus, metal products of size fractions 0.16-0.4 mm, 0.4-1.6 mm, and +1.6 mm were obtained with a total nickel content of about 21.94% and a total yield of fractions of 43.6%. The slag fractions of refining slags contain no more than 0.5% nickel.

When working with electric furnace slags, sample preparation also included the production of size classes -0.16 mm, 0.16-0.4 mm, 0.4-1.6 mm, and +1.6 mm. The prepared size classes were sent both to the magnetic separation stage and to the gravity separation stage.

It was found that repeated crushing and grinding operations of the initial raw material particles lead to the fact that the obtained slag particles acquire a rounded and spherical shape. In further separation processes, especially gravity separation methods, this improves the separation process of the metal phase and the slag fraction.

The yield of magnetic fractions (metal phase) in the magnetic separation process and the yield of heavy fractions (mainly metal granules and aggregates with granules) during wet gravity separation in the studied electric furnace slag samples is about 8-11.6%.

Chemical analysis data show that the nickel content in the obtained metal products is about 0.9-4.75%.

Since granulated electric furnace slags contain moisture under industrial conditions, an enrichment option was investigated that involves a "wet technology." In this option, the enrichment of crushed electric furnace slags will be carried out on magnetic separators adapted to the properties of the initial raw material. Enrichment of electric furnace slags by "wet" technology allows obtaining a metal concentrate with a nickel concentration of 0.9 to 4.75% with a yield of 2-5%. The nickel content in the slag phase is 0.12-0.25%.

The proposed technological line for enriching electric furnace slags (Figure 6) consists of a hopper with a feeder, a belt conveyor, a ball mill, a spiral classifier, a sump with a pump, magnetic separators, a sludge settler, and a pump.

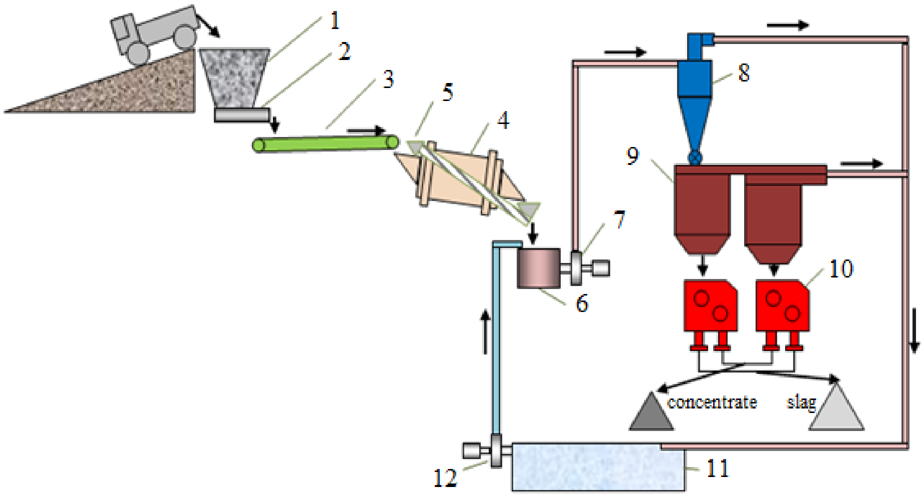


Figure 6. Technological Line for Processing Electric Furnace Slags: 1 – receiving hopper; 2 – feeder; 3 – belt conveyor; 4 – ball mill; 5 – spiral classifier; 6 – sump; 7, 12 – pumps; 8 – hydrocyclone; 9 – hydroclassifiers; 10 – magnetic separators; 11 – sludge settler.

It should be noted that the cost of equipment for the technological line for processing electric furnace slags with an automatic control system will be $380,000. The installed power of the electrical equipment on the technological line is about 160 kW. The operating personnel of the technological line is one person.

The refining slag processing scheme includes stages of grinding, air gravity separation, and final product finishing operations of magnetic separation.

The proposed line for processing refining slags, characterized by a higher nickel content (7.15-10.1%), includes: ball mill MSh1 1500x3000; air gravity separator type VGS-2; magnetic drum separator MBS-300.

The refining slag processing scheme (Figure 7) provides for the supply of slag ground in a ball mill to a gravity separator, where it is separated into size classes. The material of size fractions 0.4-1.6 mm and +1.6 mm is fed to a magnetic separator, where it is separated into magnetic (metallic) and non-magnetic (slag) fractions.

The cost of the equipment complex for processing refining slags, including an automatic process control system, will be $280,000, and for processing electric furnace slags – $380,000, with a payback period of 0.54 months and 0.84 months, respectively.

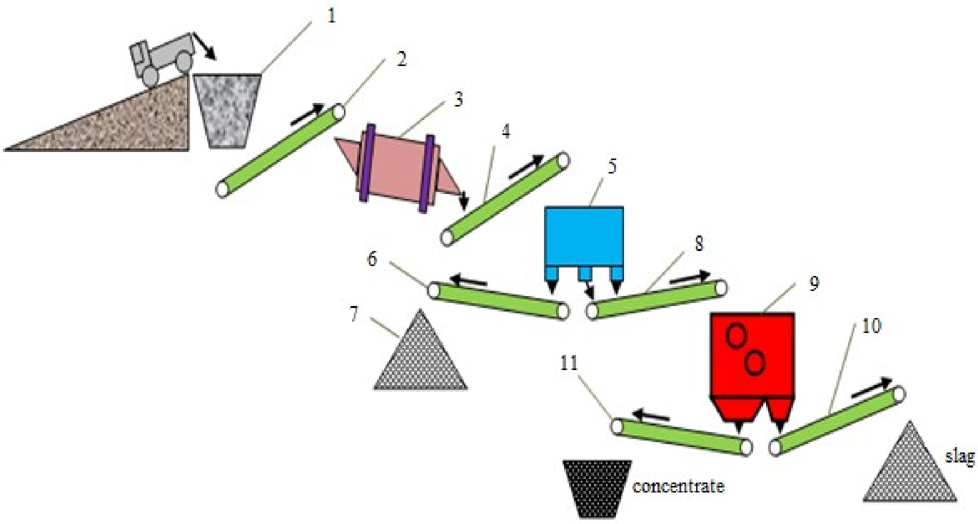


Figure 7. Technological Line for Processing Refining Slags: 1 – receiving hopper with feeder; 2, 4, 6, 8, 10, 11 – belt conveyors; 3 – ball mill; 5 – gravity separator; 7 – storage of fraction -0.16 mm; 9 – magnetic separator.

The developed and proposed technological schemes for enriching electric furnace slags by "wet" technology and refining slags by "dry" technology allow utilizing about 1200 tons of nickel per year or extracting 31.6% and 94.65% of nickel from slags, respectively.

Conclusions

Based on the results of studies of samples of electric furnace and refining slags from ferronickel production using oxidized nickel ore from the Guatemala deposit at PRONICO S.A. by X-ray spectral microanalysis (RSMA) on the Selmi REM-106I installation, it was determined that the main amount of nickel is concentrated in metal phase granules of various shapes in compounds with iron and sulfur, with a concentration in some cases exceeding 70%.

The studied high-magnesia (31.5-34.7% MgO) acidic (CaO + MgO/SiO_2 = 0.72-0.74) granulated electric furnace slags from ferronickel production, containing up to 0.31% Ni, are more than 95% represented by the 0.55 mm fraction, while the highly basic ((CaO + MgO)/SiO_2 over 3.0) self-disintegrating refining slags, with a nickel concentration of 9.3 to 10.95%, are almost 40% represented by the fraction less than 0.5 mm. To more fully disclose the grain, the initial slags were crushed to size classes: –0.16 mm; 0.16-0.4 mm; 0.4-1.6 mm and +1.6 mm in experimental ball mills.

Based on studies of the properties of the initial raw material and its movement in the working zones of separation devices, a new method for enriching ferroalloy slags by the wet method using a modernized magnetic separator adapted to the characteristics of the initial raw material was developed, which allowed for improved nickel extraction from electric furnace slags. The studies on the enrichability of electric furnace slags according to the developed technological scheme allowed obtaining a metal concentrate containing 0.9-4.75% nickel.

The developed and proposed technological schemes for enriching electric furnace slags by "wet" technology and refining slags by "dry" technology allow for the utilization of about 1200 tons of nickel per year, or the extraction of 31.6% and 94.65% of nickel from slags, respectively.

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