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INCREASING THE RECOVERY RATIO OF IRON ORES IN THE COURSE OF PREPARATION AND PROCESSING

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ABSTRACT

Iron is the base of modern economy. In Russia, iron reserves are plentiful, with magnetite quartzites forming the core of the country's ore base.

Oxidized ferruginous quartzites are a major source of replenishing mineral resources of Russia.

The article studies the material composition and preparation characteristics of four representative samples of oxidized iron ore with different iron content. As the key preparation process, both strong and weak magnetic separation was used, with multi-stage grinding. The possibility to apply fine grinding using IsaMill method was explored.

The result is a conceptual technology of comprehensive processing of mature tailings remaining after brown iron ore preparation which enables to obtain iron-containing concentrate suitable for smelting under Romelt process to yield pig iron and slag to be used in aggregates production.

The work shows the possibility of obtaining light brown iron oxide pigments from disposal sites of Kamysh-Burun iron ore plant.

Introduction

Iron can rightfully be called the base material of present-day economy. In its major alloys, pig iron and steel, it is used practically in every branch of industry, with the share of iron making up around 95% of present-day metallurgical production. The explanation to this is that after aluminium, iron is second most common metal occurring in the earth's crust. Besides that, iron deposits are abundant, relatively easy to access and in most cases are worked by open-cut method; iron smelting process in inexpensive and industry-wide, and iron alloys are processable, meeting the requirements of most industries [1, 2].

In Russia there are around 200 iron ore deposits, and the mined ores to be processed are mostly magnetite quartzites that need beneficiation. Methods of processing for one or another kind of raw material depend primarily on the difference in physical (or physico-chemical) properties of the particles to be separated. The major technique of ferruginous quartzites beneficiation is low intensity magnetic separation (LIMS) [1–5]. The advantages of magnetic methods are minimal environmental footprint, high rate of productivity and relatively low production costs [5].

Oxidized ferruginous quartzites (OFQ) are a major source of replenishing mineral resources of Russia. Another substantial additional source of iron could be various secondary materials. The most common methods used in concentration of OFQ are magnetic-flotation, magnetic-gravity flotation, gravity separation, magnetic roasting, and other technological processes [3–9]. The challenge of essentially different stages within the beneficiation process complicates the product recovery and promotes the growth of ore processing costs. That is why developing a technology of producing iron ore concentrates that would only involve magnetic methods is vital. This research aims to accomplish this task.

Exploring the application of magnetic methods in dressing crude iron ores

The subject of the research was oxidized ferruginous quartzites (OFQ) of Kursk Magnetic Anomaly.

The possibility of crude ore beneficiation was investigated using four representative technological samples (Samples 1, 2, 3, and 4).

The preparation of technological samples for beneficiation included grinding, reduction, and selecting the weighed portions for technological investigation and various tests. The experiments in controlling the largeness of grain size, ore pretreatment and beneficiation were done using standard laboratory equipment: Mastersizer 2000 diffraction testing instrument, MShL-7 ball mill, Bond ball mill, IsaMill M4 mill, LIMS-25/10 magnetic drum separator, and SLON 100 vertically pulsating high-gradient magnetic separator.

Both the starting materials and products of concentration were subjected to analysis using EDX-7000 Energy Dispersive X-ray Fluorescence Spectrometer.

The result of the investigation is the study of material composition, physico-mechanical properties, grindability and preparation characteristics of the representative technological samples.

The content of Fe_{total} in the first three samples is around 43.2, 42.7 and 43.5 % accordingly; the content of SiO_2 is 40.6, 41.8 and 41.6 % accordingly; the content of magnetic iron is 11.40 %, 12.31 %, and 12.67 % accordingly. The prevalence of ferric iron over the ferrous one shows the high

Table 1. **Test results for OFQ wet magnetic separation**

Sample	Type of product	Yield, %	$\beta_{Fetotal}$, %	β_{SiO2}, %	$\varepsilon_{Fetotal}$, %	ε_{SiO2}, %
Sample 1	Magnetite concentrate	10.70	66.00	7.20	16.33	1.90
	Hematite concentrate	41.60	62.47	17.90	60.08	18.34
	Combined concentrate	52.30	63.19	15.71	76.40	20.24
	Tailings	47.70	21.40	67.90	23.60	79.76
	Feed	100.00	43.26	40.61	100.00	100.00
Sample 2	Magnetite concentrate	11.70	66.10	4.90	18.09	1.37
	Hematite concentrate	40.10	62.58	16.20	58.69	15.53
	Combined concentrate	51.80	63.07	13.65	76.40	16.90
	Tailings	48.20	20.60	72.10	23.22	83.10
	Feed	100.00	42.76	41.82	100.00	100.00
Sample 3	Magnetite concentrate	9.90	66.10	8.00	15.05	1.83
	Hematite concentrate	40.30	62.71	16.90	58.14	15.76
	Combined concentrate	53.20	63.10	15.24	73.19	17.59
	Tailings	49.80	23.40	71.50	26.81	82.41
	Feed	100.00	43.47	43.21	100.00	100.00
Sample 4	Magnetite concentrate	7.19	60.49	9,06	8.99	2.43
	Hematite concentrate	42.09	60.58	8.86	52.68	13.94
	Combined concentrate	49.28	60.57	8.89	61.67	16.37
	Tailings	50.72	36.58	44.11	38.33	83.63
	Feed	100.00	48.40	26.75	100.00	100.00

oxidation degree of the ore. The content of phosphorus in oxide form was, accordingly, 0.14, 0.9 and 0.09 %. The distribution of total iron content in all samples and grain-size classes is fairly even.

Sample 4 contains a bit more iron, namely, 48.4 % of total iron. The content of magnetic iron is 5.01 %, which shows the high oxidation degree of the ore. The content of S_{total} is 0.3 %, of P_2O_5 is 0.07 %. The distribution of total iron in all grain-size categories is fairly even.

The investigated physico-mechanical properties allow to classify Samples 1 to 3 as solid ones and Sample 4 as a medium one in respect of resistance to ball milling in the lower size range appropriate for the use of ball mills.

Considering the low specific magnetic susceptibility of hematite and martite, the concentration is to be performed at high field density values (1.0 to 1.2 T). However, the presence of magnetite grains and clots in the operating area of a high grade separator is unacceptable since the matrices of the separator working elements get clogged with magnetite. Consequently, there is a need for two or more stages of separation in order to separately produce magnetite and hematite concentrates [4–9].

Low intensity magnetic separation (LIMS) was done on a laboratory drum separator PBM-25/10 under concurrent mode with drum rotation frequency of 35 min^{-1}. The field density in the separator varied in the range of 0.06 to 0.18 T as a result of changing distance between the permanent magnets and the working area of the drum shell. The experiment determined the recommended field density of 0.18 T for stage 1 of LIMS, and 0.06 T for stage 2.

The tailings obtained after weak-field LIMS were subjected to further magnetic separation in order to get hematite concentrate. The wet high intensity magnetic separation (WHIMS) aimed at obtaining hematite concentrate was carried out on a SLON 100 vertically pulsating high-gradient magnetic separator using matrices with stem diameter of 1.5, 2.0, 3.0 and 4.0 mm. The frequency of pulsation was 250 min-1, with the density of external magnetic field of 1.0 to 1.2 T, wash water rate of 10 liters per minute, and the weight of experiment sample of 200 g. The experiment determined that with WHIMS it is recommended to use a matrix with 3-mm stems at the field density of 1 T for stage 1, and a matrix with 1-mm stems at the field density 1.2 T at stage 2.

The results of concentration process obtained following the method shown in Figure 3 as a result of grinding in a ball mill to the grain size of P_{95} = 44.6 μm (P_{80} = 29.8 μm) are listed in **Table 1**.

The combined magnetic concentrates can be used, for example, as feed in blast-furnace process.

The lower technological indicators in Sample 4 can be explained by the fact that the content of magnetic iron in this sample is considerably lower than in Samples 1 to 3. A decision was made to continue the investigation of Sample 4 due to the fact that the positive experimental evidence obtained with this sample will yield similar results for Samples 1 to 3.

In international practice iron industry production facilities have successfully introduced the advanced energy-efficient Glencore Technology fine grinders operating on IsaMill technology [10, 11]. In order to investigate the effect of grinding size of less than 45 micron on the technology indicators of magnetic separation outcomes, experiments were done using a 4-liter IsaMill M4 for OFQ occurring in Russia, which have not previously been regarded as starting materials for beneficiation. The experiments were carried out under the following conditions: mill spindle rotational speed of 1,500 rpm, 50 % of solid matter in the mill feedstock, 2.5 kg of feed including ceramic grinding media of the following diameter: 3.5 mm (70 %), 2.0 mm (25 %), and 1.5 mm (5%). The grain size largeness of the grinding products was con-

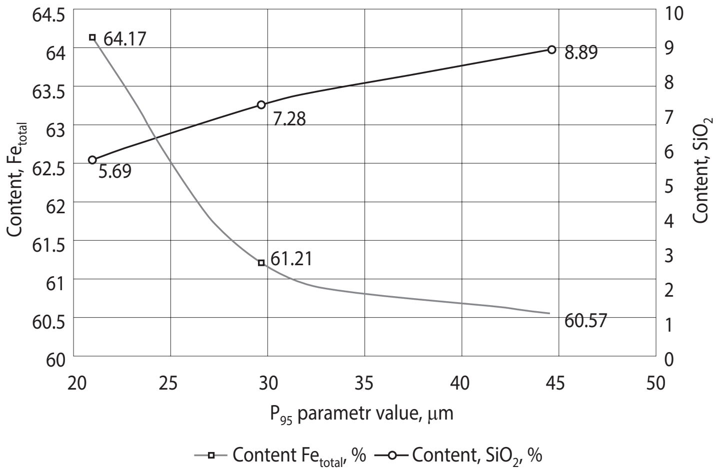

Fig. 1. Dependence of iron and silica content in the concentrate on grinding size

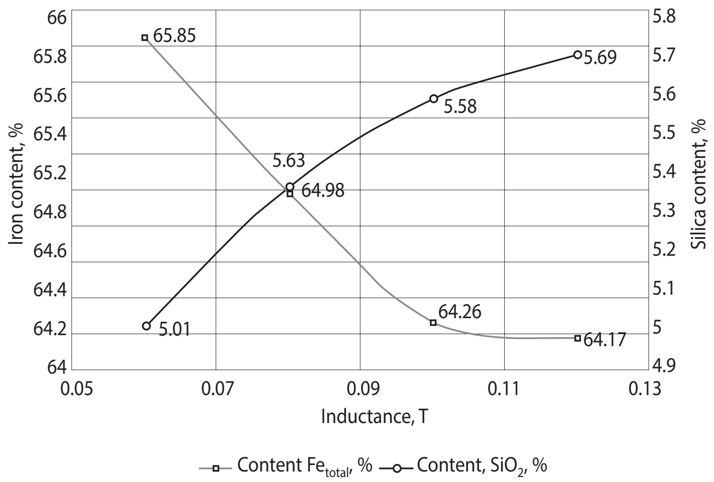

Fig. 2. Dependence of iron and silica content in the concentrate on magnetic field induction

Table 2. **Results of magnetic separation of OFQ Sample 4**

Type of product	Yield, %	$\beta_{Fe_{total}}$, %	$\beta_{Fe_{total}}$, %	$\varepsilon_{Fe_{total}}$, %	ε_{SiO_2}, %
Magnetite concentrate	9.62	69.98	5.18	13.94	1.92
Hematite concentrate	38.39	64.81	7.79	51.52	11.50
Combined concentrate	48.01	65.85	7.27	65.46	13.42
Tailings	51.99	32.08	43.30	34.54	86.58
Feed	100.00	48.29	26.00	100.00	100.00

trolled using Mastersizer 2000 diffraction testing instrument by Malvern Panalytical Ltd (UK).

The beneficiation of Sample 4 was carried out following the method shown in Figure 3. A ball mill was used at stage 1, and at stage 2 IsaMill was used. The results of magnetic separation obtained while grinding with various grinding size and field density at stage 2 of LIMS of 0.12 T are shown in **Fig. 1**.

The results obtained show that the best technological indicators of processing are achieved at the size of P_{95} = 21 μm (P_{80} = 10.3 μm).

For this size, the possibility to improve the quality of magnetic concentrate due to magnetic field density varying in the range of 0.06 to 0.12 T while processing in a magnetic drum separator at stage 2 was investigated. The results of investigating the dependence of iron and silica content on magnetic field density are shown in **Fig. 2**.

In order to obtain a concentrate with the content of Fe_{total} no less than 65 %, the following conditions must be observed at stage 2 of separation: grind size P_{95} = 21 μm (P_{80} = 10.3 μm), magnetic field density in LIMS = 0.06 T, in WHIMS = 1.2 T (1-mm stem matrix). The results of magnetic separation are listed in **Table 2** and shown above in **Fig. 3**.

The obtained combined magnetic concentrate is comparable in quality to iron ore concentrates produced by domestic iron ore plants. As was already mentioned, magnetite and hematite concentrates can be used in combination as well as separately. The quality of magnetic concentrate allows to use it as feed for direct reduction of iron.

It is apparent that before they are used in blast furnace processes and direct reduction plants, the obtained concentrates must first be subjected to agglomeration. Agglomeration is possible by method of briquetting, in particular, by extrusion. This method is truly universal and is suitable for practically any type of feedstock [12–20].

Comprehensive reprocessing of technology-related iron-containing materials

Iron ore beneficiation followed by metallurgical processing generates big amounts of iron-rich wastes (tailings, sludge, slag, metallurgical dust, etc.) which, if processed appropriately, can be converted into saleable products. It is also notable that such wastes often contain more iron in terms of the equivalent amount than some ores. Reprocessing these wastes also allows to successfully tackle environmental challenges in the areas where mining and processing as well as metallurgical plants operate [21, 22].

A typical example of technology-related sources of iron is the disposal sites of Kamysh-Burun iron ore plant located in the Republic of Crimea, which has been shut down since 2002. The plant used to process bog iron ores of now abandoned Kamysh-Burun and Eltigen-Ortel deposits, namely, two basic industrial types of ore, tobacco and brown, classified as complex ores with increased content of phosphorus (0.6 to 1.1 %) and arsenic (0.07 to 1.3 %). The iron content could be as high as 30 to 40 %.

Verkhne-Churbash sludge depository stores 24.2 mln tons of waste that pollute both air and water in the near vicinity of the city of Kerch. Of these, 19.8 to 21 mln tons can be reprocessed using open-cut method.

National University of Science and Technology "MISIS" conducted a number of studies investigating the preparation characteristics of two groups of samples from Kamysh-Burun iron ore plant mature tailings. The iron content in the samples from near-surface layers of the sludge dump was around 8±0.5 %; the samples taken at the depth of 2 m contained 40±1 %.

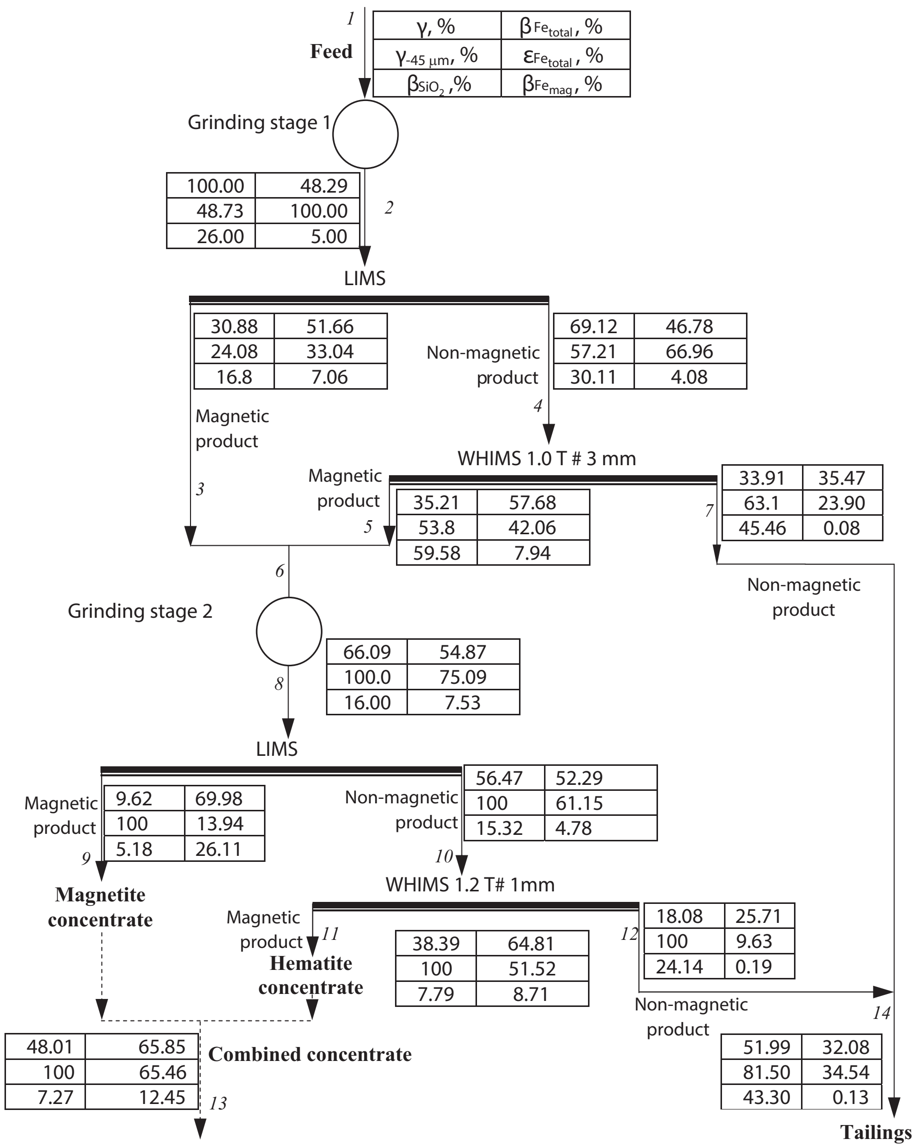

Fig. 3. Qualitative-quantitative process scheme for OFQ magnetic separation

Investigation for iron deportment in the samples from Verkhne-Churbash sludge depository (VCh) and Kamysh-Burun iron ore plant waste dump (KB) using Mossbauer spectrometry shows that iron minerals in the samples under study are technology-related types of iron hydroxides, including superparamagnetic hydrogoethite and small quantities of iron silicates. In KB samples about half of iron minerals were represented by weakly magnetic hydrogoethite. The sample composition allows to consider these wastes as feed to yield yellow and brown iron oxide pigments.

The result of preparation characteristics investigation and experimental validation of technological solutions proposed for reprocessing the mature tailings of Kamysh-Burun iron ore plant is a conceptual technology of comprehensive processing which includes:

– multistage magnetic separation in high-intensity and high-gradient separators;

– recovering the magnetic fraction using Romelt process to yield pig iron and slag to be used in aggregates production;

– several stages of ultrasonic dispersion of nonmagnetic fraction under ultrasound frequency of 18 to 22 kHz and field density of 3 to 4 w/cm^2;

– precipitation of coarse-grained fraction and fine magnetic particles directing them to waste dump or to combined magnetic product used for smelting under Romelt process;

– dehydration, drying and heat treatment of the precipitated fine product to obtain iron oxide pigments with colours varying from light brown to red depending on the temperature.

The metal and pigment obtained are suitable for saleable product manufacturing [22].

Conclusion

One of the trends in enhancing the efficiency of domestic industrial enterprises is the possibility to include treatment of oxidized ferruginous quartzites as part of mineral processing.

The article investigates the material composition and preparation characteristics of four representative samples of oxidized ferruginous quartzites mined at Kursk Magnetic Anomaly.

The article explores the possibility of using the advanced IsaMill technology in a fine grinding cycle for a certain type of ore.

A new technology of magnetic separation of oxidized ferruginous quartzites is developed. The technology involves two-stage grinding using ball mill at stage one and fine grinding with IsaMill technology at stage two. The magnetic separation is conducted by stage under strong and weak magnetic fields.

Applied in practice, the technology leads to obtaining of either magnetite and hematite concentrates separately, or a combined magnetite-hematite concentrate, all comparable in quality to iron ore concentrates produced by domestic iron ore plants. The technological indicators for the combined magnetite-hematite concentrate are as follows: yield 48.01 %, content of Fe_{total} = 65.85 %, SiO_2 = 7.27 %, recovery of Fe_{total} = 65.46 %.

In laboratory conditions, the mature tailings of bog iron ores processing yielded a concentrate suitable for smelting under Romelt process to produce pig iron and slag to be used as raw material for aggregates.

The possibility of obtaining light brown iron oxide pigments from disposal sites of Kamysh-Burun iron ore plant is shown.

REFERENCES

1 Rovenskikh M. V., Kobzeva A. G. Analysis of iron ore reserves in Russia and worldwide. *Digital economy: Challenges and prospects*. 2019. pp. 318–323.
2. Tsvetkova A., Katysheva E. Present problems of mineral and raw materials resources replenishment in Russia. *International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM. 2019.* Vol. 19. Iss. 5.3, pp. 573–578. DOI: 10.5593/sgem2019/5.3/S21.072.
3. Aleksandrova T., Nikolaeva N., Lieberwirth H., Aleksandrov A. Selective disintegration and concentration: Theory and practice. *E3S Web of Conferences, 56.* 2018. DOI: 10.1051/e3sconf/20185603001.
4. Pelevin A. E. Methods of enhancing the efficiency of iron ore resources beneficiation. *Chernaya metallurgiya. Byulleten nauchno-tekhnicheskoy i ekonomicheskoy informatsii*. 2019. No. 2. pp.137–146. DOI: 10.32339/0135-5910-2019-2-137-146.
5. Karmazin V. V., Karmazin V. I. Magnetic, electric, and specialised methods of mineral processing: Textbook for higher education. In 2 volumes. Stereotype edition 3. Moscow. "Gornaya kniga" publishing house. 2017. Vol. 1: Magnetic and electric methods of mineral processing. 672 p.
6. Golenkov D. N., Chanturiya V. A., Shelepov E. V., Ignatova T. V. Increasing the reserves of iron ores by involving oxidized ferruginous quartzites in the processing scheme. *Challenges and prospects of efficient mineral processing in the 21st century (Plaksin readings, 2019): Materials of international conference. Irkutsk, September 9–14, 2019.* pp. 278–280.
7. Patra S. et al. Mineralogical and Chemical Characterization of Low Grade Iron Ore Fines from Barsua Area, Eastern India with Implications on Beneficiation and Waste Utilization. *Journal of the Geological Society of India*. 2019. Vol. 93. No. 4. pp. 443–454.
8. Maksimov I. I., Sentemova V. A. Aspects of processing of oxidized ferruginous quartzites with increased content of magnetite. *Obogashchenie rud*. 2012. No. 3. pp. 7–10.
9. Quast K., Skinner W. Influence of matrix type on WHIMS performance in the magnetic processing of iron ores. *Minerals Engineering*. 2020. Vol. 152. June 15. 106346. DOI: 10.1016/j.mineng.2020.106346.
10. Anderson G. S., Bandarian P. A. Improving IsaMill™ energy efficiency through shaft spacer design. *Minerals Engineering*. 2019. Vol. 132. pp. 211–219.
11. David D., Larson M., Le M. Optimising Western Australia Magnetite Circuit Design. *In. Proceedings MetPlant*. Perth, Australia. 2011. pp. 552–562.
12. Nazarenko M. Yu., Kondrasheva N. K., Saltykova S. N., Bazhin V. Yu. Physical properties of briquettes produced from shale fines and wood dust. *Izvestiya Tomskogo politekhnicheskogo universiteta. Inzhiniring georesursov*. 2016. Issue 327 (3). pp. 67–74.
13. Kondrasheva N. K., Saltykova S. N. Estimating the possibility of industrial use for oil shales and ash-shale wastes. *Zapiski Gornogo instituta*. 2016. Vol. 220. pp. 595–600. DOI: 10.18454/PMI.2016.4.595.
14. Nazarenko M. Yu., Bazhin V. Yu., Saltykova S. N., Sharikov F. Yu. Changing the chemical composition and properties of oil shales under heat treatment. *Koks i khimiya*. 2014. No. 10. pp. 46–49.
15. Trushko V. L., Utkov V. A. Developing import-substituting technologies of enhancing sintering machine productivity and sinter cake strength. *Zapiski Gornogo instituta*. 2016. Vol. 221. pp. 675–680. DOI:10.18454/PMI.2016.5.675.
16. Aleksandrova T. N., Rasskazova A. V. Investigating the dependence of the quality of coal fuel briquettes on the manufacturing parameters. *Zapiski Gornogo instituta*. 2016. Vol. 220. pp. 573–577. DOI: 10.18454/PMI.2016.4.573.
17. Bizhanov A. M., Bragin V. V., Bardavelidze G. G., Pigarev S. P. Metallurgical characteristics of blast furnace extrusion briquettes (BREX) based on hematite concentrate. *Metallurgist*. 2020. Issue 9. pp. 17–25.
18. Nikulin A. N. 3D modeling of an extrusion shaper. *European science*. 2015. No. 2. pp. 8–12.
19. Shuvalov Yu. V., Tarasov Yu. D., Nikulin A. N. Validation of optimum technologies of obtaining fuel-energy feedstock based on solid combustible coal-containing wastes. *Gornyi informatsionno-analiticheskiy byulleten*. 2011. No. 8. pp. 243–247.
20. Argimbaev K. R., Kornev A. V., Kholodnyakov G. A. Validating the feasibility of involving iron-containing tailings in processing with subsequent agglomeration of the obtained concentrates. *Zapiski Gornogo instituta*. 2013. Vol. 206. pp. 120–124.
21. Petrov G. V., Boduen A. Ya., Popov A. A., Fokina S. B. Chemical concentration of steelmaking dusts. *Chernye metally*. 2016. No. 10. pp. 65–68.
22. Yushina T. I., Krylov I. O., Valavin V. S., Sysa P. A. Producibility of iron-bearing materials from industrial waste of Kamysh-Burun iron ore plant using Romelt process (part II). *Gornyi Zhurnal*. 2017. No. 7. pp. 68–72. DOI: 10.17580/gzh.2017.07.13.

Authors contributions:

Kuskov V. B.: designed the methods of investigating the preparation characteristics of various iron ore types; processed the experimental results.

Lvov V. V.: designed the methods of investigating the preparation characteristics of various iron ore types; designed process schemes of iron ore treatment using IsaMill technology.

Yushina T. I.: examined the material composition and developed the methods of investigating the processing and preparation characteristics of mature iron ore processing wastes; participated in developing the processing schemes for comprehensive reprocessing of mature iron-bearing tailings with the use of ultrasonic treatment and Romelt process; processed and analyzed the experimental results.