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DEVELOPMENT OF CONCENTRATION TECHNOLOGY FOR MEDIUM-IMPREGNATED HEMATITE QUARTZITE OF KRYVYI RIH IRON ORE BASIN

Introduction. *Trends in developing Ukraine's metallurgy in the context of using its mineral raw base indicate prospects for mining hematite quartzite deposits.*

Problem Statement. *The problem of producing high-quality hematite ore concentrates is associated with the fact that aggregates of martite, goethite, marshallit quartz, and other low hard minerals can be easily reground while crushing and grinding. This results in increased content of fine particles (slimes), which decreases selectivity of separating ore and nonmetallic minerals. One of the ways to solve this problem is gentle ore grinding.*

Purpose. *Developing a technology of dry and wet concentration for hematite quartzite from Kryvyi Rih Iron Ore Basin.*

Materials and Methods. *While conducting the research, a set of methods are used including generalization of research data; chemical and mineral analysis of ore and concentration products prior to and after concentrating by magnetite and gravitation methods; mathematical modeling of processes; technological testing in laboratory and industrial conditions.*

Results. *Magnetic and gravitation separation is used for hematite ore concentration. Sintering ore with Fe content of 55.1% and concentrates of 62.32—64.69 % Fe have been produced from hematite ore. Iron extraction in marketable pro¬ducts makes up 73.6—80.49 %.*

Conclusions. *There have been developed technologies for dry and wet concentration for hematite quartzites of Kryvyi Rih Iron Ore Basin. For the first time, magnetic separation has been suggested to be used for hematite ore concentration. This has enabled producing concentrates with an iron content over 64.0%, decreasing ore grinding front by at least 40 % as compared with the initial one, and reducing operation and capital expenses by over 30 %.*

Keywords: hematite quartzite, open-circuit air separator, cyclone, and magnetic separator.

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The world's projected iron ore resources estimated at 790.9 billion tons are concentrated in the deposits of 98 countries. The world reserves of iron ore total 464.24 billion tons. Out of them, 206.9 billion tons are proven reserves. The three countries — China, Brazil, and Australia — have a share of 65% in the world marketable iron ore production, with China being the leader [1—3]. Ukraine is the leader in the proven reserves of iron ore (Fig. 1) and the seventh country in the iron ore (IO) production. The total reserves of explored iron ores in Ukraine, which according to the State Register of Reserves is about 30 billion tons, are concentrated in 52 deposits, out of which 24 ones have been developed. In addition, the State Register of Reserves does not include about 10 billion tons explored reserves of iron ore [4, 5].

Ukraine's reserves allow not only to meet the country's domestic needs, but also to export iron ore. Ferrous metallurgy is the basic branch of the Ukrainian economy, as in 2015, the share of metallurgy in the structure of Ukrainian exports was the largest among all industries (24.8 %). The share of exports amounted to 63.0 % of the total sales of the industry. Ferrous metals traditionally dominate in the structure of exports of metallurgical products, their share increased from 83.2 %, in 2008, to 85.3 %, in 2015. Despite a significant reduction in the share of ferrous metal products, from 12.8 to 9.7 %, this indicates that the raw materials continue to dominate in the structure of Ukrainian metallurgical export [6, 7].

The Kryvyi Rih iron ore basin is the main raw material base of the metallurgical complex of Ukraine. It concentrates 77 % of the in-place reserves of ore [4, 8] and 80 % of the existing production capacity for extraction and processing of iron ore. In 2016, the enterprises of the basin produced 74.6 million tons of raw iron ore, which accounted for 75.5 % of the total production in Ukraine. The dynamics of ore and concentrate production and marketable iron ore product exports are given in Table 1 [9].

The main products of mining corporations are rich iron ores with a mass iron fraction of 54—61 %,

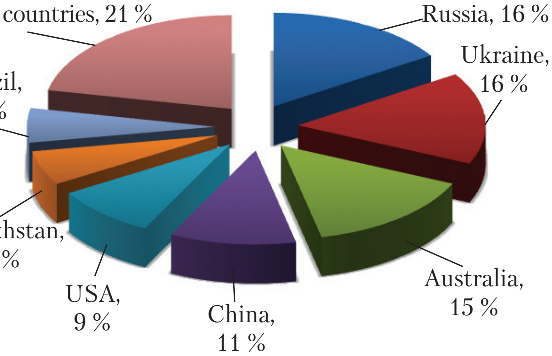

Fig. 1. Distribution of total iron ore reserves by country, % of world reserves

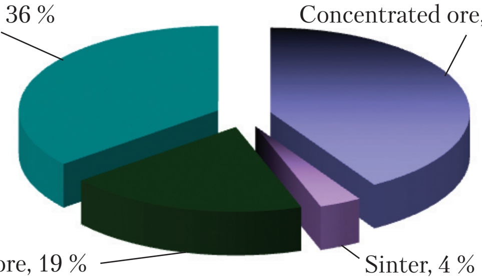

Fig. 2. The structure of production of commercial iron ore products by mining enterprises of Ukraine

concentrate with a mass iron fraction of 64—66 %, as well as iron ore pellets and sinter. The mass fraction of iron in industrial ores ranges from 16 to 70 %. The minimum mass fraction of iron in the raw material that is suitable for blast furnace smelting is 55%. Ores containing less than 50 % of iron are concentrated. They are used for obtaining marketable products (concentrate with a mass fraction of iron 62—67 %) [10]. The structure of production of marketable iron ore products by mining enterprises in Ukraine varies depending on demand in consumer markets and pricing policy. According to the data of 2016, the share of production of certain types of marketable products in the total output is as follows: sinter ore (19.4 %), concentrate (41.3 %), iron pellets (35.9 %), and sinter (3.4 %) (Fig. 2).

Hematite quartzites that have been piled as a result of preproduction mining of magnetite ores for the period of operation of Kryvbas mining and processing plants (over 60 years) are of special interest [11—16].

Hematite ores have a significant place in possible reserves of iron ores and are the main iron ore raw material for the long-term development of ferrous metallurgy in many countries. They make up about 23% in the total amount of concentrated ores. The largest processing plants are located in Canada, the United States, and Brazil.

The hematite ferrous quartzite reserves in Kryvbas account for 12% of the total ore reserves and their accompanying mining reaches 15—30 % of raw ore production. At the beginning of 2017, the explored reserves of magnetite quartzite of the five mining and processing plants of Kryvbas amounted to about 5 billion tons, the reserves of rich iron ore of seven operating mines in the basin totaled about 1 billion tons, and the projected oxidized quartzite reserves up to a depth of 1 km within the mining allotments of the existing mining enterprises are estimated at 50 billion tons [4, 11].

Hematite iron quartzites are a product of magnetite quartzite weathering. They are considered promising iron ore raw materials of the Kryvyi Rih basin [17, 18]. Competitive hematite concentrate shall contain, at least, 64.0—66.0 % of iron, which is equivalent to magnetite concentrates with a mass fraction of iron of 67.0—8.0 %in terms of silica content [19]. In this term, the deposits of the Ingulets Mining and Processing Plant are rather promising [17, 20].

The Ingulets deposit is the raw material base of the Ingulets Mining and Processing Plant (INMPP) that mines and processes poor magnetite ores. In recent years, the INMPP quarry has recorded deposits of rich hematite ores that were not mined during previous mining operations (so-called "lost deposits"). The hematite quartzite layers of the fifth and sixth ferruginous horizons contain bodies of rich hematite ores. The total mass fraction of iron in their composition ranges from 46 to 69 % and averages about 55 %. According to the mining technology used at the plant, rich ores together with hematite quartzites of the fifth and sixth ferruginous horizons were dumped. In recent years, rich ores have been selectively extracted and subsequently accumulated within a specially organized dump [17, 20]. In view of the above, it is necessary to assess the possibility of selective extraction and enrichment of rich hematite ores in order to produce from them agglomerated iron ore, as well as agglomerated and fine concentrates. The development of optimal technology for the enrichment of hematite ores shall be based on detailed technological research.

Many methods are used to enrich hematite iron ores, including: magnetizing roasting followed by magnetic separation in a low-voltage field [19], gravity concentration [21, 22], wet magnetic separation in a strong field [21, 23, 24], direct and reverse flotation with the use of cationic or anionic reagents [25—27]. Methods that combine two or more of the above mentioned are used as well [28].

Today, at 110 overseas iron ore beneficiation enterprises (approximately 63 % of the total number of enterprises), due to the development of enrichment equipment and technologies, there is a

Table 1. **Ore and Concentrate Production, Export of Marketable Iron Ore Products in 2007—2016 thousand tons [9]**

Region	Year									
	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Ore and concentrate production										
Ukraine	77753.5	72529.0	66500.5	78158.0	80610.6	80836.4	84680.4	82286.9	80342.0	74648.3
Kryvbas	62687.4	57430.3	51587.9	62279.0	64383.3	64236.6	66689.0	64060.4	61581.7	56360.0
Export of marketable products										
Ukraine	21183.0	22662.0	28709.0	33007.0	34565.0	35045.0	37813.0	41019.0	45468.0	37795.0
Kryvbas	10987.0	12736.0	18259.0	20934.0	22368.0	23323.0	24777.0	27703.0	31650.0	24026.0

tendency to process hematite and blended ores of various qualities, from poor (containing less than 30 % of iron) to rich (up to 60 % of iron). Outside Ukraine, fine-disseminated poor hematite ores are not concentrated by gravity methods.

The gravitational methods are used in the beneficiation of large- and medium-disseminated easily concentrated hematite ores. They have become widespread mainly in such countries as India, Australia, Canada, Sierra Leone, and Sweden [21, 22]. The gravitational methods make it possible to obtain concentrates with a mass fraction of iron of 62.5—65 %. Gravitational separation of hematite ores is made mainly in the case of a size larger than 0.5 mm. In this case, the exposure of minerals is not crucial, because the size of their shots coincides with the size of gravity concentration.

Hematite ore beneficiation plants use fine screening as an auxiliary process that, to some extent, improves the quality of the concentrate due to the distribution of the product for its more efficient beneficiation [28]. At the Wabush factory (Canada), fine screening is used to separate the concentrate of the first stage of high-intensity magnetic concentration. The product contains 53—55 % of iron. This process allows to obtain both undersize concentrate (with an iron mass fraction of 58 %) and oversize product (35 % of iron) [29]. At the Caue mine (Brazil), a fine screen is used to select a grade from –0.15 to +0.07 mm, which feeds the Jones separator. At the Samarco factory (Brazil) this process is used in the flotation concentrate grinding cycle. At the Hongquan enterprise (China), the technology of enrichment of poor hematite ore involves fine screening after weakly magnetic concentration. The undersize products are sent to the third stage of magnetic concentration in order to increase the mass fraction of iron to 67 % [29].

For medium- and fine-grained hematite and martite ores, magnetic concentration in a strong field is used [21, 23, 24]. The Concessaine factory (Brazil) processes hematite and itabirite ore with an iron mass fraction of 48—52 %. The deslimed fraction –1 mm is sent for concentration, after which a concentrate with an iron mass fraction of 67.7 % is obtained. In Port Cartier (Canada), a concentrate with an iron content of 66 % is enriched to get a concentrate containing 68—69 % of iron [24]. At U.S. and Mexican factories, the predominant method of concentration is high-gradient magnetic separation on DR-317 separators. Deslimed product with a size from –0.5 to +0.01 mm is used as a process feed. The concentrate with an iron mass fraction of 67—68 % is extracted. Similar results in terms of the quality of concentrate have been obtained at several other factories for the enrichment of large or medium-disseminated hematite ores by high-gradient magnetic separation with the use of Jones separator [19, 24].

Other similar examples from the practice of concentration of weakly magnetic iron ores with the use of high-intensity polygradient magnetic separators can be cited. In these cases, coarse-grained deslimed rich material is processed. Especially interesting is the well-known experience of the Tilden mine in Minnesota (USA) [19, 23, 24], which uses iron taconites as crude material. The technologies for processing taconites, like in the case of hematite quartzites, involved various concentration methods, including polygradient magnetic separation, flotation, and magnetizing & roasting methods [30, 31]. However, all these methods did not yield any positive results. Only the technology developed by the U.S. Mining Bureau, which involves the use of selective flocculation in combination with reverse cationic flotation, with starch and amines as reagents has been successful. The difficulty of enriching the Tilden iron taconites is that in order to release minerals, the ore shall be ground to a size less than 0.020 mm with a fraction content of 75—80%. That is, such material is characterized by a large amount of chips. No cases of concentrating minerals of this size by mechanical means have been reported so far.

In Ukraine, hematite ores have not been concentrated on an industrial scale. However, there have been made studies with the use of magnetizing roasting, magnetic, flotation, gravitational methods and their combinations for hematite ore concentration in Ukraine

In the case of magnetizing roasting, having been ground, hematite raw materials were subjected to regenerative roasting, with hematite replaced by magnetite:

$$6Fe_2O_3(\text{hematite}) = 4Fe_3O_4(\text{magnetite}) + O_2. \quad (1)$$

Magnetite attached to hematite is removed from the reduction products by magnetic separation in a weak field [19].

The magnetizing roasting has been abandoned because of a high energy consumption and a significant amount of harmful emissions. An alternative option is the high-gradient magnetic separation technique.

As a result of research based on the wet polygradient magnetic separation, the Institute for Mechanical Processing of Ferrous Metals has developed a technology for enrichment of hematite quartzites at the Kryvyi Rih Oxidized Ore Mining and Processing Plant (KOOMPP) [19, 32].

According to the design, the KOOMPP technological scheme involves three-stage grinding of crude ore from a size of 1200 — 0 mm to a size of 18—0 mm. The iron ore magnetic concentration process flow chart consists of two stages of grinding and two stages of magnetic concentration. Gradual magnetic concentration is carried out first in weak magnetic fields on drum separators of PBM-120/300 type with, at least, 0.13 T induction of a magnetic field on the surface of the drum. Further, the process takes place in strong magnetic fields on electromagnetic separators of 6ERM-35/315 type. The strongly magnetic fractions are separated on a rotor with an induction up to 0.4 T. The nonmagnetic products from the first rotor are repeatedly cleaned on the second and third rotors with a magnetic field induction of 1.2 T. At the first stage, magnetic concentration is carried out at a fragmentation size of 75 %, grade —0.074 mm, at the second stage, at a fragmentation size of 95 % grade —0.044 mm. Having been enriched, the concentrate is thickened on radial thickeners with a diameter of 24 m and dehydrated on disk vacuum filters of Du-160 type. The standard indicators for this technique are as follows: iron mass fraction in crude ore is 36.0 %, iron mass fraction in concentrate is 61%, iron extraction to concentrate is 64.0 %, concentrate yield is 37.8 %, the mass share of iron in tails is 20.8%. Based on the quality of the concentrate, the iron content in pellets is taken 58.73%, and the base-to-silica ratio is 0.35.

In further studies [19, 33, 34], to improve the oxidized ore magnetic concentration process flow design, there has been developed a technology that involves separation of crushed source material into two streams, their separate concentration to obtain magnetic products, supply of a thin magnetic product to the control classification operation at the second stage of grinding. As a result, from the ore with an iron mass fraction of 38.5 % a concentrate with an iron mass fraction of 63.0 % at a yield of 39.6 % and extraction of 64.8 % has been obtained.

The main disadvantage of the research to improve the magnetic concentration scheme is that the authors tried to transform the whole product of the first enrichment stage into the magnetic product. However, the presence of quartz grains with small enclaves of magnetite equates them in terms of magnetic properties to hematite ore grains. While enriching the ore by the magnetic method, these particles are extracted into the magnetic product and weaken the concentrate. Therefore, it is necessary to try to separate, at least, part of the concentrate by the magnetic method, and to enrich the rest of the product by the flotation, gravity or other techniques.

The highest increase in the mass fraction of iron in the concentrate (2.9 %) has been obtained in the case of desliming of all crushed crude ore and the gradual separation of the concentrate [35, 36]. This is because of the fact that the difficulties of concentrating weakly magnetic iron ores are associated with their strong slime contamination, with slime particles sticking on the surface of both ore and non-ore minerals while grinding the crude material. Non-metallic fine particles (quartz, clay impurities, etc.) usually stick to ore particles, while ore particles (iron hydroxides, hematite, martite, etc.) stick to non-ore particles [36, 37]. Thus, when the fragmentation size is reduced three times, the share of the stuck ore particles with a size of –0.005 mm increases from 2.1 to 9.83 %, and that of particles larger than 0.005 mm grows from 1.10 to 6.72 %. For the non-ore particles, the share of the stuck grains smaller than 0.005 mm varies from 2.60 to 13.19 %, and that of particles larger than 0.005 mm ranges from 0.31 to 6.14 % [19, 36].

During wet enrichment in a strong magnetic field (0.6—1.4 T), fine particles more intensively stick to the surface of large grains. On ore mineral grains, depending on the size, the share of particles smaller than < 0.005 mm reaches from 2.65 to 12.11 %, while on the non-ore mineral grain it ranges from 3.14 to 15.48 %. The specific magnetic susceptibility of the ore phase decreases from 13×10^{-3} m³/kg to 10.8×10^{-5} m³/kg, whereas that of the non-ore phase increases from 1.6×10^{-6} m³/kg to 6.6×10^{-6} m³/kg i.e. the magnetic properties of minerals become less contrast. In addition, slime with a size less than 0.010 mm significantly affect the rheological properties of the fine pulp. Thus, at the fragmentation size 95 %, grade –0.074 mm at the final stage, the mass fraction of slime changes from 4—5 to 20—25%, and the viscosity increases from 0.25×10^3 to 5×10^3 Pa · s, times, which also negatively affects the process of concentration of fine-grained hematite quartzites.

In further studies, the scheme has been improved through the use of concentrate flotation technique [19, 32]. Flotation enrichment of magnetic product of high-intensity magnetic separation (HIMS) (with an iron mass fraction of 61 %) has enabled obtaining a concentrate with an iron mass fraction of 65.0 % and its extraction of 67.4 %.

The processing of hematite ores is an important issue, which is justified, firstly, by the fact that the enrichment will reduce the cost of production of concentrates mined together with magnetite quartzite, at mining and processing plants, with the costs of their mining included in price of magnetite quartzite. Secondly, the use of hematite ores will significantly expand the iron ore base of Ukraine and ensure a more rational use of mineral resources.

The analysis of the main directions and approaches to the processing of poor hematite ores has shown that for the production of competitive iron ore it is necessary, first of all, to decide on the choice of process flow scheme for its concentration. It should be noted that the possibilities for improving the qualitative and quantitative indicators of concentration have not yet been exhausted. The review of the current state of hematite iron ore concentration has shown that the most promising and environment friendly method for processing hematite ores is magnetic separation in a high-intensity (high-gradient) magnetic field in air, water or in their combination. Process flow charts for hematite ore concentration shall be developed given the parameters of mineral dissemination. At the same time, it is necessary to minimize the re-grinding of ore grains, as well as to reduce energy consumption for grinding industrial products.

When enriching hematite ores, it is important to solve the problem of stabilizing the quality of crushed ore entering the grinder. This is possible due to dry magnetic pre-enrichment [19, 38, 39]. The possibility of dry magnetic separation, as an effective operation of pre-enrichment of hematite quartzites, is one of the most pressing problems today. Recently, the issue of preliminary enrichment of poor hematite quartzites has been closed and none of technologies for processing oxidized ores has mentioned it. In addition, this operation helps improve ore concentration and reduce fluctuations in the material composition of concentrates.

The purpose of this research is to develop the technology for concentrating medium-disseminated hematite quartzites of Kryvbas, given the present-day requirements for the quality of iron ore prepared for metallurgical treatment.

To achieve this, the research has solved the following tasks:
- to study the material composition of crude materials, to establish the influence of ore quality on the indicators of its grinding;
- to study the possibility of pre-enrichment of medium-disseminated hematite quartzites of Kryvbas for stabilizing the quality of crude ore;
- to determine the main factors influencing the process of magnetic separation for obtaining concentrates of stable high quality;
- to develop technologies for enrichment of medium-disseminated hematite quartzites of Kryvbas in water and air environments.

While researching, we used the following research methods: generalization of scholarly research information; X-ray phase and mineral analyzes of ore and concentrated products. The mineralogical and technological studies are based on the results of geological, mineralogical observations, chemical analysis and technological tests of rich hematite ores of the fifth and sixth ferrous horizons of the Saksaganska Formation of the Ingulets deposit.

Totally, 25 ordinary samples of rich hematite ores are taken, including 5 samples in the quarry face and 20 samples in the ore stock pile. The tests are made by the point-furrow method, the length of the test intervals, depending on the homogeneity of the ore material, varies from 10 to 15 m. The mass of ordinary samples is 15—20 kg, which corresponds to the total material mass required for mineralogical studies, chemical analyzes, and in-process tests. Reduced phase and silicate chemical analyzes are made for the material of each ordinary sample.

For microscopic studies, the necessary preparations from the material of each ordinary sample are made: ores and powders for binocular studies, transparent and polished specimens for microscopic studies. Mineralogical properties of many ores and host iron rocks (diagnostics of minerals, study of the conditions of their formation, quantitative mineralogical calculations, microphotography, etc.) have been studied based on standard methods, with the use of serial binocular, petrographic, and mineralogical microscopes. Based on the mineralogical study and chemical analysis, the mineralogical properties of mineral and rock components are established. These data are further used to make large samples for in-process tests.

Three large laboratory samples of rich hematite ores and one combined laboratory sample, each weighing about 150 kg, are used as source materials in the in-process tests. Laboratory samples are composed of materials taken in the quarry face and in the ore stock pile of all ordinary samples. The combined laboratory sample is composed of the material of three large laboratory samples.

For technological research, standard methods are used in accordance with the Government Standards of Ukraine DSTU 3195-95, 3196-95, 3198-95, 3207-95, 3210-95; DSTU ISO 3082: 200, MOD; DSTU ISO 10836: 200, MOD).

For dry magnetic concentration (DMS), a drum separator with the upper supply of the output power supply BS-31,5 / 30-N manufactured by the research and production company *Prodekologiya* is used. Laboratory studies of magnetic concentration in a strong field in an aqueous environment are performed on a separator of 259-CE type, which simulates the process of an industrial separator 6ERM 35/315.

Gravitational concentration is performed on SKM-2 concentration table at a load of 15—20 kg / h and different sizes of the source material: 1—0 mm, 0.5—0 mm, 0.1—0 mm, and 0.074 mm. When enriching the material on the concentration table, the parameters successively vary: the angle of inclination of the deck, from 4 to 100 °; the stroke of the deck, from 10 to 16 mm; and the oscillation frequency of the deck, from 4 to 7 Hz.

The program of in-process tests includes a detailed study of the material's particle size composition, the study of ore properties in terms of concentration, experiments with the use of existing laboratory equipment, analysis of the results, and load removal from the equipment.

The test sample is composed of the averaged carefully stirred material of all ordinary samples.

The material of each initial sample is subjected to grinding to a particle size that provides the release of individual and aggregate ore and non-ore minerals. Preliminary tests have shown that it is sufficient to grind the source material to a size of 95 % of the grade less than 0.074 mm. The particles of more fragile ore minerals are almost completely (for different samples, from 97 to 99 %) exposed and concentrated in the material fraction –0.050 mm. Particles of stronger quartz minerals are also almost completely exposed and have a size of 95 % of the grade less than 0.074 mm [20].

To make the whole complex of research on DMS, ore samples are cut and crushed to different sizes, namely 20—0 mm, 10—0 mm, 5—0 mm, and 1—0 mm. Subsequently, the prepared samples are studied by the magnetic separation and gravity techniques. Having been studied, they are used for taking samples for chemical analysis and mineralogical study.

The algorithm consists of the following successive stages: dry magnetic separation of the entire sample in one stage; separate dry separation of grades 20—10 mm and 10—0 mm, separation of the obtained products and industrial product having a size of 20—10 mm, crushed to 10—0 and 5—0 mm, and separation of crushed material in two stages. When studying ore samples having a size of 1—0 mm, direct dry magnetic separation in one stage is made.

To select the optimal mode of dry magnetic separation and equipment for it, a matrix of experimental planning, which includes more than 200 basic experiments has been compiled.

In the course of research, it is necessary to study the main factors influencing the process of magnetic separation, because of the following reasons:

- Hematite ores belong to weakly magnetic minerals that are characterized by a low specific magnetic susceptibility. Therefore, their separation requires a force that is approximately 200 times higher than the extraction of minerals from strong magnetic ores. Therefore, in the course of the research, it is necessary to study the effect of strength on the drum on the quality of the concentrated products;
- the speed of drum rotation largely determines the separator performance and the quality of the separated products. In research, the speed of drum rotation is chosen depending on the size of the material and the required quality of the finished products: ready-made concentrates or tails.

The maximum allowable speed of the drum rotation υ, at which the nonmagnetic fraction is removed and the angle of separation of tails from its surface (angle of fan opening) β, is determined by the formula:

$$F''_M < F''_n = m \times \left(\frac{\upsilon^2 (R + 0{,}5d)^2}{R^3} - g \times \cos\beta\right) \times \times \frac{1}{1 + \alpha_m}. \quad (2)$$

where F''_M is force of magnetic attraction of tails containing a certain amount of magnetic mineral, N; F''_n are forces that separate the tail from the drum, N; α_m is content of magnetic mineral, n.u.; m is mass of material, kg; R is drum radius, m; d is particle size, m; g is the acceleration of gravity, m/s^2.

Proceeding from the above

$$\beta = \arccos\left[\frac{\upsilon^2 (R + 0{,}5d)^2}{R^3 g} - \frac{F'_m (1 + \alpha_m)}{g}\right]. \quad (3)$$

Tails are separated from the drum at a high rotation speed. For them to fly over the partition, the angle of the fan shall be $\beta \le 90°$.

Having analyzed the above formulas, it should be noted that the higher is the speed of rotation, the larger are the tail parts, and the smaller is the content of the magnetic fraction, the smaller is separation angle β. Therefore, the research program includes experiments aiming at studying the effect of the speed of drum rotation, the angle of fan opening, and the length of the working area of separation on the final separation of the material.

When doing experiments, it is necessary to take into account that the ratio of the diameters of the largest and the smallest ore grains entering the separator shall not exceed the equal settling factor.

During a detailed geological study of the Ingulets deposit, the mineral composition of samples of rich hematite ores and some of their characteristics have been established. The main ore-forming minerals are hematite (58.16 %) and quartz (38.56 %). The former is represented by martite, iron mica, and small quantities of dispersed hematite. There are seldom relite inclusions of magnetite in martite aggregates, the amount of which naturally increases with the depth of ore occurrence. Quartz is the main non-metallic mineral of rich ores [17, 20].

In the composition of hematite ores of the fifth and sixth ferrous horizons, there are four main groups of minerals [17, 20, 32]:

- granular ore minerals that include five minerals and mineral varieties: martite, iron mica, goethite, lepidocrocite, and magnetite. The particle size ranges from 0.1 to 0.01 mm, the average size is 0.05—0.07 mm. Siltstone material is formed while crushing and grinding individual and aggregate minerals to the stage of their release. When concentrating ore, it is easily separated from particles of non-metallic minerals;
- fine ore minerals that include dispersed hematite and dispersed goethite. The particle size varies from 0.01 to 0.001 mm and less. Having been crushed and ground, the aggregates of these minerals are transformed into argillite (0.01—0.001 mm) and perlite (less than 0.001 mm) material. This product is virtually inseparable with the use of mechanical concentration methods;
- minerals of the quartz group: quartz, chalcedony, and opal; having been crushed and ground the individual and aggregate minerals form siltstone non-metallic material with a size of 0.1—0.01 mm. This product, having been enriched by mechanical methods, is easily separated from ore mineral particles of the same size;
- other minerals that include weathered ferrous silicates and carbonates, newly formed non-metallic silicates and carbonates, and other minerals. Individual and aggregate minerals of this group, having been crushed and ground are transformed, mainly, into argillite and perlite material that is practically not concentrated or hard-to-concentrate with the use of mechanical methods.

Thus, in a simplified version, having been crushed and ground, all individual and aggregate minerals of the studied hematite ores are transformed into two graded products:

- the granular fraction: martite, iron mica, goethite, lepidocrocite, magnetite, and quartz;
- the tailing fraction: dispersed hematite, dispersed goethite, weathered relict and newly formed silicates, carbonates, sulfates, and other minerals.

In reality, the process is a little bit more complicated. For example, weak martite aggregates are easily crushable while crushing and grinding. Marshalite quartz is also crushable. Because of this, one of the main problems of ore preparation is the organization of gentle grinding of ore. When developing the concentration technology, it is necessary to provide techniques that allow timely removal of particles ready for enrichment. That is, while preparing ore, it is necessary to prevent re-grinding of minerals and, as a consequence, their transformation into sludge.

The mineral composition of the sample is determined by the chemical composition of hematite ores. In the technological samples, the average mass fraction of iron (Fe_{tot}) is 46—54 %. The mass fraction of iron that is part of magnetite (Fe_{magn}) is insignificant because of the intensity of hypergenic changes in the ores and averages 0.16 %. The mass fraction of iron that is part of silicates and carbonates is also insignificant and averages 0.43 %. The main factor determining the decrease in the mass fraction of iron in the ores is the presence of rock particles that contain low-iron minerals [16]. Their removal from the ore mass is the main task of ore concentration for the production of sinter ore, sinter concentrate, and concentrate.

Rich hematite ores are characterized by a low specific fracture energy. Their strength according to M.M. Protodiakonov scale in absolute terms is lower than that of ferrous quartzites, as well as shales and non-metallic rocks. This difference allows selective separation while crushing combinations of ores and rocks.

Ore minerals differ in density and specific magnetic susceptibility. The density of martite, iron mica, and magnetite is 5150—5200 kg/m^3, that of goethite and lepidocrocite is 4000—4400 kg/m^3, and that of minerals of the quartz group is twice lower, from 1900—2200 kg/m^3 (opal) to 2650 kg/m^3 (quartz). Therefore, beneficiation of these ores using gravity equipment can be effective. Magnetite belongs to ferromagnetic materials; martite, iron mica, goethite, and lepidocrocite are paramagnetic substances, minerals of the quartz group are diamagnetic materials.

Therefore, iron-containing minerals can be extracted by magnetic separation in air or water. For this process, a complicating factor is the presence of magnetite in hematite ore. Therefore, in the process flow diagram, magnetic separation in a weak field shall be a preliminary to high-gradient magnetic separation.

The process of dry magnetic separation of hematite ores is based on the magnetic and gravitational properties of the particles to be separated, i.e., on the values of specific magnetic susceptibility and density as a function of particle mass. The latter factor is more important in the dry separation of weakly magnetic ores than in the separation of strongly magnetic materials [38, 39].

At the first stage of technological research, the possibility of obtaining sinter ore from the ores of the Ingulets deposit has been considered. To obtain it from hematite ore, dry magnetic separation in a strong field created by high-energy systems from permanent magnets made of Nd-Fe-B alloys is used as the main concentration method.

The studies have been made with the use of samples of different sizes. The particle-size analysis of ore samples of different sizes has shown that when crushing ore to a particle size of 20–0 mm and 10–0 mm, the material is distributed rather evenly over the fractions. The fractions less than 2 mm are enriched with ferrous minerals, according to chemical analysis. The mass share of iron in the fractions of 2—0 mm is 53.0—53.4 %, while

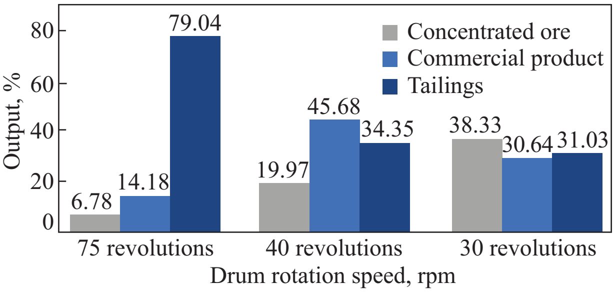

Fig. 3. Influence of the drum rotation speed on the yield of hematite ore concentrated products

that in the fractions of 20—2 mm is 39.2—43.25 %. When crushing the material to a size of 5—0 mm, 1—0 mm, this difference is leveled. It should be noted that the fraction less than 0.1 mm accumulates fine-grained marshalite quartz, the particle size of which is < 0.1 mm. This is because of the reduced mass share of iron (43.1—43.6 %) in the fractions of 0.1—0 mm. The number of dust-like classes (–0.1 mm) in ore of 20—0, 10—0, and 5—0 mm ranges from 5 to 7 %, while in the fraction of 1—0 mm, the number of particles of grade 0.1—0 mm accounts for 30 %. Therefore, when developing the technology of dry ore concentration, it is necessary to preliminary remove dust from the material to ensure not only the separation, but also the possibility of partial enrichment of source materials. Hence, ore shall be prepared for beneficiation in two stages in a gentle mode, with the use of pre-screening before the second stage of crushing.

The analysis of the results has shown that the best concentrate quality indicators are reported for magnetic separation of 20—0 mm ore grains. As the size of the ore grains decreases, its moisture content increases, which causes deteriorating selectivity of dry magnetic separation.

The optimal speed of drum rotation is determined with the use of material with a size of 20—0 mm. The research results are shown in Fig. 3.

It has been established that as the speed of drum rotation increases, the quantitative indicators of magnetic separation deteriorate, in particular, the yield of the tail fraction sharply increases and, consequently, the qualitative indicators do not improve. Therefore, the optimal speed of drum rotation is 30 rpm.

As a result of DMS experiments, a concentrated iron ore with an iron mass fraction of 54.4—63.46 % has been obtained from ore grains having a size of 20—0 mm, in one stage, with the use of a drum magnetic separator. The analysis of the research results has shown that in the tests, the yield of concentrated ore varies depending on the quality of the source ore. It makes up 10.31 % for the ore with an iron mass fraction of 46—48 %, 10.97—19.97%, for the ore with an iron fraction of 49—51%, and 35.94—54.87 % for the ore with an iron fraction 52—54 %. While separating 10 mm ore grains, the extraction of iron to the concentrated ore increases by 4—5%.

Further, the influence of magnetic field induction on the extraction of the magnetic product has been studied. It has been established that for extracting commercial concentrated ore with the maximum output it is necessary to use a drum magnetic separator with a field induction of 0.5 T in the process of the main separation. However, for re-separating the nonmagnetic product, the magnetic field induction shall be raised to 0.7—1.1 T. The exposed iron-containing minerals and their rich clusters are maximally extracted to the additional secondary concentrate. The yield of nonmagnetic product decreases by 10—15 % for the ore with an iron mass fraction of 46—48 %, by 12—32 % for the ore with an iron fraction of 49–51 %, and by 14—30 % for the ore with an iron mass fraction of 52—54 %. Re-separation of the nonmagnetic product with an iron mass fraction of 50.31 % on a 1RS-22/30-R-07.036 separator with the magnetic field induction of 1.1 T has allowed obtaining an additional magnetic product (22.88 % of the source material with an iron mass share of 55.2 %) and increasing the extraction of iron to the concentrated ore by 24.72 %.

Thus, as a result of dry magnetic separation, a commercial product, sinter ore with an iron mass fraction of 55—63.46 %, and an industrial product with an iron mass fraction of 34.3—46.6 % have been obtained. The industrial product is further ground to 90 % of the grade –0.05 mm. Thereafter, its enrichment in the aqueous medium has been studied.

The analysis of the research results has shown that with the help of gravity concentration one can get the highest quality concentrated ore with a maximum material exposure: the iron mass fraction in hematite concentrate is 68.2 %, with 90 %, grade –0.05 mm, in crushed source materials. However, for such grinding a maximum loss of iron in tails is reported. Therefore, it should be noted that to obtain optimal results from the separation of source materials by the gravity methods, the size of crushed ore grains shall not exceed 65 %, grade –0.05 mm. The product of gravitational concentration formed by separating the material with a size of 0.5—0 mm in the amount of 17.8 % of the source material is recommended to be ground to a size of 80 %, grade –0.05 mm, and having been ground, to undergo magnetic separation in a strong field. As a result of the research, hematite concentrate with an iron mass fraction of 61.6—62.8 % has been obtained. The output of commercial products increases 5.63—7.76 %, with the extraction of iron into the concentrate as a whole ranging within 6.89—10.3 %.

The analysis of the research results on magnetic separation in an aqueous medium has shown that hematite concentrates with a mass fraction of iron 62.8 % can be produced from the source ore, at a yield of 53.67 %, and concentrated ore with an iron mass fraction of 62.4 % can be obtained from the DMS nonmagnetic product, at a yield of 40.45 %. The lower yield of the product in the second case is explained by the fact that the iron-containing minerals have already been partially transformed into a commercial product by dry magnetic separation. It should be noted that the separation of DMS nonmagnetic product makes it possible to obtain additional 24.14 % high-quality concentrate and to increase the iron extraction by 31.71 %, from 52.25 % to 83.96 %. At the same time, in the case of wet magnetic separation of the source ore without prior beneficiation the iron extraction accounts for 74.05 %

that is by 9.91 % less as compared with the DMS method.

The experiments on dry concentration of ore crushed in air to 90 %, the grade –0.05 mm, have been made with the use of a mill with a ventilated circuit. To prevent re-grinding of ore mineral particles, the source material is ground in three stages with separation of the finished product after each grinding stage. The fine product is further separated in an air separator. The fractions are separately transported firstly to a tubular magnetic separator, where the concentrated ore is extracted. The industrial product is re-separated in two successive high-intensity cyclone magnetic separators. Dry separators for concentration of fine hematite ores have been developed at the Kryvyi Rih National University. Two configurations of separators, tubular and cyclone ones having systems on permanent high-intensity Ni-Fe-B magnets, have been designed [36, 37]. The tubular separator is a section of pipeline through which fine ore moves in an air stream. The cyclone separator (Fig. 4) is at the same time a dedusting plant. As a result of passing the ore through these plants, a concentrated ore with an iron mass fraction of 62—64% has been obtained, with iron extracted into a concentrate of 74—76 % and tailings. The mass fraction of iron in the tails does not exceed 17%.

The analysis and synthesis of the research results have allowed developing five options of the process flow diagrams for concentration of Ingulets deposit hematite quartzites in water (4 options) and air (1 option) environments. The same ore preparation scheme is provided for all options. It consists of two stages of crushing in an open cycle to a size of –20 mm. The crushed ore is further sent for concentration.

Four options of process flow diagrams of hematite ore concentration in aquatic environment, with and without preliminary beneficiation of the source material have been developed. The options differ in the cycles of finishing the DMS nonmagnetic product: with the help of the magnetic and the gravity-and-magnetic methods.

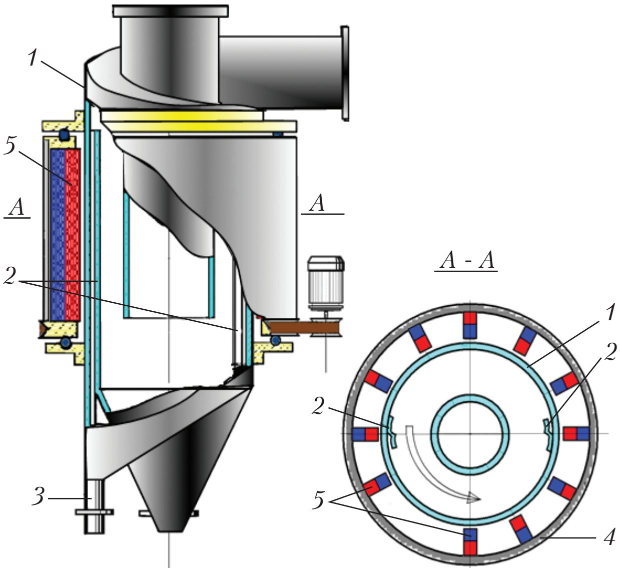

Fig. 4. Schematic diagram of a cyclone with a magnetic field: *1* — housing; *2* — trap; *3* — connection pipe; *4* — magnetic circuit; *5* — magnets

Crushed hematite ore is characterized by the presence of material that may be removed in the form of sinter at the beginning of the process flow diagram. For this purpose, the schemes of options 1 and 2 provide for dry magnetic separation with the use of complexes such as *Prodekologiya* DMSC with an increased induction on the drum surface. It is recommended to send the DMS nonmagnetic product for additional enrichment. As a result of dry magnetic separation of hematite ore, 40.32 % sinter with an iron mass fraction of 55.19 % has been obtained..

Also, when doing after-treatment of nonmagnetic product, it is recommended to grind the product in two stages. The first stage is the open cycle with subsequent grading according to the maximum size of 0.2 mm. The second stage is grinding to the grade +0.2 mm in the closed cycle with a grading by 0.16 mm grain. This scheme reduces the formation of hematite sludge and, accordingly, the loss of mineral with sludge.

According to the first option of the technology for finishing the nonmagnetic product, the DMS is carried out by means of combined gravity and magnetic methods. The gravity concentration cycle is a preliminary to magnetic separation in a strong field, which allows obtaining 10.86 % of high-quality hematite concentrate with an iron mass fraction of 66.7 %. The light fraction of gravity concentration is sent to high-gradient magnetic separation (HGMS), with the help of which an additional 7.8 % concentrate with an iron mass fraction of 62 % has been obtained. This technological solution allows obtaining 18.62 % of conditioned hematite concentrates with an iron mass fraction of 64.69 %. The first commercial product is sinter ore (40.32 %). The end-to-end extraction of iron into commercial products in this scheme makes up 73.6 %.

According to the second option, the DMS nonmagnetic industrial product is finished with the use of magnetic separation in strong fields only. This technological solution, in addition to sinter ore (40.32 %), enables obtaining 24.48 % of hematite concentrates with an iron mass fraction of 62.32 %. In this case, the end-to-end extraction of iron into commercial products accounts for 80.49 %.

Two process flow diagrams of ore processing without preliminary enrichment have also been developed. According to such options (options 3 and 4) all the ore is sent for gentle grinding in an aqueous medium, which is followed by gravity and magnetic concentration of ore (option 3) or only the magnetic separation of the source material (option 4). The gravity and magnetic concentration of ore enables obtaining 57.12 % of hematite concentrate with an iron mass fraction of 62.98 %. The extraction of iron into the concentrate is 77.2 %. By the fourth option, 53.67 % of hematite concentrate with an iron mass fraction of 62.0 % has been obtained. The extraction of iron into the concentrate is 74.05 %.

Since the hematite concentrates obtained by the first option have a higher mass fraction of iron (64.69 % vs. 62.0—62.98 %), the technology of concentration of Ingulets rich hematite ores is recommended as the main option. An alternative to this option is the ore treatment in air, with the use of separators developed at the Kryvyi Rih National University. The technology allows obtaining sinter ore and concentrate with an iron mass fraction of 62—64 %, with extraction of 72.4 % of iron into commercial products.

The trends in the metallurgical industry of Ukraine in the context of the use of its mineral resource base have indicated the prospects for the development of deposits of hematite quartzites. The research has established as follows:

1. Hematite ores of the Ingulets deposit are weakly magnetic oxidized iron rocks. The ore minerals are mainly martite and goethite. Their content averages 41 %. The major nonmetallic mineral is quartz. These ores contain from 46–48 to 52—54 % of iron. Having been crushed and ground, the individual and aggregate minerals of hematite ores are transformed into granular and sludge products. The aggregates of martite, goethite, marshalite quartz, and other minerals with a low strength factor are easily crushable. Therefore, while preparing the ore, it is necessary to prevent re-grinding of minerals and, as a consequence, their transformation into sludge.

2. In order to stabilize the quality of the source ore and to obtain an additional commercial product (sinter ore), it is necessary to use preliminary enrichment of Kryvbas medium-disseminated hematite quartzites. The use of dry magnetic separation makes it possible to stably obtain high-quality concentrates, to reduce the front of grinding and enriching at least by 40 % of the source ore, and to cut operating and capital expenses by more than 30 %.

3. The best indicators of sinter quality have been reported for magnetic separation of 20—0 mm ore grains. As the size of the ore grains decreases, its moisture content increases, which worsens the selectivity of the dry magnetic separation process. It has been established that for extracting commercial concentrate with the maximum output, it is necessary to use a drum magnetic separator with a magnetic field induction of 0.5 T, in the process of the main separation. However, when re-separating the nonmagnetic product, the magnetic field induction shall be raised to 0.7—1.1 T. In this case, the exposed iron-containing mi-

nerals and their rich clusters are extracted as much as possible into an additional secondary concentrate.

4. Technologies of dry and wet concentration of Kryvbas hematite quartzites have been developed. They involve the magnetic separation in a strong field and the gravity separation., Sinter ore with an iron mass fraction of 55.1 % and concentrates with an iron mass fraction of 62.32—64.69 % have been obtained from hematite ore. The extraction of iron in commercial products reaches 73.6—80.49 %.

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РОЗРОБКА ТЕХНОЛОГІЙ ЗБАГАЧЕННЯ СЕРЕДНЬОВКРАПЛЕНИХ ГЕМАТИТОВИХ КВАРЦИТІВ КРИВБАСУ

Вступ. Тенденції розвитку металургійної галузі України в контексті використання її мінерально-сировинної бази вказують на перспективи розробки родовищ гематитових кварцитів.

Проблематика. Проблема отримання високоякісних концентратів при збагаченні гематитових руд пов'язана з тим, що у процесі дроблення та подрібнення сировини агрегати мартиту, гетиту, маршалитизованого кварцу й інших мінералів з низьким коефіцієнтом міцності легко піддаються переподрібненню. В наслідок цього у продуктах підвищується вміст тонких частинок (шламів), що знижує селективність розділення рудних та нерудних мінералів. Організація щадного подрібнення руди є одним з перспективних шляхів вирішення окресленої проблеми.

Мета роботи. Розробка технології сухого й мокрого збагачення гематитових кварцитів Кривбасу.

Матеріали та методи. Використано метод узагальнення наукової інформації; виконано хімічний та мінеральний аналізи руди та продуктів збагачення сировини до й після її збагачення магнітними та гравітаційними методами; здійснено математичне моделювання процесів, технологічні випробування в лабораторних та промислових умовах.

Результати. При збагаченні гематитових кварцитів використано магнітну та гравітаційну сепарацію. З гематитової руди отримано аглоруду з масовою часткою заліза 55,1 % і концентрати з масовою часткою заліза 62,32—64,69 %. Вилучення заліза в товарні продукти склало 73,6—80,49 %.

Висновки. Розроблено технології сухого й мокрого збагачення гематитових кварцитів Кривбасу із застосуванням щадного подрібнення руди. Вперше при збагаченні гематитових руд запропоновано суху магнітну сепарацію, що дозволило отримати концентрати з масовою часткою заліза понад 64,0 %, зменшити фронт подрібнення руди не менше ніж на 40 % від початкового, і як наслідок, — експлуатаційні та капітальні витрати більш ніж на 30 %.

Ключові слова: гематитові кварцити, повітряно-прохідній сепаратор, циклон, магнітний сепаратор.