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INCREASING THE EFFICIENCY OF TITANIUM-IRON ORE ENRICHMENT THROUGH USING NEW TYPE SEPARATORS

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Abstract: *The object of the research is technologies and technical means for selective destruction of mineral matrices of complex multicomponent titanium ores of primary deposits and beneficiation of minerals with altered magnetic properties. The aim of the work is to increase the efficiency of enrichment of titanium-iron ores by preliminary high-temperature treatment using new-type separators. This is achieved by substantiating the targeted selective destruction of mineral complexes and changing the magnetic properties of ore minerals as a result of temperature-controlled oxidation reactions. Methods of complex generalization, analysis and evaluation of practical experience and scientific achievements in the field of creation and introduction of new technologies and technical means for increase of efficiency of enrichment of titanium ores on the basis of separators of new type by substantiation of the directed selective destruction of mineral complexes and change of magnetic properties of ore minerals are described. It was found that for ilmenite, the main titanium component of raw materials, a low mass fraction of titanium is typical - no more than 30.0%, and ilmenite has lamellar-thin nano inclusions of hematite - 31.53 vol. %, which are difficult to remove from the ilmenite matrix. It is proved that in titanium-containing ores selective opening of splices occurs due to recrystallization of grains due to previous reduction, strengthening of bonds in hematite-ilmenite contact zones and non-ore inclusions and creation of a network of germinal cracks inside nano splices due to exposure to mineral matrix. C. It is shown that the use of magnetic separation of raw materials after high-temperature treatment reduces the mass fraction of harmful elements such as silicon, aluminum and calcium oxides from 11.89 to 1.2% in the concentrate product and allows to increase the mass fraction of titanium oxide from 32.3 up to 37.6%, and total iron from 33.86 to 42.29%; The technology of complex ore beneficiation has been developed to provide concentrates used for the extraction of titanium slag (mass fraction of titanium oxide - 80-81.84%) and high-purity metallic iron Fe with an average chemical composition of Fe 0.993 Ti 0.006. The results of development and implementation of new generation technologies and separators in the enrichment and processing of titanium ore were obtained in the laboratories of the State Higher Educational Institution (KVUZ) "Kryvyi Rih National University" (Krivoy Rog, Ukraine) and implemented at the Public Joint Stock Company (PJSC) » (Zaporozhye, Ukraine) and the State Institute for the Design of Mining Enterprises SE" Krivbasproekt "(Krivoy Rog, Ukraine). The developed technologies are also the basis for the feasibility study of ore processing technology of the Abu Galaga field (Egypt), in the design of the industrial complex and can be useful for other enterprises in developed mining countries. Research and implementation of new technologies and technical means using dry magnetic separation will allow for the stable production of high-quality concentrates, as well as the reduction of the grinding and enrichment front by at least 15–20% of the original, which will reduce operating and capital costs by more than 30% and will become a powerful technological reserve for the development of mining production.*

Keywords: *technologies, separators, magnetic enrichment, titanium ores, process efficiency*

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 vol. 30, issue 4 / 2024
pp. 44-55

1. Introduction

Problem statement. The current state of the mineral resource base and objectively established trends in the development of metallurgical production necessitate the creation and widespread use of technologies for the comprehensive and more complete extraction of useful components in the processing of ore raw materials [1], [2]. The efficiency of the enrichment process depends on how fully the ore preparation has ensured the disclosure of mined minerals with minimal regrinding. This problem is especially relevant for titanium ores, which are distinguished not only by the complexity of their material composition, but also by uneven dissemination and size of useful components, and close mutual intergrowth of valuable and rock-forming minerals [3], [4]. The organization of low-waste technologies for processing mineral raw materials is associated with selective destruction. The titanium industry is no exception, and in its development it is equally important to address issues of not only the comprehensive use of raw materials, but also the expansion of the sphere of influence in the world through the development of technologies for the enrichment of complex titanium ores from primary deposits, both domestic and global [5], [6]. Therefore, increasing the efficiency of titanium-iron ore beneficiation by preliminary high-temperature treatment using new type separators is an urgent scientific, practical and social task that requires an urgent solution [7], [8].

The object of the research is technologies and technical means for selective destruction of mineral matrices of complex multicomponent titanium ores of primary deposits and beneficiation of minerals with altered magnetic properties.

The subject of the research is the processes of targeted selective destruction of intergrowths and changes in the structure, texture of ore and magnetic properties of minerals, as well as the patterns of their separation during beneficiation of complex multicomponent titanium ores of primary deposits.

Research methods - a set of research methods was used in the work, including: generalization of scientific information; X-ray phase and mineral analysis of ore and beneficiation products of raw materials before and after heat treatment; study of magnetic and structural properties of minerals and mineral complexes; thermodynamic calculations and thermodynamic modeling of processes; technological tests in laboratory conditions; methods of experiment planning; methods of statistical processing of research results; regression and factor analysis to establish analytical patterns and substantiate optimal parameters for the process of separating minerals of a polycomponent system.

The aim of the work is to increase the efficiency of enrichment of titanium-iron ores by preliminary high-temperature treatment using new-type separators. This is achieved by substantiating the targeted selective destruction of mineral complexes and changing the magnetic properties of ore minerals as a result of temperature-controlled oxidation reactions.

The following tasks are solved in the work:

– to analyze the chemical composition of hard-to-enrich titanium ore and obtain a thermodynamic model of the effective magnetization of the mineral components of the ore;

– to establish the effect of temperatures in the range of 850–1050°C on the mineral matrix “hematite-ilmenite” and recommend a scheme for a modernized separator for material whose temperature exceeds 150°C;

– to perform a technical and economic calculation of the results of the activities of a new enterprise for the production of titanium products.

2. Researching existing solutions to the problem

Industrial reserves of primary hematite-ilmenite ores are known in Ukraine, China, Canada and Egypt. These ores are characterized by very fine mutual intergrowth of hematite and ilmenite, or rutile. Today, Ukraine is the leading titanium-ore province in the world and occupies a leading position in the extraction of ilmenite concentrates and the production of titanium products. A significant part of the issues of selective destruction of mineral complexes has been studied and developed in the works of Revnivtsev V.I., Olofinsky M.F., Gaponov G.V., Zarogatskogo L.P., Kostin I.M., Finkelshtein G.A., Khopunov E. A., Yashina V.P., Kozina V.Z., Pervukhina A.V., Shatailova Yu.V., Pilov P.I., Mladetskogo I.K., Urvantseva A.I., Chanturii V.A., Chaplygina N.N., Vigdergauz V.E. and others [9], [10].

An analysis of the work revealed the need to improve the energy efficiency of processing difficult-to-dress titanium ores from primary deposits by using the technology of controlled selective destruction of polymineral complexes. This is ensured by exposure to high temperatures, weakening the boundaries of mineral intergrowths, due to the accelerated diffusion of atoms of various minerals in these boundaries. Selective (controlled) destruction is a process of sequential transformation of the original ore structure by targeted formation and development of micro- and macrocracks in its various elements at the corresponding

vol. 30, issue 4 / 2024
pp. 44-55

structural levels. An analysis of the practice of enrichment of primary titanium ores showed that complex hematite-ilmenite ores are enriched using gravity, electrical and magnetic methods. They are then sent for high-temperature treatment and metallurgical processing [11], [12].

3. Research results

Analysis of the chemical composition of the refractory titanium ore showed that the mass fraction of titanium oxide is 32.3%. A high content of the ore component - polymineral inclusions "hematite-ilmenite" - 58.5% was established. To identify and confirm the features of the polymineral complexes "hematite-ilmenite", microprobe studies were carried out, which were carried out using a scanning electron microscope microanalyzer REMMA-102-02 (Fig. 1).

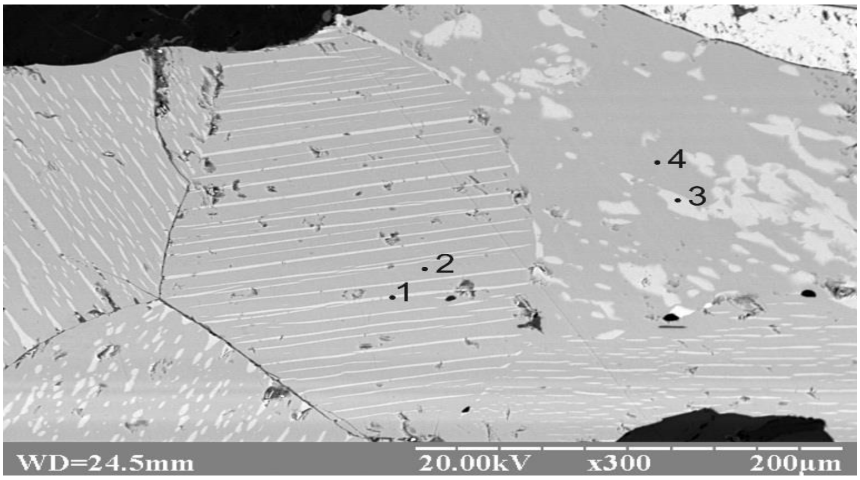

Fig. 1. Ilmenite grains with hematite admixture (photo): 1, 2, 3, 4 – thin section probing points

Points 1, 3 were located in hematite inclusions, points 2, 4 – in the ilmenite field of the matrix. The results of studies of difficult-to-process hematite-ilmenite ore of the primary deposit are given in Table 1. Statistical processing of microprobe analysis data separately for hematite and ilmenite is given in Table 2.

Table 1. Results of microprobe study of polymineral complexes

Element	Dot 1	Element	Dot 2	Element	Dot 3	Element	Dot 4
Mg	0.73	Mg	1.76	Mg	0.60	Mg	1.75
Al	1.03	Al	1.14	Al	0.84	Al	1.18
Ca	1.24	Si	1.31	Si	1.12	Si	1.35
Sc	1.29	Ca	1.23	Ca	1.10	Ca	1.16
Ti	12.64	Sc	1.40	Sc	1.25	Sc	1.36
V	2.05	Ti	34.93	Ti	10.15	Ti	34.79
Cr	1.18	V	2.04	V	2.02	V	1.86
Mn	1.63	Cr	1.13	Cr	1.17	Cr	1.15
Fe	75.78	Mn	1.86	Mn	1.54	Mn	1.86
Au	2.43	Fe	51.23	Fe	77.64	Fe	51.05
Total	100.00	Au	1.97	Au	2.57	Au	2.49
		Total	100.00	Total	100.00	Total	100.00

The analysis revealed the chemical composition features of hematite and ilmenite grains, which have a high mass fraction of titanium (more than 10%). The analysis of the mineral composition showed that ilmenite has lamellar-thin inclusions of hematite (31.53 vol.%), measured in micrometer units. The ore of such polymineral inclusions contains 58.5% of "hematite-ilmenite". The presence of a large number of harmful elements, such as silicon, sulfur, phosphorus, magnesium, chromium, was also established. It was determined that silicates in the sample are presented in the form of olivine, pyroxene and actinolite - 16.4%. The content of plagioclase is 8.2%, and the content of sulfide minerals (pyrite, chalcopyrite, pyrrhotite) is 7.5%.

Analysis of the physical properties of the minerals that make up the raw material showed that their magnetic properties are low-contrast. In addition, some of the non-metallic (silicate) minerals are present as fine inclusions in ore grains, so the non-metallic component can be completely separated from the ore component only after selective disclosure of the non-metallic phase.

Table 2. Microelement composition of hematite and ilmenite grains of titanium ore

Element	Hematite				Ilmenite			
	Dot 1	Dot 3	Dot 5	average	Dot 2	Dot 4	Dot 6	average
Mg	0.73	0.60	0.71	0.68	1.76	1.75	1.05	1.52
Al	1.03	0.84	0.99	0.95	1.14	1.18	1.31	1.21
Si	-	1.12	1.19	1.16	1.31	1.35	1.34	1.33
S	-	-	0.97	0.97	-	-	0.99	0.99
Ca	1.24	1.10	1.15	1.16	1.23	1.16	1.18	1.19
Sc	1.29	1.25	1.24	1.26	1.40	1.36	1.44	1.40
Ti	12.64	10.15	14.50	12.43	34.93	34.79	32.95	34.22
V	2.05	2.02	2.00	2.02	2.04	1.86	1.89	1.93
Cr	1.18	1.17	1.19	1.18	1.13	1.15	1.01	1.10
Mn	1.63	1.54	1.56	1.58	1.86	1.86	1.89	1.87
Fe	75,78	77.64	67.17	73.53	51.23	51.05	48.16	50.15
Co	-	-	1.58	0.53	-	-	1.54	0.51
Ni	-	-	1.31	0.44	-	-	1.26	0.42
Cu	-	-	1.48	0.49	-	-	1.36	0.45
Au	2.43	2.57	2.96	2.65	1.97	2.49	2.63	2.36
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

The data from studying the mineral and chemical composition of the ore characterize it as a difficult-to-brine and hard-to-recover raw material, i.e. it is problematic to obtain monofragments of ilmenite and hematite in the process of mechanical destruction. Most of the ilmenite fragments will be “contaminated” by hematite inclusions even at very small sizes [13], [14].

As a result of magnetic enrichment of the original ore with a mass fraction of titanium oxide of 32.3%, a “rough” concentrate with a mass fraction of TiO^2 of 34.8% was obtained. It is represented mainly by polymineral intergrowths of “hematite-ilmenite” (76.67%). Non-metallic minerals that contaminate the concentrate are olivines and pyroxene (13.81%), sulfides (2.53%), as well as plagioclases and actinolite, which together make up 1.87%. Other minerals account for 5.13%. The release of minerals by mechanical disintegration methods is ineffective. This is confirmed by the results of magnetic separation of the original ore.

The efficiency of separation of ore minerals according to Hancock-Luycken is 15.76%, non-metallic - 22.66%. It is practically impossible to release "hematite-ilmenite" intergrowths with a size of lamellar hematite impregnation at the level of 0.00065 mm by mechanical methods [15], [16]. When analyzing the results of derivatographic studies of the oxidation of synthetic ilmenite, it was found that ilmenite begins to oxidize at a noticeable rate at temperatures of about 400 °C. At temperatures of ≃1000 °C, the degree of oxidation is close to 100%. Oxidation was carried out in air by heating to 1100 °C at a rate of 10 deg / min., holding the ore sample for 10, 20, 30, 40, 60 minutes. The results of studies of changes in ore mass during high-temperature processing (HTP) are shown in Fig. 2.

The increase in the mass of the sample is determined not only by the oxidation of the iron present in ilmenite from Fe^{2}+ до Fe^{3}+, but also the oxidation of magnetite to hematite, which is accompanied by a noticeable release of heat: $2Fe_3O_4 + 1/2O_2 = 3Fe_2O_3 + 231$ МДж.

The decrease in the sample mass is caused by the removal of sulfur and oxidation of pyrite. The amount of magnetite, depending on the holding time in the furnace, fluctuates from 8.2 to 10.03% in sample 1, and from 4.18 to 4.75% in sample 2. The authors suggest that in the presence of oxygen in the temperature range of 850-1050° C, the following oxidation reactions of pyrite occur:

$FeS_2 + 4O_2 = FeS_2O_8$; $2FeS_2O_8 \leftrightarrow Fe_2O_3 + SO_2 + SO_3 + O_2$;

$FeS_2 + 3O_2 = FeSO_4 + SO_2$;

$4FeS_2 + 11O_2 = 2Fe_2O_3 + 8SO_2$;

$10Fe_2O_3 + FeS = 7Fe_3O_4 + SO_2$;

$5FeSO_4 + FeS = 2Fe_3O_4 + 6SO_2$;

$3FeS_2 + 8O_2 = Fe_3O_4 + 6SO_2$.

In this case, the decomposition of pyrite can, on the one hand, promote the formation of predominantly hematite rims (peripheral zones), and on the other hand, lead to the formation of titanium-enriched magnetite in the central parts of ore inclusions. Due to the oxidation of sulfides during high-temperature processing of material samples, the amount of sulfur in the ore is reduced to a minimum (from 0.32 to 0.000008%).

In addition to the formation of magnetite in the altered samples, an increase in the amount of silicates is noted in them. In sample 1 - by 6.75-10.53%, in sample 2 - by 3.99-4.69%. This occurs due to the diffusion of iron cations at high temperatures: $2FeO + SiO_2 = Fe_2SiO_4$. The absence of actinolite in the samples is explained by the fact that actinolite thermally decomposes at temperatures above 850°C.

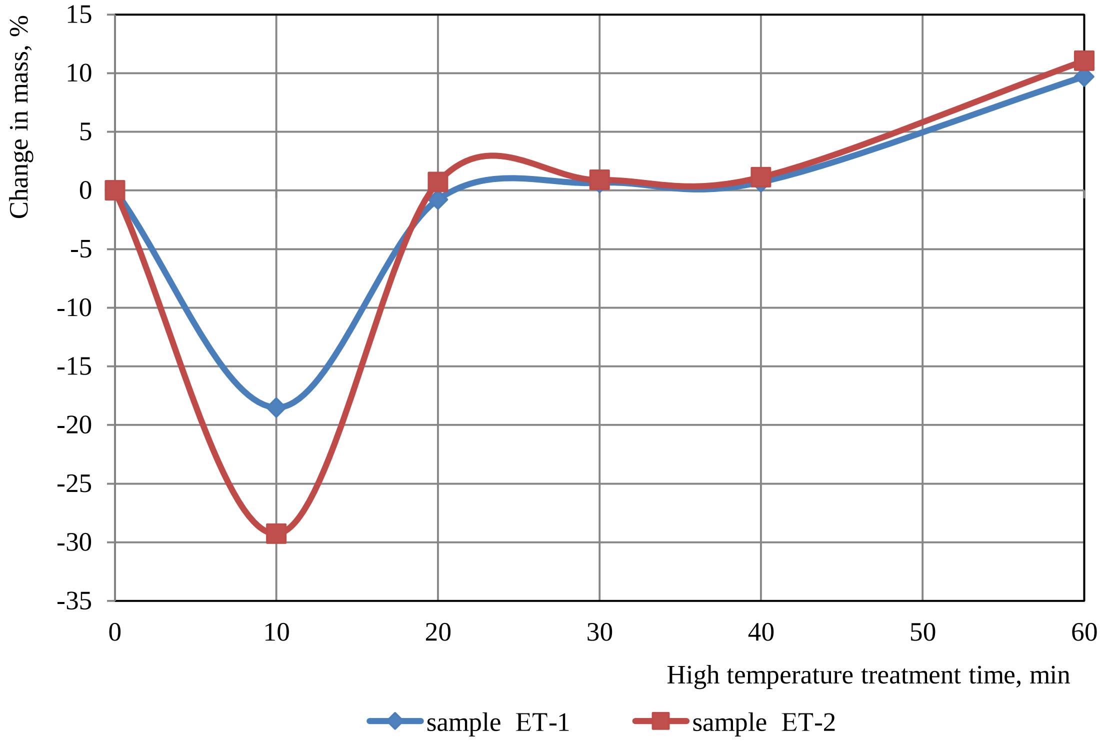

Fig. 2. Change in ore mass during high-temperature processing

We have established that as a result of the effect of temperatures in the range of 850-1050°C on the mineral matrix "hematite-ilmenite", a change in the texture of the ore occurs. The creation of a network of embryonic cracks inside the intergrowths and the occurrence of decription rims of hematite allows, during further destruction, to increase the selectivity of the opening of intergrowths by an order of magnitude and to reduce the time of ore grinding by 7.8 times [17], [18].

Elevated temperatures (above 800°C) lead to the irreversible entry of ferric iron into the ilmenite lattice. This process is possible based on the replacement of titanium and ferrous iron with oxidizing iron. When assessing the results of selective destruction of mineral matrices, it was established that the central parts of ore grains are prone to cracking. Ore inclusions look homogeneous; as an exception, they contain rare relict remains of hematite.

Next, experiments were conducted to open up newly formed mineral intergrowths (Fig. 3). The figure shows the dependences of the degree of opening of minerals before (opening of grains) and after (opening of plagioclase, ore grains, silicates and magnetite) high-temperature treatment (HTT) on the grinding time. The analysis of the experimental results showed that: with increasing grinding time, the degree of mineral disclosure increases from 12-22% (depending on the mineral) to 92-99% (with a grinding time of 40 minutes). Further grinding of the products is impractical, since it leads to the formation of a large amount of sludge. Regardless of the grinding mode, preliminary softening of the ore provides an increase in the efficiency of magnetic enrichment of ore minerals compared to the enrichment of the original ore by 16.57-17.42%. For the selective destruction of mineral intergrowths, high-temperature treatment of hematite-ilmenite ore is necessary, which causes accelerated diffusion of atoms of various minerals to the planes of intergrowths.

The actual composition of hematite-ilmenite grains after high-temperature treatment can be described by the resulting equation of the result of oxide reactions in a furnace at high temperatures:

$$0{,}69\ (Fe, Mg, Mn)\underline{TiO_3} + 0{,}31(Fe, V, Al, Cr)_2O_3 + (Co, Ni)_xO_y \rightarrow$$

$$\rightarrow 0{,}53\ (Fe,Mg,Mn)TiO_3 + 0{,}16\ (Fe,Mg)_2TiO_5 + 0{,}16\ (Fe,Mg, Ni)(Fe, V, Al, Cr, Mn, Co)_2O_4.$$

From the analysis of the above reaction, it can be concluded that as a result of exposure to high temperatures, altered ilmenite is formed, which will be the main mineral phase. The average empirical formula of altered ilmenite is $(Fe_{1,080}\ Mg_{0,129}\ Mn_{0,004}\ Cr_{0,002}\ V_{0,002})\ Ti_{0,890}\ O_3$ determined by chemical analysis. Magnetite, which is formed within the mineral matrices "ilmenite-hematite" has the empirical formula $(Fe_{0,968}Cr_{0,010}Ti_{0,007}Mg_{0,004}V_{0,003}Al_{0,003}Ni_{0,002})_3O_4$. After high-temperature processing of the sample material, hematite grains can be described by the formula: $(Fe_{0,791}Ti_{0,135}Mg_{0,024}V_{0,005}Cr_{0,004}Al_{0,0035}Mn_{0,001})_2O_3$.

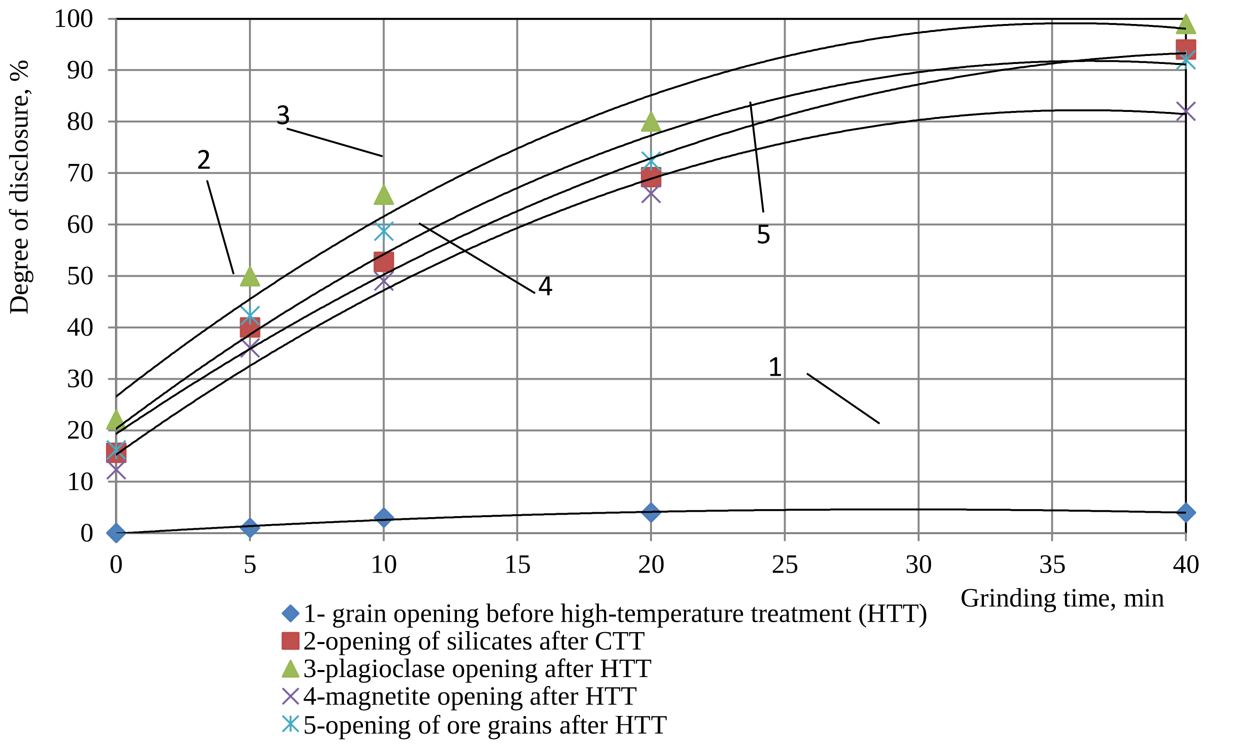

Fig. 3. Kinetics of mineral release before and after WTO treatment

After high-temperature softening of the ore, the product was subjected to magnetic separation in a weak and strong magnetic field. Analysis of the mineral composition of the products of magnetic separation of the altered open ore showed that weakly magnetic minerals enter the magnetic product obtained at 0.2 T. Non-metallic minerals (pyroxene + olivine, plagioclase, etc.) enter the non-magnetic product. The authors were the first to establish that at a temperature of 850-1050 °C, the ore structure changes due to the homogenization of the original ore inclusions and the formation of new mineral phases (hematite, magnetite, ilmenite, fayalite, etc.). They are distinguished by magnetic properties, which allows, when using magnetic separation of raw materials after high-temperature processing, to reduce the mass fraction of harmful elements in the concentrate: silicon, aluminum and calcium oxides from 11.89 to 1.2% and to increase the mass fraction of titanium oxide from 32.3 to 37.6%, and total iron from 33.86 to 42.29%;

The recommended technology for obtaining titanium slag was used by the Institute of State Enterprise "GPI Titan" (Zaporozhye, Ukraine). As a result, titanium slag with the average chemical formula was obtained: Fe0.197Mg0.271Mn0.004) (Ti1.094Al0.041V0.0075Cr0.0025)2O5. The slag also contains tiny balls of high-purity metallic iron Fe with the average chemical composition Fe0.993Ti0.006 [19], [20]. The idea of selective separation of refractory titanium ores of primary deposits at high temperatures is implemented in the design of an improved magnetic-gravity separator with air or water flow cooling (Fig. 4). The essence of the proposed changes lies in the possibility of high-quality separation of heated material. This ensures maximum contrast of the magnetic properties of its components.

Modernized magnetic separator. It consists of a non-magnetic inclined body 1 (see Fig. 4), onto the upper part of which material 2 (its temperature exceeds 150°C) is fed uniformly across the entire width by means of a device for its distribution 5. The separator has a divider (gate) for separation products 3 (concentrate 7, middlings 8 and tails 9), a magnetic system 4, which consists of a movable surface 6 (magnetic circuit), on which permanent magnets 10 are installed, as well as a bath with a heated water outlet branch pipe 11 of a magnet irrigation system 12 with nozzles 13 (see Fig. 4, a) or a system for removing hot air from the magnetic system 14 (see Fig. 4, b).

The separator operates as follows. The material to be separated 2 enters the housing 1 from the hopper 5 and is distributed in a uniform layer. Under the action of gravity, the material particles roll down and enter the magnetic field of the system of magnets 4, fixed on the movable surface 6. The magnetic particles are concentrated in places of the greatest field gradient opposite the magnets 10. The movable magnets 4 allow the magnetic particles to enter the concentrate hopper 7, and the weakly magnetic aggregates - into the hopper 8. Non-magnetic particles roll into the hopper 9 with the help of dampers 3. The liquid for cooling the magnets enters through the branch pipe 12 into the nozzles 13 and is discharged through the branch pipe 11

 vol. 30, issue 4 / 2024
pp. 44-55

in an amount ensuring immersion of part of the magnets of the system 4 into it. Vibration of the housing 1 reduces the contact of the particles with the non-magnetic material and also prevents heating of the magnets. Cooling of the magnetic system 4 by an air flow is performed in the same way [21], [22].

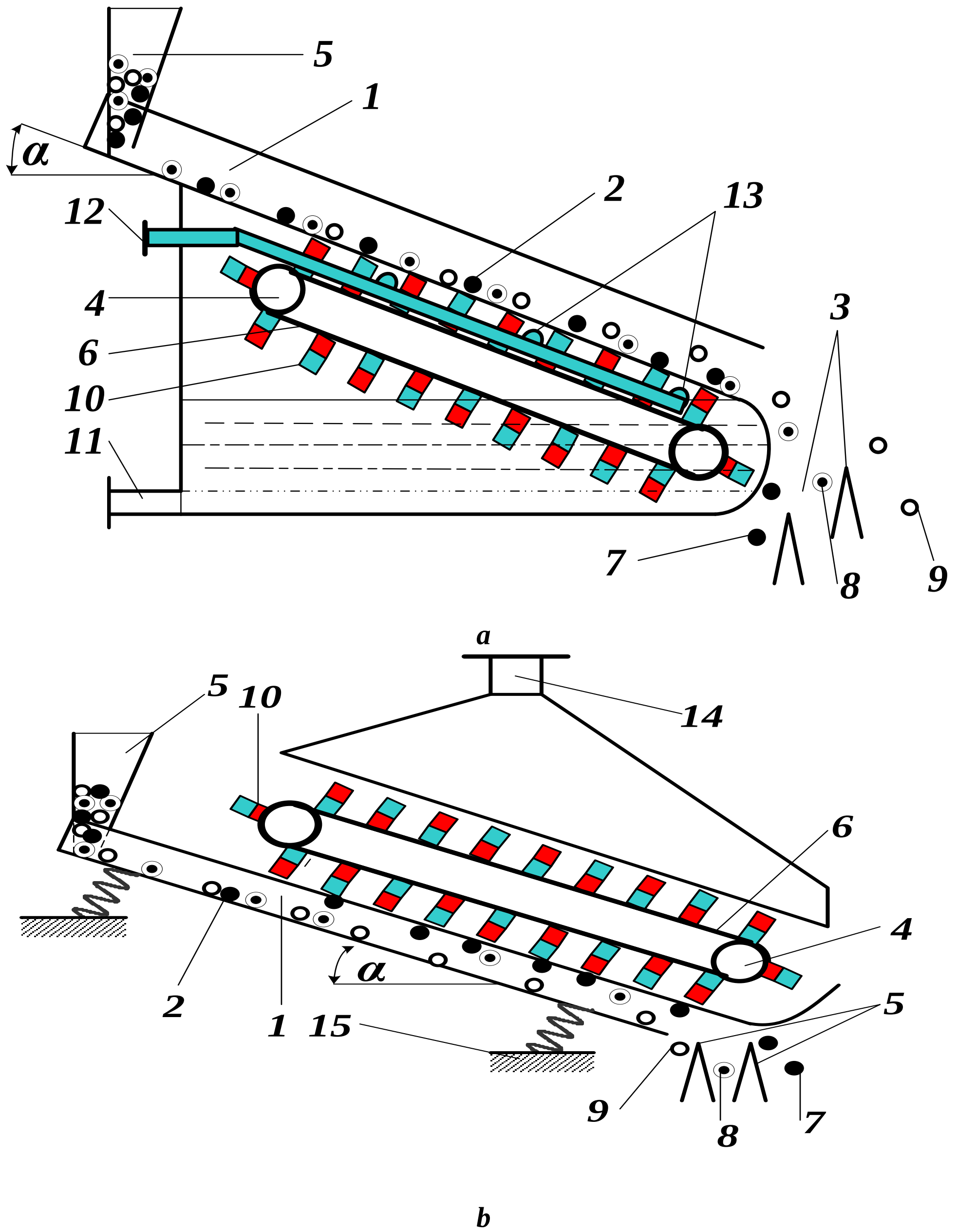

Fig. 4. Schematic diagram of the modernized separator for hot material with water (a) and air cooling of magnets (b): 1 - inclined body, 2 - separated hot material, 3 - separator (damper), 4 - magnetic system, 5 - device for separating material, 6 - magnetic circuit, 7 - concentrate bin, 8 - bin for middlings, 9 - bin for non-magnetic product, 10 - permanent magnets, 11 - heated water outlet pipe, 12 - magnet irrigation system, 13 - nozzles, 14 - system for removing hot air from the magnetic system, 15 - shock absorbers

4. Efficiency of the research

Technological efficiency. The authors obtained a thermodynamic model of the effective magnetization of the mineral components of the ore, in which, unlike those previously proposed for simulating the magnetic order in minerals, average molecular fields are used, approximated by the Hamiltonian function, or the operator of the total energy of the system. This allows, during high-temperature processing, to justify the possibility of changing the magnetic properties of ilmenite and the optimal composition of the feedstock, which is characterized as a composite system with a hematite content range from 15% to 60% [23], [24]. As a result of laboratory studies of the technology of selective destruction of mineral complexes and magnetic separation of hematite-ilmenite ores, a concentrate with a mass fraction of titanium oxide of 34.8% was

vol. 30, issue 4 / 2024
pp. 44-55

obtained, which is represented mainly by polymineral inclusions of "hematite-ilmenite" (76.67%). The non-metallic minerals that contaminate the concentrate are olivines and pyroxene (13.81%), sulfides (2.53), as well as plagioclases and actinolite, which together make up 1.87%. The share of other minerals is 5.13%. Due to the fact that the contrast of the properties of minerals: structural, elastic and strength characteristics, is insufficient to create a stress concentration gradient in the corresponding zones, the disclosure of minerals by mechanical disintegration methods is ineffective, which is confirmed by the results of magnetic separation of the original ore. The efficiency of separation of ore minerals according to Hancock-Luycken is 15.76%, non-metallic - 22.66%. It is practically impossible to disclose the solid substance "hematite-ilmenite", with lamellar impregnation of hematite at the level of 0.00065 mm, by mechanical methods [25], [26].

A technology for selective destruction of minerals of complex polycomponent titanium ores of primary deposits is recommended, due to the targeted change in the mechanism of crack formation. The idea of selective separation of new mineral types of ores is implemented in the design of an improved magnetic separator. Measures have been developed to increase the efficiency of magnetic enrichment of complex polycomponent titanium ores by 16.57-17.42%. A technology for complex ore processing has been proposed, ensuring the production of concentrates used for the extraction of titanium slag (weight fraction of titanium oxide - 81-84%) and high-purity metallic iron with an average chemical composition of Fe0.993Ti0.006. The developed technologies are the basis for the feasibility study of the ore processing technology of the Abu Galago deposit (Egypt), when designing the industrial complex of the State Enterprise "GPI Institute of Titanium", Zaporozhye, Ukraine [27], [28].

Economic efficiency. The technical and economic calculation confirmed the positive results of the new enterprise, namely: the payback period of capital investments in terms of net profit is 2.71 years, the profitability of products in terms of net profit is 37.83%, the expected annual economic effect from the implementation of the enrichment technology of hematite-ilmenite ores of primary deposits is 159,042 thousand UAH, the average annual discounted flow value NPV is 7,070,000 UAH or 328.98 thousand USD, the average annual discounted economic effect is 4,466 thousand UAH or 207.7 thousand US dollars.

Environmental safety (efficiency). The developed technology for the enrichment of hematite-ilmenite ores using new separators allows obtaining concentrates without the use of flotation and chemical methods, thereby ensuring the environmental safety of the environment.

5. Perspective research directions

The authors have developed new generation magnetic separators at the invention and patent level (utility model patents: Centrifugal magnetic separator UA No. 51638 U; Device for magnetic cleaning of liquids and gases UA No. 67185 U; Multi-product magnetic separator UA No. 68638 U) for enrichment of iron and titanium ores and dust collection during their processing. They have been implemented at mining and processing plants in Kryvbas (Ukraine) and make it possible to reduce dustiness of the air in workplaces and emissions into the atmosphere, as well as to increase the economic efficiency and environmental safety of the processes of processing rock mass and enrichment of ore raw materials, including titanium-containing ones [29], [30].

In addition, the design of the triboelectrostatic separator (utility model patents UA No. 91469 and UA No. 91470), in which more intensive charging of particles and selective separation of positively charged particles occurs (Fig. 5).

It has been established that the apparatus for the effective separation of oxidized iron ore minerals requires several charging and separation systems. After passing several stages of charging and separation, the separated flow is completely cleared of positively charged particles. The maximum concentration of particles per unit volume of gas (with an increase in this concentration, the efficiency of the apparatus will decrease) is calculated, which is equal to 2.74·106 m-3, which corresponds to the maximum permissible concentration of material in the carrier air equal to 41.3 g/m^3, which ensures the normal operation of the separator.

Research and implementation of new technologies and technical means using dry magnetic separation will allow for the stable production of high-quality concentrates, as well as the reduction of the grinding and enrichment front by at least 15–20% of the original, which will reduce operating and capital costs by more than 30% and will become a powerful technological reserve for the development of mining production [31].

In our opinion, the following new scientific and methodological provisions deserve attention:

1. An increase in the coefficient of disclosure of ore and non-metallic minerals is substantiated by reducing the strengthening of bonds in the contact zones of grains due to the accelerated diffusion of atoms of various minerals to the planes of fusion and the boundaries of concentrations of local defects and the creation of a network of embryonic cracks inside nanosprouts and, as a consequence, the recrystallization of individuals.

vol. 30, issue 4 / 2024
pp. 44-55

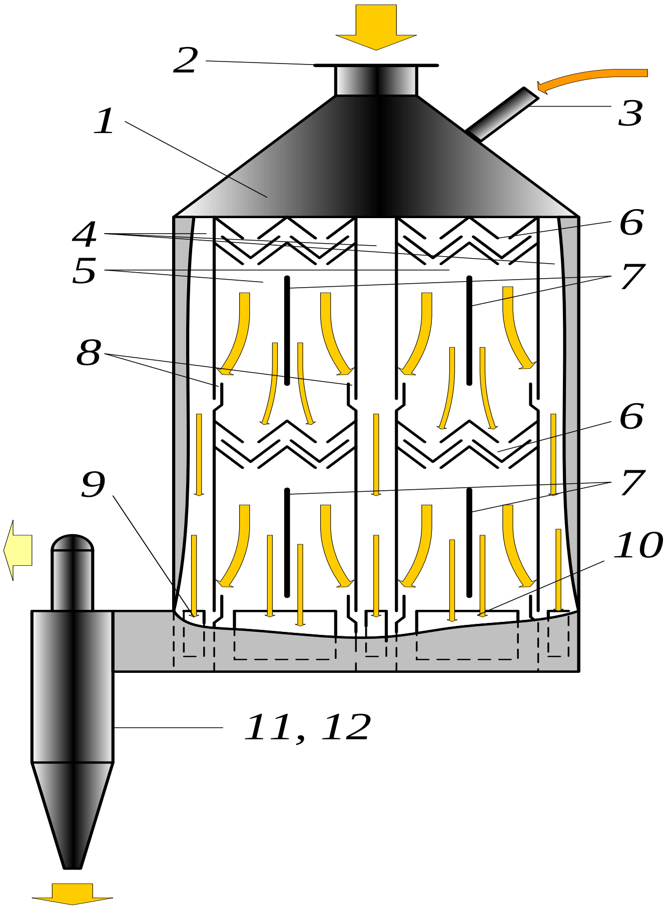

Fig. 5. Triboelectrostatic separator (diagram): 1 - working chamber; 2 - separation product feed pipe; 3 - additional loading pipe; 4 - negative deflection electrodes; 5 - separator sections; 6 - particle charging devices; 7 - positive deflection electrodes; 8 - horizontal slots; 9, 10 - collectors; 11, 12 - cyclones.

2. An increase in the difference in the contrast of magnetic properties of hematite-ilmenite ore minerals during their high-temperature processing was established due to the formation of new homogeneous ore and non-ore minerals with a minimum content of impurities that have different magnetic favorability, which makes it possible to increase the efficiency of raw material enrichment in absolute terms by 16.57%.
3. A thermodynamic model of the effective magnetization of the mineral constituents of the ore was obtained, in which, unlike those previously proposed, to simulate the magnetic order in minerals, average molecular fields are used, which are approximated by the Hamiltonian function (Hamiltonian), or the operator of the total energy of the system, which allows us to substantiate the possibility of changing magnetic properties of ilmenite and the optimal composition of the raw material, which is characterized as a composite system with a range of hematite content from 15% to 60%.

6. Conclusions

Based on many years of research and the results obtained, a modernized separator scheme for material with a temperature exceeding 150 °C is recommended for the new enterprise; the authors have made the following conclusions.

It is shown that the enrichment technology for hard-to-enrich hematite-ilmenite ores of the primary deposit involves a combination of a highly efficient magnetic separation process and ore softening under the influence of temperatures within 1000-1050 °C.

According to this technology, using modernized magnetic separators, titanium concentrate was obtained from ore with a content of Fetotal -37%, TiO2 - 32.7% and V2O5 -0.3%. Titanium slag with a mass fraction of titanium oxide of 80-81.84% and high-purity metallic iron with an average chemical composition of Fe0.993Ti0.006 were obtained in the metallurgical process. It was established that as a result of magnetic enrichment on modernized separators of crushed ore with a mass fraction of titanium oxide of 32.3% (after high-temperature treatment - HTT), a "rough" concentrate with a mass fraction of titanium oxide of 37.6%, total iron - 42.29% was obtained in laboratory conditions.

 vol. 30, issue 4 / 2024
pp. 44-55

At the same time, the mass fraction of harmful elements: silicon, aluminum and calcium oxides in total amounted to 1.2%. The efficiency of separation of ore minerals according to Hancock-Luiken using the proposed technology was 17.42% against 15.76% using the technology without preliminary HTT, and non-metallic minerals - 45% against 22.66%.

It has been determined that as a result of the impact of temperatures in the range of 850-1050 ° C on the mineral matrix "hematite-ilmenite", the texture of the ore changes through the creation of a network of embryonic cracks inside nano-growths and the emergence of decrepitation rims of hematite, the thickness of which increases with the lengthening of time around the ore grains of ilmenite. This allows, with further destruction, to increase the selectivity of the opening of the intergrowths by an order of magnitude and reduce the time of ore grinding by 7.8 times.

The positive results of the new enterprise's activities have been confirmed by technical and economic calculations, namely: the payback period for capital investments in terms of net profit is 2.71 years, the profitability of products in terms of net profit is 37.83%, the expected annual economic effect from the implementation of the enrichment technology for hematite-ilmenite ores from primary deposits is 159,042 thousand UAH, the average annual discounted flow value NPV is 7,070,000 UAH or 328.98 thousand USD, the average annual discounted economic effect is 4,466 thousand UAH or 207.7 thousand USD.

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