



Assessment of the Efficiency of Hematite Quartzite Enrichment Technologies

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Abstract

The present paper deals with the problem of developing an efficient technology for the enrichment of hematite ores. The aim of the research is to investigate the process properties of thinly disseminated hematite ores of Ukraine, taking into account their mineralogical characteristics, to develop flowsheets for the enrichment of hematite ores and to assess the efficiency of mineral separation during enrichment by gravity, magnetic, and flotation methods.

The research was carried out on a sample of hematite ores from the Kryvyi Rih iron ore basin of Ukraine, which consisted of 9 mineralogical ore types, distinguished by the quantitative ratio of the main groups of ore and non-ore minerals. As a result of WLIMS magnetic separation with a magnetic field induction of 0.07 T, an iron-containing concentrate with a mass fraction of 63.5% iron was obtained from ore with a size of minus 0.074+0 mm, with a total iron recovery of 12.8%.

It was found that with an increase in the magnetic field induction from 0.2 to 0.8 T, the recovery of total iron in the WHIMS magnetic product increased from 78.8 to 86.9%. The mass fraction of total iron in the WHIMS magnetic product was 57.9–59.8%. Losses of total iron with the non-magnetic product ranged from 21.2 to 13.1% with a mass fraction of total iron of 32–27.8%. The mass fraction of SiO₂ in the magnetic product was 11–13.8%.

Flotation research resulted in a hematite concentrate with a mass fraction of total iron of 64.05–65.95%, with iron recovery in the concentrate of 60.3–70.68%. Based on the results of process tests, seven variants of flowcharts for the enrichment of hematite ores were developed. The schemes were evaluated by the Hancock efficiency criterion, which ranged from 42.49–64.7%. The magnetic flotation technology for the enrichment of hematite quartzite was recommended for implementation. This technology makes it possible to obtain a commercial concentrate with a mass fraction of total iron of 37.02% from hematite ore with a mass fraction of total iron of 65.41%.

Keywords: hematite quartzite, technology, efficiency, magnetic separation, gravity, flotation

Introduction

Hematite ores take a significant share in potential iron ore reserves and are the main iron ore raw material for the prospective development of ferrous metallurgy in many countries. They account for about 23% of the total volume of ores being processed. Ukraine's hematite ferruginous quartzite reserves are concentrated mainly in Kryvbas and amount to 12% of total iron ore reserves [1,2,3].

In today's mining environment, it is necessary to have detailed information about the process properties of ores to respond to the following questions: what kind of scheme and efficiency is required for ore enrichment, and what sort of commercial products will be obtained.

The key enrichment criterion for most industrial ore types is the granulometric parameters of minerals. Their estimation makes it possible to determine the opening of minerals in the process of ore crushing and grinding and, based on the data obtained, to calculate the main indicators of enrichment and further determine the type of ore in terms of enrichment.

Hematite ores of different types differ in textural and structural features and mineral composition, which necessitates the use of different methods and technologies for their enrichment. At the same time, a competitive hematite concentrate should contain at least 64.0–66.0% iron, which is equivalent to magnetite concentrates with a mass fraction of iron of 67.0–68.0% in terms of silica content [4].

The mineral composition of hematite ores comprises martite, hematite-martite, limonite-martite, hematite, martite-limonite, and limonite varieties of hematite ores. The total iron content of these ores varies from 46 to 69 m.%. [5].

By textural features, they are broad-, medium-, thin-, and vaguely layered. The structure of hematite quartzites is divided into fine, very fine, and fine-grained kinds. According to physical properties, oxidized quartzites are classified as strong, very strong, weak, and very weak [6,7].

Based on the size of ore inclusions, hematite quartzites of the Kryvyi Rih iron ore basin are classified as thinly inclusions, very thinly inclusions and dispersed inclusions and are considered to be hard-to-dress raw materials [8]. The most

Tab. 1. Ratio of combined hematite-quartzite species in the process sample for research
 Tab. 1. Stosunek połączonych gatunków hematytu i kwarcytu w próbce procesowej do badań

Combined Mineralogical Varieties of Hematite Quartzites		The Content in the Composition of the General Process Sample, mass %
Index	Name	
1o	Iron-iron-mica quartzites	2,18
2o	Iron-mica martite quartzites	11,40
3o	Marschlitic iron-mica martite quartzites	8,36
4o	Martite quartzites	27,45
5o	Martite quartzites marshallitized	24,60
6o	Hettitized martite quartzites	10,31
7o	Quartzites dispersedhematite-martite and martite-dispersedhematite (suric)	6,64
8o	Magnetite-bearing martite quartzites (weakly weathered)	4,50
9o	Shale and ore-free quartzites	4,56

frequently used quartzites are those with very thin inclusions of ore and non-ore minerals (0.01–0.07 mm), where the ore minerals are exposed at a size of -0.05 mm. Hematite quartzites of the Kryvyi Rih iron ore basin are divided into: "lean" ores containing less than 40% iron, ores with an average iron content of 40% to 50%, and "rich" ores with an iron content of 50% and above [9].

"Rich" ores and ores with medium iron content are enriched by selective screening or dry magnetic separation. The commercial product is sinter ore with a mass fraction of iron of 55–64%.

"Lean" ores are mainly mined together with magnetite quartzites. Their associated production reaches 15–30% of the total production of magnetite ores, which is about 22.5–45 million tons per year. These ores are characterized by a complex and variable mineral and chemical composition and a thinly disseminated structure from 0.001 to 0.1 mm. "Lean" hematite quartzites of the Kryvyi Rih iron ore basin are classified as hard-to-dress ores due to the presence of a significant amount of low-magnetic fine-grained and fine-grained iron oxides and hydroxides. Among them there are the following varieties: martite-iron-ore quartzites; iron-mica-martite quartzites; iron-ore-martite marshallitized quartzites; martite quartzites; martite marshallitized quartzites; martite goethite quartzites; dispersed-hematite-martite quartzites; martite magnetite-containing quartzites; shales and ore-free quartzites. [10,11,12].

The analysis of the world practice of hematite ore enrichment shows that various methods and technologies can be used for their processing. Hematite quartzite enrichment can be carried out by gravity [13,14,15], magnetic [13,16–22], flotation [23–27], combined; magnetic-gravity or magnetic-flotation methods [28–31].

The methods depend on the textural and structural features of the ore, dissemination of ore and non-ore minerals, and the composition of waste rock. The combination of methods ensures an increase in the efficiency of hematite quartzite enrichment. The magnetic method of hematite quartzite enrichment allows to obtain iron ore concentrate with a total iron content of 59.9–63.5 mass % with the recovery of total iron in the concentrate of 68–75%; flotation method – 62–65.6 mass % with the recovery of total iron in the concentrate of 70.2–77.8%; gravity method – 66.9–68.3 mass%. The combined magnetic and gravity method – up to 67–68 mass % with the recovery of total iron in a concentrate of 66–67%; the combined magnetic and flotation method – up to 67–68 mass %, with the recovery of total iron in a concentrate of 70.1–75.6% [3].

The choice of a particular method is determined by the efficiency of the process, material composition, capital and operating costs.

The research is aimed at studying the processing properties of thinly disseminated hematite ores of Ukraine, taking into account their mineralogical characteristics. Based on the results obtained, to develop flowsheets for the enrichment of "lean" hematite ores and to evaluate the efficiency of mineral separation during enrichment by gravity, magnetic, and flotation methods.

Materials

The study received 200 in-line samples of 9 mineralogical varieties of hematite quartzites of the Kryvyi Rih iron ore basin, which in certain proportions made up the technological sample for research (Table 1). The formed sample was then submitted for process research in order to develop a technology for the enrichment of hematite quartzite and to determine the effectiveness of various methods and their combinations.

The quantitative ratio of the main groups of ore and non-ore minerals in the composition of the studied samples of hematite ores of the Kryvyi Rih iron ore basin has allowed us to focus on the main groups of minerals:

Martite, iron mica, goethite, lepidocrocite, and magnetite are granular ore minerals.

Aggregates of dispersed hematite and dispersed goethite are fine ore minerals.

Quartz, chalcedony, opal are minerals of the quartz group [10, 12, 15].

Individuals and aggregates of weathered ferruginous silicates and carbonates, newly formed iron-free silicates and carbonates make up the fourth type.

Martite is the main ore mineral in hematite ores. In the process of weathering, the structure of ore layers is kept. [32–33]. Figure 1 shows the nature of the change in the internal structure of martite aggregates depending on the intensity of primary magnetite replacement.

The martitization process gradually captured magnetite crystals and aggregates in the direction from the peripheral to their central zones. Figure 2 shows the direction of martite replacement of magnetite from the initial stages (Figure 2, a) to the formation of almost monomineral pseudomorphoses of hematite on magnetite (Figure 2, c). The average size of martite in the ores of the fifth ferrous horizon is 0.072 mm, and the sixth ferrous horizon is 0.064 mm.

Iron mica is represented by small flaky inclusions in the quartz matrix of non-metallic layers – the so-called

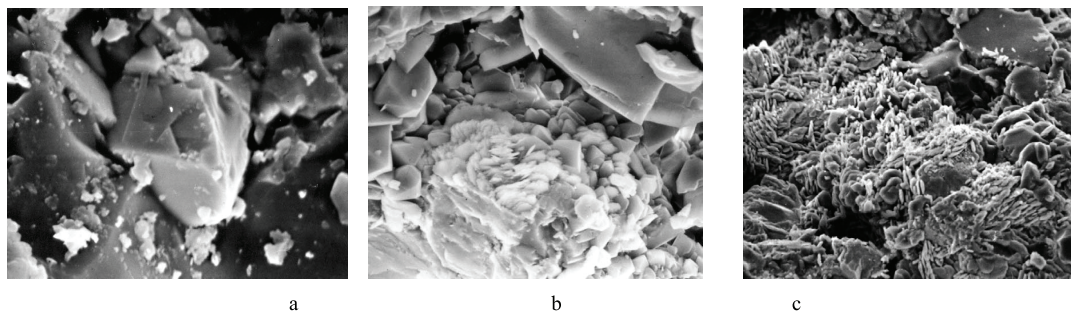


Fig. 1. Changes in the internal structure of individuals and aggregates of magnetite (well-faceted octahedral and cubo-octahedral crystals) in the process of its increasing (a → b) replacement by martite (aggregates of thin flaky crystals of ferrous mica). Scanning electron microscope MREM-100. Magnification: a – 1500x; b – 2000x; c – 1000x; d – 800x

Rys. 1. Zmiany struktury wewnętrznej osobników i agregatów magnetytu (dobrze fasetowanych kryształów ośmiościennych i sześciennieośmiościennych) w procesie jego narastającej (a → b) wymiany przez martyt (agregaty cienkich płatkowatych kryształów miki żelazistej). Skaningowy mikroskop elektronowy MREM-100. Powiększenie: a – 1500x; b – 2000x; c – 1000x; d – 800x

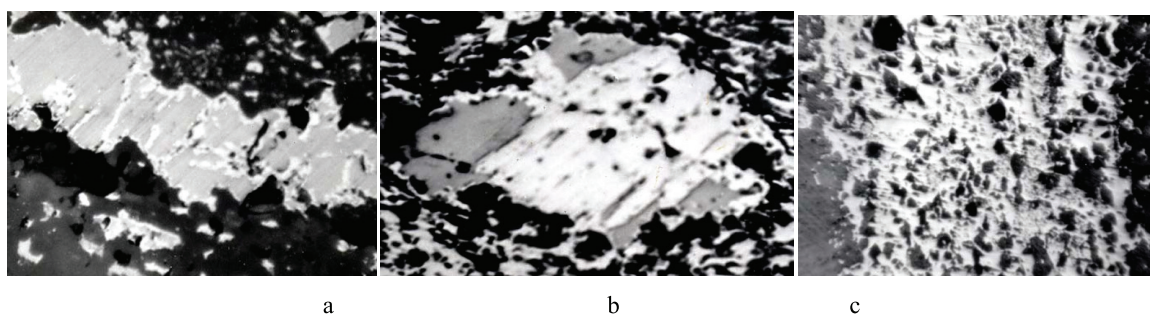


Fig. 2. Structure of ore layers of hematite quartzite with different degrees of magnetite martitization: a – the initial stage of magnetite martitization in a ribbon-like ore layer of magnetite quartzite; b – idiomorphic crystal of magnetite with the manifestation of its replacement by martite along the cracks of octahedral separation; c – monomineral banded aggregate of martite in the ore layer of martite quartzite. White – martite; light gray – magnetite; dark gray – quartz; black – voids. Reflected light; never parallel; magnification: a – 32x; b, c – 42x; d – 25x

Rys. 2. Struktura warstw rudnych kwarcytu hematytowego o różnym stopniu martyzacji magnetytu: a – początkowy etap martyzacji magnetytu we wstęgowej warstwie rudy kwarcytu magnetytu; b – idiomorficzny kryształ magnetytu z zastąpieniem go martytem wzdłuż pęknięć separacji oktaedrycznej; c – monomineralne pasmowane kruszywo martytu w warstwie rudy kwarcytu martytowego. Białe – martyt; jasnoszary – magnetyt; ciemnoszary – kwarc; czarny – puste przestrzenie. Odbite światło; nierównoległe; powiększenie: a – 32x; b, c – 42x; d – 25x

"Emulsion iron mica" [32,33]. The size of its crystals ranges from 0.001 to 0.05 mm in maximum dimension (Figure 3, a, b).

In the composition of ferruginous-martite and martite-ferruginous quartzites, tabular, lamellar and flaky crystals of iron mica are present not only in the non-ore but also in the ore layers. They are characterized by a much larger size – from 0.02 to 1.0 and more mm (Figure 3, d).

Dispersed hematite is represented by very small flaky crystals ranging in size from 0.001 to 0.01 mm [32–36]. Dispersed hematite and kaolinite-dispersed hematite aggregates form in hematite quartzites as smears, and rarely as independent layers up to 10 mm thick.

Goethite is most abundant in the upper crustal horizons of the weathered fifth-sixth ferruginous horizons. It develops by metasomatic replacement and ore minerals or fills cracks and voids, forming intersecting or harmonious veins with rock layering, containing veins up to a hundredth of 5–6 cm or more (Figure 4).

Magnetite in goethite-hematite quartzites is present in small volumes (no more than 1–2 vol%) (Figure 5). The average size of relict magnetite formations in hematite quartzites of the fifth ferruginous horizon is 0.024 mm, and of the sixth ferruginous horizon – 0.021 mm.

Quartz is the main non-ore mineral of hematite quartzites. It is the basic component of non-ore layers and is present

in ore layers in the amount of up to 30–40 vol.% with grain size from 0.01 to 0.1 mm, sometimes up to 0.3 mm (Fig. 6). Often, in non-ore layers of hematite quartzite, a subparallel orientation of elongated quartz individuals is noted (Fig. 6, b).

In the non-metallic layers, quartz individuals often contain thin (up to 0.01 mm) inclusions of iron mica, rarely martite, and dispersed hematite.

The weathering crust of the studied deposit often contains products of marshallitization of ferruginous quartzite formed under the influence of alkaline hypergenic solutions (Fig. 7).

The role of minor and accessory minerals is played by about 20 other minerals and mineral types that are part of the studied hematite ores.

Methods

Processing tests included studies by gravity, magnetic and flotation methods. The studies were conducted in laboratory conditions.

Gravity enrichment was carried out at a screw sluice at a feed material size of 0.5–0.074 mm.

Magnetic separation of hematite ore was carried out in two stages. First, WLIMS separation was performed on a drum magnetic separator with a magnetic field induction of 0.07 T. The purpose of the WLIMS separation is to remove strongly magnetic minerals from the hematite ore to protect

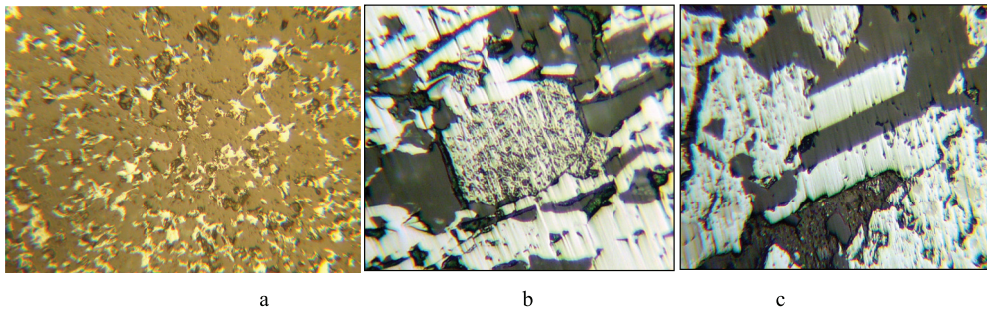


Fig. 3. Composition and structure of non-metallic (a) and ore (b, c,) layers of iron-mica-martite quartzite; a – small flaky inclusions of iron mica in quartz aggregates from non-metallic layers of ferruginous martite quartzite; b – large iron mica leists in the ore layer of martite-ferruginous quartzite; porous oval crystal in the center is martite; c – large tabular crystals of iron mica in an alpine iron-mica quartz vein from the ferruginous martite-iron-mica quartzite ore bed; relict magnetite inclusions (light gray) are present in the martite aggregates surrounding the veins. White: porous – martite, smoothly polished – iron mica; light gray – magnetite; dark gray – quartz; black – voids. Reflected light; never parallel; magnification: a, b – 20x, c, d – 35x

Rys. 3. Skład i struktura warstw niemetalicznych (a) i rudnych (b, c,) kwarcytu żelazowo-mikowo-martytowego; a – drobne płatkowate wtrącenia miki żelazowej w agregatach kwarcowych z niemetalicznych warstw żelazistego kwarcytu martytowego; b – duże miki żelazowe w warstwie rudy kwarcytu martytowo-żelazistego; porowaty owalny kryształ w środku to martyt; c – duże tabelaryczne kryształy miki żelazowej w alpejskiej żyłę kwarcowo-żelazowo-mikowej ze złoża żelazistego martytowo-żelazowo-mikowego kwarcytu; w skupiskach martytu otaczających żyły obecne są reliktove inkluzje magnetytu (jasnoszare). Białe: porowate – martytowy, gładko wypolerowany – mika żelazowa; jasnoszare – magnetyt; ciemnoszare – kwarc; czarny – puste przestrzenie. Odbite światło; nierównoległe; powiększenie: a, b – 20x, c, d – 35x

the magnetic system of the WLIMS separator from blockage. Subsequently, the non-magnetic WLIMS product was fed to the WHIMS separation, which was carried out in a 259-CE rotary type separator. The magnetic field induction at the WHIMS separation varied from 0.2 to 0.8 T.

In order to obtain high-quality hematite concentrates, reverse cation flotation was studied in the current work. The following reagents were used in the experiments: amines Lilaflot-811M, Lilaflot-D817M and Lilaflot-D819MI as collectors, dextrin as a selective flocculant and depressor of iron ore minerals, caustic soda as a medium regulator.

Research on the cationic flotation of quartz from a magnetic hematite product was carried out on a laboratory flotation machine 237 Fl with removable chambers of 0.5, 1 and 3 liters. To determine the optimal flotation mode, the "Latin square" design method was used during the studies. After determining the optimal conditions and flotation scheme, studies were conducted on the principle of a continuous process to specify the developed process mode, to find out the effect of circulation of industrial products on the enrichment indicators and to determine the points of their feeding into the process.

Hancock's efficiency criterion was chosen as the efficiency criterion for the hematite quartzite enrichment technology:

$$E = \frac{\varepsilon_k - \gamma_k}{100 - \frac{\alpha}{\alpha_m}} * 100\% \quad (1)$$

where

ε – the concentrate recovery, %;

γ_k – concentrate yield, %;

α – iron content in the final product, %;

α_m – iron content in the final product, %;

The estimates of the enrichment results were monitored by chemical analysis and mineralogical studies. Quality control of separation products is performed by measuring the mass fraction of iron by chemical methods. The process experiments were carried out in accordance with the State Standards of Ukraine DSTU 3195-95, 3196-95, 3198-95, 3207-95, 3210-95; DSTU ISO 3082: 200, MOD; DSTU ISO 10836: 200, MOD).

Results and discussion

The issue of ore preparation is critical for hematite quartzites of the Kryvyi Rih iron ore basin due to the mineral composition.

The main direction of further advancement of hematite quartzite enrichment is the development of ore preparation schemes that ensure the separation of mineral grains with minimal formation of fine grains of 0.01–0.016 mm using new grinding processes. In our previous studies, we recommended the use of HPGR crushers – high-pressure roll presses. In these crushers, material crushing occurs in a layer of ore lumps that crush each other. Such crushing allows the grains to be opened without re-grinding and produces material with a particle size of 1.2 mm. This makes it possible, in the first stage of magnetic separation, to dump waste rock in the amount of 49.22% [37–38].

The use of dry magnetic pretreatment in hematite ore enrichment schemes solves an important issue of stabilizing the quality of crushed ore, reducing the ore grinding front by at least 40% of the initial one, and, as a result, reducing operating and capital costs by more than 30% [4,39–40].

This paper considers a different problem. Namely, the development of an effective technology for enrichment of "lean (poor)" thinly fractured hematite ores of the Kryvyi Rih iron ore basin of Ukraine.

Due to the fact that the hematite ores under study contain jaspillites, chlorite, dispersed hematite-chlorite schists and low-ore quartz layers, which are very challenging to process, the feasibility of using gravity enrichment, namely screw separation, in the processing technology of hematite quartzites was studied.

Ore with a size of -0.5+0.07 mm was sent to the screw separation. As a result, three products were obtained: concentrate, industrial product and light fraction (Table 2).

As can be seen from Table 2, the enrichment of the feed ore with a particle size of -0.5+0.07 mm at the screw sluice produced a high quality concentrate: The mass fraction of total iron in the hematite concentrate was 63.7%. However, the concentrate yield is low and amounts to 6.22%. The recovery of total iron in the concentrate was 8.57%.

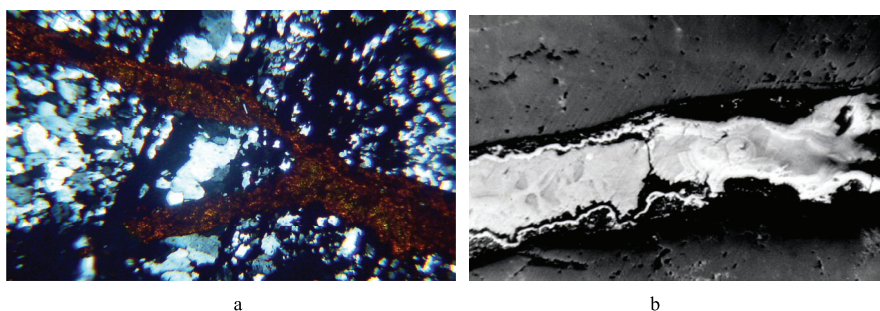


Fig. 4. Dissecting veins of goethite in non-ore layers of iron mica-martite (a) and martite (b) quartzites; a – transmitted light; never intersecting; magnification 35x; light – quartz, dark gray – goethite; black – iron mica; b – reflected light; never parallel; magnification 22x; light gray – goethite; dark gray – quartz; black – voids

Rys. 4. Preparowanie żył getytu w nierudnych warstwach kwarcytów mikro-martytowych (a) i martytowych (b) a – światło przechodzące; nierównoległe; powiększenie 35x; jasny – kwarc, ciemnoszary – getyt; czarny – mika żelazna; b – światło odbite; nierównoległe; powiększenie 22x; jasnoszary – getyt; ciemnoszary – kwarc; czarny – puste przestrzenie

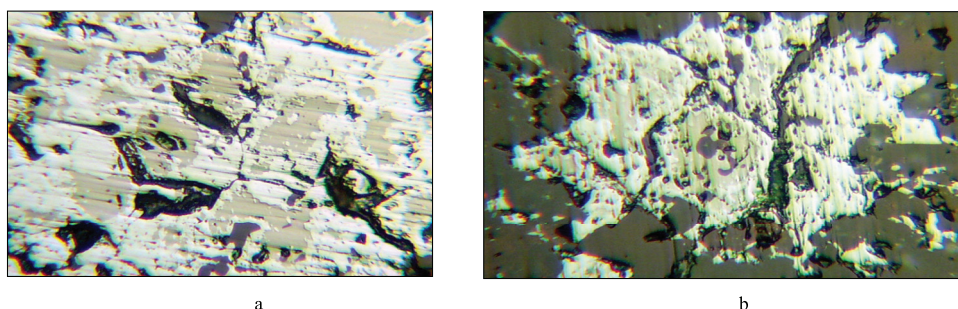


Fig. 5. Relict inclusions of magnetite (light gray) in aggregates of newly formed martite (white) from ore layers of magnetite-martite quartzite. Reflected light; never parallel; magnification 37x. Dark gray – quartz; black – voids

Rys. 5. Reliktowe wtrącenia magnetytu (jasnoszare) w agregatach nowo powstałego martytu (białego) z warstw rudnych kwarcytu magnetytowo-martytowego. Odbite światło; nierównoległe; powiększenie 37x. Ciemnoszary – kwarc; czarny – puste przestrzenie

The industrial product and the light fraction of gravity concentration, which were formed during the separation of material with a particle size of $-0.5+0.07$ mm, were further sent for grinding to a particle size of 80% of the class minus 0.05 mm and then for flotation.

At the next stage of research, magnetic beneficiation of ore and its products was performed in a magnetic field with an induction of 0.07 T and 0.2–0.8 T.

Before magnetic beneficiation, the ore was crushed to different sizes; 0.25–0 mm, 0.2–0 mm, 0.15–0 mm, 0.074–0 mm, followed by beneficiation in a magnetic separator with a magnetic field induction of 0.07 T and 0.2–0.8 T. Magnetic separation of the crushed ore in a magnetic separator with a magnetic field induction of 0.07 T (WLIMS) was performed to protect the magnetic system of separators with a magnetic field induction of 0.2–0.8 T (WHIMS) from strongly magnetic minerals. As a result of WLIMS separation, two products were obtained: magnetic (concentrate) and non-magnetic industrial product – the starting product for WHIMS separation. The results of the experiments are shown in Fig. 8.

The analysis of the separation parameters of the WLIMS separation products revealed the possibility of extracting iron-containing concentrate with a mass fraction of 63.5% from ore with a particle size of minus 0.074+0 mm. The recovery of total iron in the concentrate amounted to 12.8%. Compared to gravity concentration, this figure is 4.23% higher.

Thus, in the technological scheme, WLIMS magnetic separation performs not only the protective function of the WNIMS separator magnetic system, but also allows to obtain

commercial products. Unfortunately, the products are characterized by low quality. The mass fraction of SiO_2 in this concentrate is 23.7%. This product is mainly represented by magnetite and maghemite, their growths with quartz and flocs.

WHIMS magnetic enrichment of samples of non-magnetic material of the WLIMS separator was performed on a rotary separator of the type 259-CE in one step with a magnetic field induction of 0.2–0.8 T. The grinding size of the samples was 90% class minus 0.05 mm (maximum grain size 0.074 mm). The results of the experiments are shown in Table 3.

The analysis of the results shows that with an increase in magnetic field induction from 0.2 to 0.8 T, the recovery of total iron in the magnetic product increases from 78.8 to 86.9%. At the same time, the mass fraction of total iron in the concentrate (magnetic product) is 57.9–59.8%. Losses of total iron with the non-magnetic product ranged from 21.2 to 13.1% with a mass fraction of total iron of 32–27.8%. The mass fraction of SiO_2 in the magnetic product was 11–13.8%. Such a product cannot be considered a concentrate and therefore was further sent for flotation processing.

Flotation enrichment

To obtain high-quality hematite concentrates, we studied reverse cation flotation. The following reagents were used in the experiments: Lilaflo-811M, Lilaflo-D817M and Lilaflo-D819MI amines as collectors, dextrin as a selective flocculant and depressor of iron ore minerals, caustic soda as a medium regulator and calcium chloride as a silica activator.

The results of the tests on the selection of the collector reagent are shown in Fig. 9. Further studies were carried out

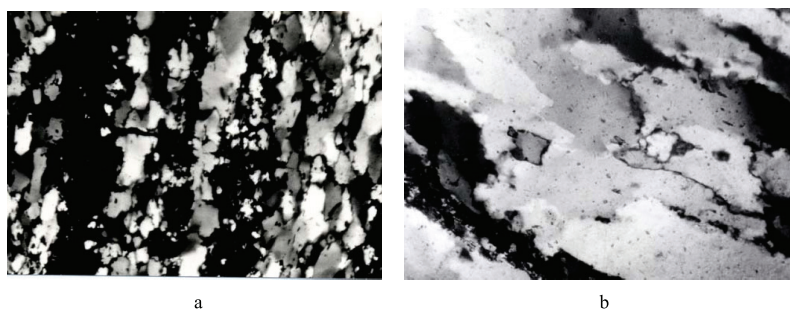


Fig. 6. Morphology of quartz individuals and aggregates from non-ore layers of iron mica-martite (a) and martite (b) quartzites. White and gray – quartz; black – martite and iron mica. Transmitted light; never intersected; 30x magnification

Rys. 6. Morfologia pojedynczych ziaren i agregatów kwarcu z nierudnych warstw kwarcytu miki-martytu żelaza (a) i martytu (b). Białe i szare – kwarc; czarny – mika martytowa i żelazowa. Światło przechodzące; nieprzecinające się; 30-krotne powiększenie

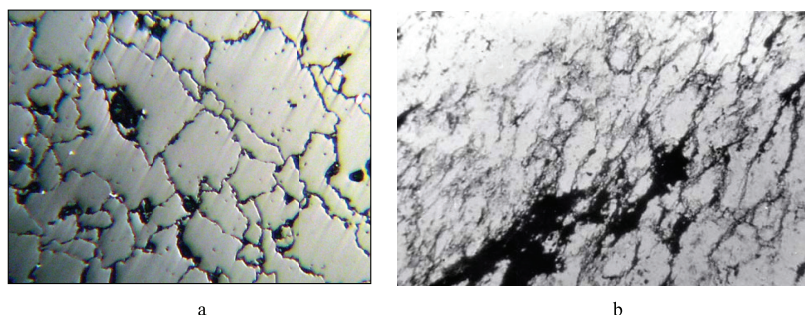


Fig. 7. Structure of marshalized quartz aggregates from non-ore layers of martite (a) and goethite-martite (b) quartzite. Along the weakened contact zones of quartz individuals, it was partially replaced by a near-crystalline goethite aggregate (b). Reflected (a) and transmitted (b) light; never parallel; magnification: a – 40x; b – 30x. a: white – iron mica; dark gray – quartz; black – voids; b: white – quartz; dark gray – dispersed goethite; black – goethite

Rys. 7. Struktura zorganizowanych agregatów kwarcowych z nierudnych warstw martytu (a) i getytu-martytu (b) kwarcytu. Wzdłuż osłabionych stref kontaktowych jednostek kwarcu został on częściowo zastąpiony przez prawie krystaliczne kruszywo getytu (b). Światło odbite (a) i przechodzące (b); nierównoległe; powiększenie: a – 40x; b – 30x. a: biała – mika żelazowa; ciemnoszary – kwarc; czarny – puste przestrzenie; b: biały – kwarc; ciemnoszary – getyt rozproszony; czarny – getyt

using Lilaflot-D817M 260 g/t, which has a higher selectivity for SiO_2 and iron-containing particles.

The optimal consumption of the depressant reagent Dextrin was tested at two dosages of 1250 g/t of dextrin and 250 g/t with the same amount of Lilaflot-D819MI. The results of the two tests are presented in the form of an iron recovery graph in Fig.10.-11.

It was determined that the recovery of total iron in the concentrate is lower when tested with a depressor flow rate of 250 g/t compared to the flow rate of dextrin 1250 g/t (Fig. 10). Thus, with a mass fraction of total iron in the concentrate of 65.8%, the iron recovery into the concentrate at a dextrin flow rate of 1250 g/t was 78%, and at a flow rate of 250 g/t – 73%.

Evaluation and analysis of the results of the kinetics of flotation separation of iron-containing minerals and quartz (Fig. 11) showed that an increase in the mass fraction of total iron in the concentrate from 55 to 65% is possible only with an increase in flotation time from 8 minutes to 20 minutes and above. At the same time, with a decrease in dextrin consumption from 1250 g/t to 250 g/t, the mass fraction of total iron in the concentrate increases by an average of 3–4%.

In flotation with cationic collectors, the pH of the medium is of great importance. Therefore, we conducted studies to determine the optimal pH of the suspension during flotation. The studies were carried out at two values of pH 11 and pH 9.5 (Figs. 12, 13).

As can be seen from the results shown in Fig. 12, the efficiency of separation of iron-containing minerals and quartz

improves with increasing pH. Thus, when the mass fraction of total iron in the concentrate is above 65%, the iron recovery in the concentrate is higher by 5% at pH 11 compared to pH 9.5.

The analysis of the results of reverse flotation kinetics (Fig. 13) allowed us to establish that the effect of pH on the quality of the concentrate is not eliminated when the flotation time is increased from 10 minutes to 20 minutes and above

As a result of the analysis of the flotation study results, the optimal reagent mode for reverse cationic flotation of quartz to produce hematite concentrate was determined: caustic soda – 1000 g/t, Dextrin – 250 g/t, Lilaflot D817 M – 260 g/t. This mode was used as the basis for a control test for flotation study of the hematite ore sample.

The study resulted in a hematite concentrate with a mass fraction of total iron of 64.05–65.95%, with iron recovery in the concentrate of 60.3–70.68%. The maximum achieved value of iron recovery was 70.68% with a mass fraction of total iron of 65.95%.

It has been established that depending on the feed material for flotation, the flowsheet for obtaining hematite concentrate changes.

Based on the data of the process experiments carried out in the laboratory, we have developed 7 variants of schemes (Table 4) using combined magnetic-gravity-flotation technologies.

According to the developed technologies, it is possible to obtain a hematite concentrate with a mass fraction of total iron of 64.14–65.95%, with a yield of 27.13–40.27%. Total

Tab. 2. Results of hematite ore enrichment using a screw separator

Tab. 2. Wyniki wzbogacania rudy hematytu za pomocą separatora ślimakowego

Name of the sample	Name	Yield %	Mass fraction of total iron, %	Recovery of total iron, %
Hematite ore, size of -0,5+0,07 mm	concentrate	6,22	63,7	8,57
	industrial product	31,76	58,33	40,07
	light fraction	62,02	38,3	51,37
	feed	100,00	46,24	100,00

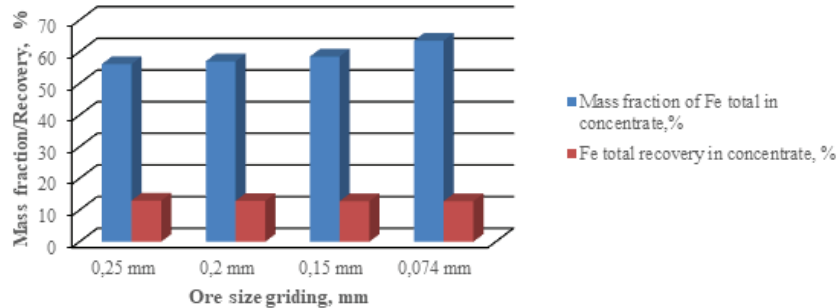


Fig. 8. Results of enrichment of hematite ore of different sizes

Rys. 8. Wyniki wzbogacania rudy hematytu o różnej wielkości

Tab. 3. Results of WHIMS magnetic separation of non-magnetic product WLIMS of hematite ore

Tab. 3. Wyniki separacji magnetycznej WHIMS produktu niemagnetycznego WLIMS rudy hematytu

Magnetic field induction, T	Product name	Yield, %	Mass fraction, %		Recovery, %	
			Fe	SiO ₂	Fe	SiO ₂
0,2	Feed	100	49,8	24,5	100	100
	Magnetic product	67,0	58,6	11,0	78,8	30,1
	Non-magnetic product	33,0	32,0	51,9	21,2	69,9
0,3	Feed	100	50,3	24,5	100	100
	Magnetic product	68,5	59,7	11,4	81,3	31,9
	Non-magnetic product	31,5	29,9	53,0	18,7	68,1
0,5	Feed	100	50,8	24,5	100	100
	Magnetic product	72,9	59,8	11,0	85,8	32,7
	Non-magnetic product	27,1	26,6	60,8	14,2	67,3
0,8	Feed	100	50,7	24,5	100	100
	Magnetic product	76,1	57,9	13,8	86,9	42,9
	Non-magnetic product	23,9	27,8	58,5	13,1	57,1

iron recovery of the concentrate ranges from 47.15 to 70.68%, depending on the combination of enrichment methods and grinding conditions of industrial products

The main criterion for the efficiency of hematite quartzite enrichment technology was the Hennock efficiency criterion, which ranged from 42.49–64.7%. According to the efficiency criterion, all scheme variants can be divided into three groups: efficient, inefficient, and ineffective.

Group I – schemes of variants 2.4, which obtained the highest concentrate values in terms of mass fraction of iron 63.77–64.7% and recovery 70.23–70.3%;

Group II – schemes of variants 1,6,7, which produce a concentrate with a mass fraction of iron in the range of 64.14–65.06% and recovery of 64.09–65.11%; efficiency criterion 55.9–58.49%.

Group III – schemes of variants 3.5, which produce a concentrate with a mass fraction of iron in the range of 64.34–65.95% and recovery of 47.15–58.30%. The efficiency criterion is 42.49–54.27 %.

Conclusions

1. The study was carried out on a sample of hematite ores from the Kryvyi Rih iron ore basin of Ukraine, which consisted of 9 mineralogical ore varieties, distinguished by the

quantitative ratio of the basic groups of ore and non-ore minerals.

2. As a result of enrichment of the feed ore with a grain size of -0.5+0.07 mm, a high quality concentrate was obtained at the screw sluices. The mass fraction of total iron in the hematite concentrate was 63.7%. The concentrate yield was 6.22%. The recovery of total iron in the concentrate was 8.57%.

3. As a result of WLIMS and WHIMS magnetic separation with a magnetic field induction of 0.07 T, an iron-containing concentrate with a mass fraction of 63.5% iron was obtained from ore with a size of minus 0.074+0 mm, with a total iron recovery of 12.8%.

4. It was determined that with an increase in the magnetic field induction from 0.2 to 0.8 T, the recovery of total iron in the magnetic product of WHIMS increases from 78.8 to 86.9 %. The mass fraction of total iron in the WHIMS magnetic product was 57.9–59.8%. Losses of total iron with the non-magnetic product ranged from 21.2 to 13.1% with a mass fraction of total iron of 32–27.8%. The mass fraction of SiO₂ in the magnetic product was 11–13.8%.

5. Based on the results of flotation studies, the optimal reagent mode of reverse cationic flotation of quartz to obtain a hematite concentrate was determined: caustic soda – 1000

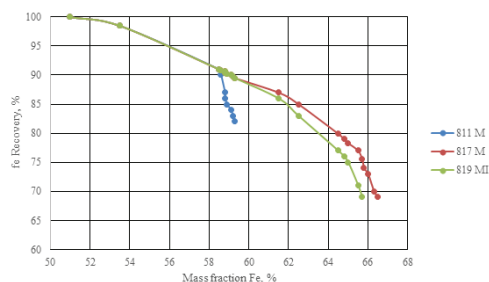


Fig. 9. Selectivity indicators of Lilafлот reagent
Rys. 9. Wskaźniki selektywności odczynnika Lilafлот

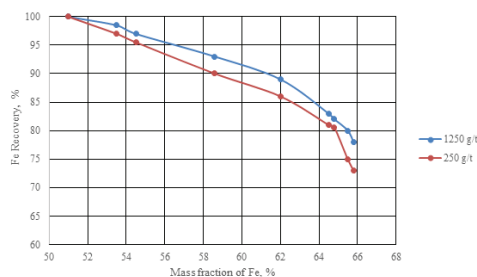


Fig. 10. Dependence of total iron recovery on the mass fraction of total iron in the chamber flotation product at different depressor flow rates
Rys. 10. Zależność całkowitego odzysku żelaza od udziału masowego żelaza ogólnego w produkcie flotacji komorowej przy różnych prędkościach przepływu w depresorze

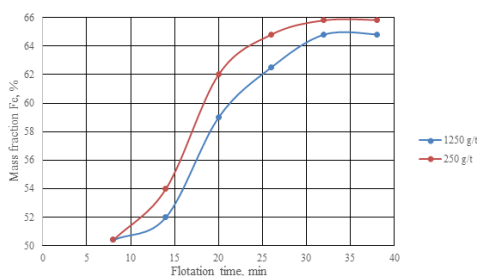


Fig. 11. Dependence of the mass fraction of total iron in the concentrate on the flotation time at different depressor flow rates
Rys. 11. Zależność udziału masowego żelaza ogólnego w koncentracie od czasu flotacji przy różnych prędkościach przepływu przez depresor

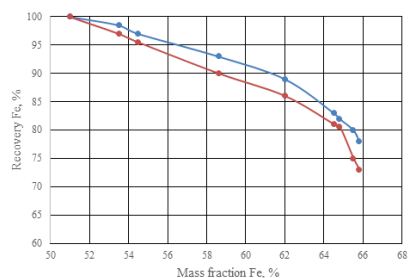


Fig. 12. Dependence of total iron recovery on the mass fraction of total iron in the flotation chamber product at different pH values
Rys. 12. Zależność całkowitego odzysku żelaza od udziału masowego żelaza ogólnego w produkcie komory flotacyjnej przy różnych wartościach pH

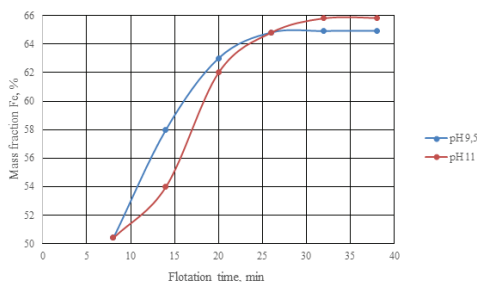


Fig. 13. Dependence of the mass fraction of total iron in the concentrate on the flotation time at different pH values
Rys. 13. Zależność udziału masowego żelaza ogólnego w koncentracie od czasu flotacji przy różnych wartościach pH

Tab. 4. Indicators of hematite ore enrichment by different flowsheets
 Tab. 4. Wskaźniki wzbogacania rudy hematytu według różnych schematów

Variant	Product name	Yield, %	Mass fraction of total iron, %	Total iron recovery, %	Hancock efficiency criterion
1*	concentrate	34,77	65,06	61,11	55,90
	waste	65,23	22,07	38,89	
	feed	100	37,02	100,0	
2*	concentrate	40,27	64,64	70,3	63,77
	waste	59,73	18,4	29,7	
	feed	100	37,02	100	
3*	concentrate	32,72	65,95	58,3	54,27
	waste	67,28	22,95	41,7	
	feed	100	37,02	100	
4*	concentrate	39,75	65,41	70,23	64,70
	waste	60,25	18,29	29,77	
	feed	100	37,02	100,00	
5*	concentrate	27,13	64,34	47,15	42,49
	waste	72,87	26,85	52,85	
	feed	100	37,02	100	
6*	concentrate	37,55	64,19	65,11	58,49
	waste	62,45	20,68	34,89	
	feed	100	37,02	100,0	
7*	concentrate	36,99	64,14	64,09	57,52
	waste	63,01	21,1	35,91	
	feed	100	37,02	100,00	

Note: *1-7 variants of flowcharts and their description

1 – 100% feed ore is crushed in 2 stages and sent to WLIMS and WHIMS magnetic separation, reverse cation flotation of hematite in one stage

2 – 100% feed ore is crushed in stage 2 and sent to WLIMS and WHIMS magnetic separation, reverse cationic flotation of hematite in two stages with additional grinding of the froth product

3 – ore is preliminarily enriched by dry magnetic separation (DMS), magnetic industrial product of DMS is crushed in two stages to 0.5 and 0.074 mm and sent to WLIMS and WHIMS magnetic separation, reverse cation flotation of hematite in one stage

4 – ore is preliminarily enriched by dry magnetic separation (SMS), magnetic industrial product of SMS is crushed in two stages to 0.5 and 0.074 mm and sent to WLIMS and WHIMS magnetic separation, reverse cation flotation of hematite in two stages with additional grinding of the froth product

5 – ore is preliminarily enriched by dry magnetic separation (DMS), the magnetic product of DMS is crushed to 0.5 mm and fed for classification by grain size of 0.074 mm The -0.5+0.074 mm fraction is fed to gravity, and the -0.074 mm fraction is fed to WLIMS and WHIMS magnetic separation. Gravity and magnetic separation products are sent to hematite flotation in one stage

6 – ore is preliminarily enriched by dry magnetic separation (DM), the magnetic product of DM is crushed to 0.5 mm and fed to the classification by grain size of 0.074 mm The -0.5+0.074 mm fraction is fed to gravity, and the -0.074 mm fraction is fed to WLIMS and WHIMS magnetic separation. Gravity and magnetic separation products are sent to hematite flotation in two stages with froth grinding

7 – 100% feed ore is crushed in stage 2 and sent to hematite flotation. The scheme consists of the main and control flotations, grinding of the froth product and its re-cleaning.

g/t, calcium chloride (5%) – 200 g/t, Dextrine – 1250 g/t, Li-laflot D817 M – 260 g/t. During flotation studies, a hematite concentrate was obtained with a mass fraction of total iron of 64.05–65.95%, with an iron recovery of 60.3–70.68%.

6. On the basis of the results of process tests, seven variants of flowcharts for hematite ore enrichment were developed. The main criterion for the efficiency of hematite quartzite enrichment technology was the Hancock efficiency criterion, which ranged from 42.49–64.7%.

7. According to the efficiency criterion, all flowchart scenarios can be divided into three groups: efficient, inefficient and ineffective. Effective technologies for the enrichment of hematite quartzite (process efficiency criterion 63.77–64.7%)

include technologies using a combination of magnetic flotation separation of ore and products of different sizes.

8. It is recommended to implement the enrichment technology using dry magnetic separation, grinding of preliminary enrichment products in two stages to 0.5 and 0.074 mm, magnetic separation WLIMS and WHIMS with magnetic field induction of 0.07 T and 0.8 T, cationic flotation of quartz from magnetic products. This technology makes it possible to obtain a commercial concentrate with a mass fraction of iron of 37.02% from hematite ore with a total mass fraction of iron of 65.41%. The concentrate yield was 39.75%, with a total iron recovery of 70.23%.

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Ocena skuteczności technologii wzbogacania kwarcytu hematytowego

W artykule podjęto problem opracowania wydajnej technologii wzbogacania rud hematytu. Celem badań jest zbadanie właściwości procesowych słabo rozsianych rud hematytu Ukrainy, z uwzględnieniem ich właściwości mineralogicznych, opracowanie schematów wzbogacania rud hematytu oraz ocena skuteczności separacji minerałów podczas wzbogacania grawitacyjnego, magnetycznego i metody flotacji.

Badania przeprowadzono na próbce rud hematytu z krzyworożskiego zagłębia rud żelaza na Ukrainie, która składała się z 9 mineralogicznych typów rud, wyróżniających się stosunkiem ilościowym głównych grup minerałów kruszczowych i nierudnych.

W wyniku separacji magnetycznej WLIMS przy indukcji pola magnetycznego 0,07 T otrzymano koncentrat zawierający żelazo o udziale masowym żelaza 63,5% z rudy o wielkości minus 0,074+0 mm, przy całkowitym uzysku żelaza 12,8%.

Stwierdzono, że wraz ze wzrostem indukcji pola magnetycznego od 0,2 T do 0,8 T, uzysk żelaza ogólnego w produkcie magnetycznym WNIMS wzrósł z 78,8% do 86,9%. Udział masowy całkowitego żelaza w produkcie magnetycznym WIMS wyniósł 57,9–59,8%. Straty żelaza ogólnego z produktem niemagnetycznym wahały się od 21,2% do 13,1% przy udziale masowym żelaza całkowitego 32–27,8%. Udział masowy SiO₂ w produkcie magnetycznym wyniósł 11–13,8%.

W wyniku badań flotacyjnych otrzymano koncentrat hematytu o udziale masowym żelaza ogólnego 64,05–65,95%, z odzyskiem żelaza w koncentracji 60,3–70,68%. Na podstawie wyników badań procesowych opracowano siedem wariantów schematów wzbogacania rud hematytu. Schematy oceniono według kryterium sprawności Hancocka, które mieściło się w przedziale 42,49–64,7%. Zarekomendowano do wdrożenia technologię flotacji magnetycznej do wzbogacania kwarcytu hematytowego. Technologia ta umożliwia otrzymanie koncentratu handlowego o udziale masowym żelaza ogólnego 37,02% z rudy hematytu o udziale masowym żelaza ogólnego 65,41%.

Słowa kluczowe: kwarcyt hematytowy, technologia, wydajność, separacja magnetyczna, grawitacja, flotacja