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DEEP CONCENTRATION OF HIGH-GRADE IRON ORE IN THE BELGOROD REGION OF THE KURSK MAGNETIC ANOMALY

The article presents the research findings on deep concentration of basic mineralogical varieties in the composition of naturally occurring high-grade ore with a view to producing high-quality iron ore feedstock for metallization deposition and integrated processing. The technology experiments used the basic tools of mineral dressing (screening, magnetic separation in weak and strong fields, gravity concentration, flotation). The technological studies demonstrate feasibility of obtaining high-quality iron ore products from natural high-grade iron ore using a simple technology. By the authors' opinion, the most efficient method to extract valuable components from loose and semi-loose ore is screening, which is proved experimentally by production of high-quality iron material from loose and semi-loose micaceous iron oxide–martite for direct reduction. It is emphasized that wet separation approaches inevitably end with considerable loss of marketable products and bring difficulties connected with dewatering and drying.

Special purpose production involves deep concentration of ore using various methods. This article presents the results of polygradient magnetic separation, gravity concentration and flotation. Polygradient magnetic separation offers a high-quality product that meets standards of such industries as powder metallurgy, manufacture of batteries, etc. Gravity separation and flotation are not recommended for application.

Keywords: *high-grade iron ore, metallization deposition, deep concentration, wet magnetic separation, polygradient separation, gravity concentration, flotation.*
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Introduction

To compete successfully on the world market of iron ore products, the domestic industry demands high-quality feedstock suitable for direct metallization deposition. The latter means that the feedstock is to be of higher metallurgical value which is governed by contents of useful components, impurities and slag-forming oxides [1–3]. A promising and secure source of raw materials for the iron industry of Russia is deep-seated deposits of naturally occurring rich ore in the Belgorod iron ore province of the Kursk Magnetic Anomaly [4]. Alongside with colossal reserves and high quality, the advantage of these ore bodies is very comfortable combination of geographical, natural and economic conditions [4, 5].

At different times (1992–2000) deep concentration of rich iron ores produced in the mentioned area (including the Yakovlevo field) was often approached using various methods. According to [6–8] the rich local deposits are composed of uniform geological and mineralogical types that belong to diverse mineral kinds depending on the presence and quantitative ratio of oregenetical and secondary associated minerals.

Technological study

The technological study into deep concentration of rich iron ore was carried out using large-volume samples of mineralogical varieties from the Yakovlevo deposit. This ore has similar composition and properties as rich ore from the other deposits in the region [3, 4].

The study objects were such mineralogical varieties as: micaceous iron oxide–martite, chloritized, semi-loose, –100 mm in size (Ya-1); martite–hydrohematite, loose, –100 mm in size (Ya-2); micaceous iron oxide–martite, loose, with chlorite, –350 mm in size (Ya-3); martite–hydrohematite–hydrogoethite, loose, clay-like (pigmented), –100 mm in size (Ya-4); martite with micaceous iron oxide, low-chloritized, loose, –350 mm in size (Ya-5); and micaceous iron oxide–martite, hard-rock, –350 mm in size (Ya-6). Total chemical compositions of bulk samples are described in **Table 1**.

Table 1. Total chemical composition of technological samples

Oxides and components	Mass percent per sample					
	Ya-1	Ya-2	Ya-3	Ya-4	Ya-5	Ya-6
Fe_{total}	66.2	62.2	67.9	53.3	68.3	58.8
FeO	2.92	5.1	3.5	5.1	3.4	5.9
Fe_2O_3	91.5	83.3	93.2	70.55	93.8	77.4
SiO_2	2.5	3.7	1.2	6.1	1.0	9.5
Al_2O_3	1.15	1.75	0.78	2.7	0.55	2.7
CaO	0.3	0.7	0.3	1.5	0.2	0.55
MgO	0.3	0.3	0.14	0.64	0.2	0.3
TiO_2	0.04	0.11	0.01	0.15	0.02	0.02
MnO	0.04	0.08	0.06	0.15	0.04	0.07
S	0.06	0.025	0.04	0.033	0.02	0.11
P_2O_5	0.04	0.05	0.06	0.06	0.04	0.05
Loss in calcination	1.22	4.83	0.55	13.0	0.41	2.84
K_2O	0.06	0.08	0.06	0.07	0.04	0.08
Na_2O	0.11	0.1	0.12	0.13	0.05	0.12

Table 2. Characteristics of fraction –1 mm of loose and semi-loose varieties

Yield of size (from –1 mm) per sample, %	Mass fraction per size (mm), %						
	+0.56	–0.56+0.28	–0.28+0.16	–0.16+0.071	–0.071+0.045	–0.045	Total
			Ya-1				
Yield	1.0	1.9	0.8	1.2	1.1	9.4	15.4
Fe_{total}	67.3	67.2	66.7	66.61	67.75	68.12	67.37
SiO_2	2.15	2.1	2.5	2.0	1.27	1.0	1.45
Al_2O_3	0.45	0.45	0.46	0.54	0.6	0.66	0.62
			Ya-2				
Yield	2.4	3.9	4.1	13.0	6.0	9,0	38.4
Fe_{total}	61.5	62.2	62.9	66.1	66.6	60.0	63.72
SiO_2	4.75	4.0	2.0	1.2	1.5	2.35	2.10
Al_2O_3	2.2	2.0	1.35	1.0	1.2	1.25	1.30
			Ya-3				
Yield	3.1	4.5	2.4	6.3	4.7	7.9	28.9
Fe_{total}	67.0	68.7	68.7	69.4	69.6	67.2	68.41
SiO_2	0.7	0.7	0.5	0.4	0.35	0.48	0.50
Al_2O_3	0.6	0.55	0.45	0.45	0.5	0.6	0.53
			Ya-4				
Yield	1.6	2.4	1.1	1.8	1.1	6.9	14.9
Fe_{total}	62.6	53.0	54.1	56.2	57.5	58.1	57.19
SiO_2	6.5	6.15	5.9	5.6	4.6	3.9	4.95
Al_2O_3	3.3	3.15	3.0	2.7	2.3	1.8	2.41
			Ya-5				
Yield	1.8	6.1	4.7	10.5	6.2	32.9	62.2
Fe_{total}	68.7	68.6	68.5	68.7	68.9	68.0	68.32
SiO_2	0.95	0.9	1.1	0.9	0.7	0.75	0.82
Al_2O_3	0.5	0.5	0.6	0.5	0.4	0.5	0.50

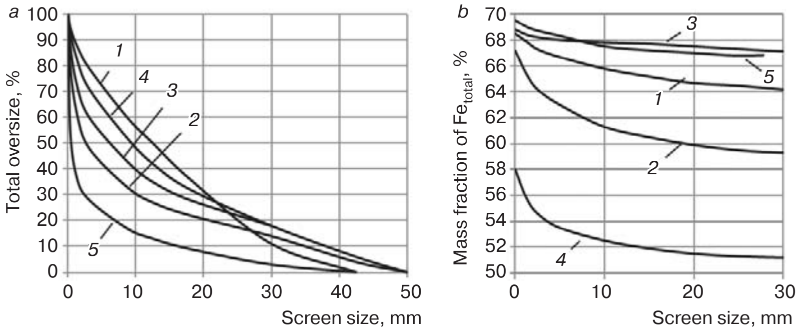

Fig. 1. Grain size composition (*a*) and size distribution of Fe_{total} (*b*) in technological samples:
1 — micaceous iron oxide–martite, chloritized, semi-loose Ya-1;
2 — martite–hydrohematiter, loose Ya-2; *3* — micaceous iron oxide–martite, loose, with chlorite Ya-3; *4* — martite–hydrohematite–hydrogoethite, loose Ya-4; *5* — martite with micaceous iron oxide, low-chloritized, loose Ya-5

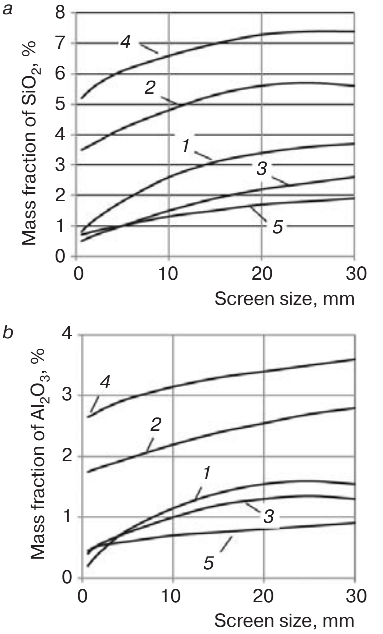

Fig. 2. Distribution of SiO_2 (*a*) and Al_2O_3 (*b*) per size grades in technological samples (the curves are explained in Fig. 1

Before primary estimation, for each mineralogical variety, a treatment scheme and a study model were developed [9, 10]. Each mineralogical variety was re-ground down to the size of –50 mm. The distribution of the size grades and chemical components (Fe_{total}, SiO_2 and Al_2O_3) is demonstrated in **Figs. 1** and **2**. The lowest size limit for similar ore is 8 mm; this particle size ensures optimal processing at the moisture content not higher than 9%.

The yield of size –8 mm ranged from 38.5 to 81.9% in the loose and semi-loose varieties, respectively, and from 15.6 to 65.5% in the other varieties. The size distribution of the chemical components (Fe_{total}, SiO_2 and Al_2O_3) has a distinct trend of increasing Fe_{total} and decreasing SiO_2 and Al_2O_3 in the line from the large to small classes (–1 mm) (see Figs. 1 and **2**). All samples contained high amount of the size –1 mm; for this reason, it was decided to analyze distribution of the main chemical components in the size less than 1 mm. From the results, deep desliming or

Table 3. Averaged characteristic of technological samples after classification by size 8 mm

Sample	Classification product		Mass percent per size		
	Size, mm	Yield, %	Fe_{total}	SiO_2	Al_2O_3
Ya-1	+8	61.5	65.45	3.13	1.36
	–8+0	38.5	67.65	1.46	0.71
	Initial	100.0	66.30	2.61	1.11
Ya-2	+8	34.5	59.57	4.17	2.29
	–8 + 0	65.5	63.66	3.52	1.48
	Initial	100.0	62.25	3.74	1.76
Ya-3	+8	44.3	67.49	1.84	1.05
	–8+0	55.7	68.25	0.78	0.62
	Initial	100.0	67.91	1.25	0.81
Ya-4	+8	53.7	51.71	6.42	2.74
	–8+0	46.3	55.19	6.01	2.49
	Initial	100.0	53.32	6.23	2.62
Ya-5	+8,0	18.1	67.42	1.52	0.7
	–8,0+0	81.9	68.47	0.85	0.51
	Initial	100.0	68.28	0.97	0.54
Ya-6	+8	84.4	58.42	10.38	2.89
	–8+0	15.6	60.45	4.97	1.52
	Initial	100.0	58.74	9.54	2.68

hydraulic classification has no noticeable effect, while wet separation processes lead to high losses of marketable products as well as to difficult dewatering and drying (**Table 2**).

The authors think the most efficient method of separating rich particles from loose and semi-loose ore types is screen sizing. The experimental results proved feasibility of producing high-quality iron ore concentrate from loose and semi-loose micaceous iron oxide–magnetite ore for direct reduction (**Table 3**).

Another simple alternative of rich loose ore separation from bulk production flow to a marketable product can be selective grinding and screening. The earlier research [6, 8] found an evident correlation between the size (adequate to the strength) and the quality of ore both within the same and different mineralogical varieties (less strong components featured higher quality). At the same time, loose and semi-loose ores contain weakly cemented rich (in terms of Fe_{total}) varieties which remain in oversize product in screening and reduce the quality ore yield. In this respect, it is required to disintegrate these varieties while more compact (hard and semi-hard rock) should remain intact. Disintegration in the selected optimal mode (rotor speed 15 m/s) was carried out on disintegrator DESI-16C **(Fig. 3)**.

The analysis of the results shows an increased mass fraction of Fe_{total} in the size –8 mm and a decreased fraction of total iron in the size +8 mm (the difference is from 0.76 to 4.09%). The mass fraction of SiO_2 in these sizes is also different (changes from 0.41 to 5.41%) **(Table 3)**. Moreover, in case of the smaller mass fraction in the feed of the disintegrator, the difference in the mass fraction of Fe_{total} between these sizes is higher.

Thus, selective grinding and screening of the fraction +8 mm after primary screening of loose and semi-loose mineralogical varieties produced 15–26% of a product suitable for metallization deposition, with Fe_{total} up to 67.5 and SiO_2 to 1.84%. The mass fractions of sulfur and phosphorus were 0.01–0.015%, and up to 0.06%, respectively, while the ratio of slag-forming basic acid oxides was 0.2–0.25%. These imply that the product satisfies the metallization deposition standards.

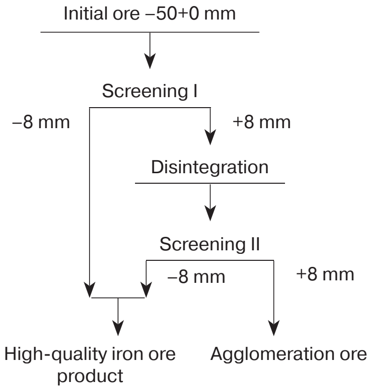

Fig. 3. Selective grinding and screening circuit for loose and semi-loose ore

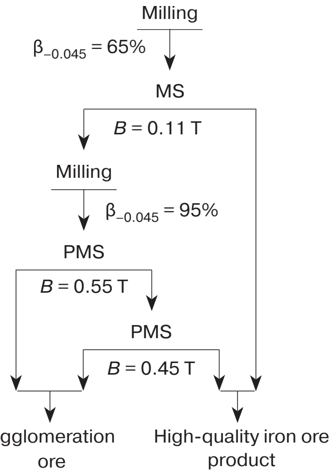

Fig. 4. Basic diagram of magnetic treatment of size –8 mm

In the meanwhile, the Yakovlevo deposit, as the other local ore bodies, contains low-grade ore (Ya-6)—carbonatized varieties with mass fractions of Fe_{total} = 55÷60% and SiO_2 = 8÷10%. Additional treatment of such varieties (grinding+screening) can produce agglomerated or lump blast-furnace ore. The low-grade varieties also include hydrohematite–hydrogoethite (pigmentated) ore types which are suitable for selected extraction and re-processing by special technology. The pilot experiments with sluicing extracted iron oxide slimes (to 50%) and compact martite varieties (Fe_{total} = 55÷60%) convenient for agglomeration. The iron oxide slimes (after thickening, roasting, drying and milling) are the feedstock for the pink-and-varnish industry (iron oxide pigments) [11].

In this manner, as the research has shown, production of iron ore material for metallization deposition can use a simple circuit with screening and selective screening.

The special-purpose production needs deep

Table 4. Averaged balance sheet data on processing of micaceous iron oxide–martite variety by different methods, %

Processing method	Technological parameters of products, %								
	Initial			High-quality			Waste (tailings)		
	Yield	Fe_{total}/SiO_2	Recovery of Fe_{total}	Yield	Fe_{total}/SiO_2	Recovery of Fe_{total}	Yield	Fe_{total}/SiO_2	Recovery of Fe_{total}
High-level magnetic separation (size –8 mm, semi-loose)	38.5	67.65/1.46	39.28	26.0	69.0/0.32	27.06	12.5	64.82/4.82	12.22
Gravity separation (size –8 mm, semi-loose)	38.5	67.65/1.46	39.28	25.6	68.51/0.15	26.45	12.9	65.94/4.06	12.83
Flotation (loose)	100.0	67.91/1.25	100.0	95.0	68.21/1.01	95.42	5.0	62.2/4.05	4.58

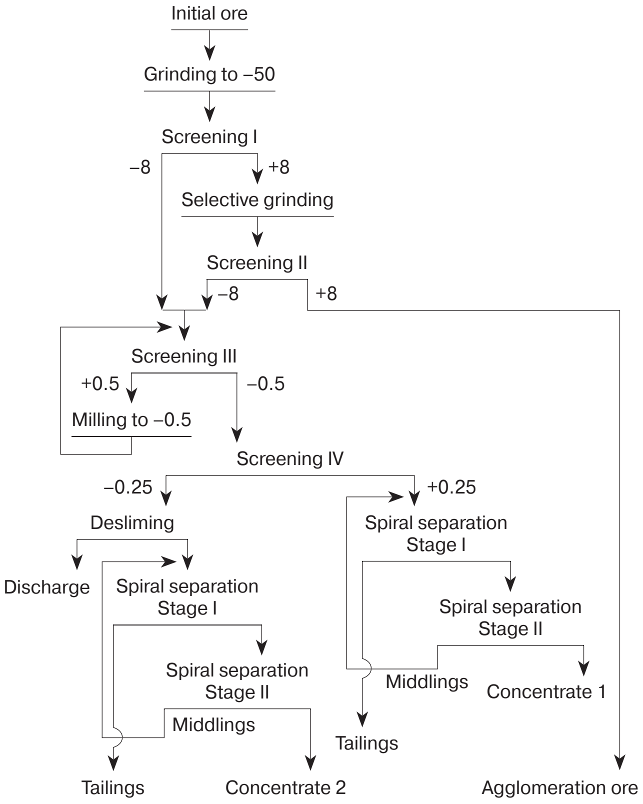

Fig. 5. Basic diagram of gravity separation

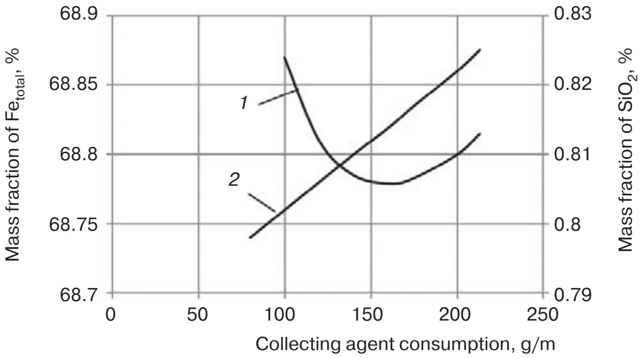

Fig. 6. Dependence of mass fractions of SiO_2 (*1*) and Fe_{total} (*2*) in flotation concentrate on consumption of collecting agent

concentration by different methods. Internationally, hematite ore is the most widely treated by polygradient magnetic separation (PMS) [12]. The magnetic processing experimentation used the circuit in **Fig. 4** and the milled size –8 mm (to 65–70% content –0.045 mm). The first stage of magnetic separation (MS) was carried out on lab magnetic separator EBM-32/20 at the field density *B* of 0.11 T to prevent PMS blockage in extraction of magnetite and relics from ore. PMS was implemented on analyzer R-40 composed of an electromagnetic system and a nonmagnetic matrix filled with checker plates made of magnetically soft material. The MS tailings milled up to the 90% content of the size –0.045 mm were subjected to PMS at *B* = 0.5 T in the gap between the plates. The effect of the magnetic field density on the separation efficiency was pre-examined. It is found that when the field density is changed from 0.3 to 0.7 T, the yield of the magnetic product reduces from 98.8 to 67.8% while the mass fractions of Fe_{total} in the concentrates differ inconsiderably: Fe_{total} = 68.03% and SiO_2 = 0.93% at *B* = 0.3 T whereas Fe_{total} = 67.85% and SiO_2 = 1.23% at *B* = 0.7 T.

The further studies assumed the field density *B* = 0.5 T. When treated by MS at *B* = 0.11 T, the variation ranges were wider: yield of the concentrate — from 0 to 33.1%, mass fraction of Fe_{total} in the concentrate — from 68.5 to 69.78%, and SiO_2 — from 0.34 to 0.59%. The PMS concentrate was scavenged on the same analyzer at *B* = 0.45 T. The total concentrate yield varied from 34.2 to 71.8%, mass fraction of Fe_{total} — from 67.17 to 69.13%, and SiO_2 — from 1.51 to 0.62%. The mass fraction of Fe_{total} in tailings was 57.21 to 67.02%, and the latter was a suitable product to be used as a feedstock for agglomeration.

On individual basis, test treatment of the size –8 mm extracted from micaceous iron oxide–martite (Ya-1) was carried out. The test deep concentration of the product gave the total concentrate with Fe_{total} = 69.0% and SiO_2 = = 0.32% at the yield of 62.3% (from the size –8 mm). Joint tailings (Fe_{total} = 65% and SiO_2 = 4.82%) are dewatered and blended with agglomeration ore. Thus, the resultant high-quality product meets requirements of the powder metallurgy, battery production, etc.

Different weights of metallic and nonmetallic minerals made grounds for undertaking test *separation by gravity*. The gravity concentration was carried out as separation in spiral sluices manufactured by SPIRIT NPF (**Fig. 5**). Selective grinding and screening of an initial sample separated the size –8 mm from it; the size +8 mm was the final product (agglomeration ore). Wet screening of the size –8 mm extracted the size –0.5 mm (size +0.5 mm was remilled down to the size –0.5 m and mixed with the size –0.5 mm produced by wet screening). Then, the size –0.5 mm was separated with regard to the size 0.25 mm. The fraction –0.25 mm was subjected to desliming, and the sands were treated on the spiral separator at two stages with production of concentrate and tailings.

The fraction –0.5+0.25 mm was processed by the same scheme. From the analysis of the results, in the gravity dressing of the size –0.25 mm, after desliming, the concentrate enjoys the increase in Fe_{total} by 0.86% and the decrease in the mass fraction of SiO_2 by 0.04–0.29%. The less increment in Fe_{total} in concentrate is observed after processing of the size –0.5+0.25 mm (not higher than 0.08–0.45%).

The mineralogical optic analysis of the gravity concentrates after treatment of the sizes –0.5+0.25 and –0.25 mm finds that the concentrates are impure with high-grade and low-grade aggregates (martite– and hematite–chlorite) of metallic and nonmetallic (chlorite) minerals. Based on the aforesaid, the gravity separation is inefficient with fine sizes of high-grade iron ore of various mineralogical varieties, and is not recommended to be used as the basic procedure.

Flotation as the main method of iron ore dressing involves some difficulties and, first and foremost, wastewater purification. Re-treatment of PMS concentrate was carried out by reverse cation flotation. The collecting agent in all tests was cation collector PA-14 (Tomah, USA); the modifying agent was the solution NaOH (pH was varied from 8–8.5 to 10–10.5); the depressing agent for iron oxides was modified corn flour. The experiments showed no essential effect of pH variation in the medium on the technological parameters of separation.

It is found that consumption of the cation collector both slightly increases Fe_{total} (from 68.76 to 68.85%) and decreases SiO_2 (from 0.82 to 0.80%) in the middlings (concentrate). Such low efficiency of flotation of the magnetic product is connected with the presence of chlorite which is tightly intergrown with metallic minerals (hematite and martite) and inextractable to froth (tailings). The influence of the reagent mode on the separation performance is illustrated in **Fig. 6** (sample Ya-3). The analysis of the magnetic product flotation shows that the mass fraction of Fe_{total} rises merely by 0.1–0.33% while SiO_2 reduces by 0.05–0.11% in all mineralogical varieties of high-grade ore.

Low efficiency of flotation in re-processing of concentrates impedes recommending this method for high-grade iron ore deposits in the region.

Conclusion

The primary investigation has shown that it is possible to obtain high-quality iron product from naturally occurring high-grade iron ore using a simple technology (**Table 4**). Moreover, re-processing of rich iron ore can be wasteless, which significantly mitigates the environmental impact in the region [5. 8]. Also, it should be emphasized that wet separation processes inevitably result in considerable loss of marketable products and bring difficulties connected with dewatering and drying.

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