Study of possibility of magnetic hydrocyclone use in concentration cycles of oxidized ferriferous quartzites

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Iron role is very essential in the up-to-date economics. Magnetite quartzites are the main source of iron making in Russia. Oxidized ferriferous quartzites are also used for accumulation of the Russian mineral and raw material base. Substantial composition and concentration capacity of the represented sample of oxidized iron ore are examined. Ore sample was ground during two stages in a ball mill and IsaMill mill. Comminuted material was classified in magnetic hydrocyclone of original construction. Magnetic system, which was mounted on the hydrocyclone, had been designed using computer software ANSYS Maxwell for simulation of electromagnetic fields and had been manufactured with use of permanent magnets made of Nd—Fe—B alloys on the base of rare earth elements. Classifying products in magnetic hydrocyclone were concentrated consequently in low- and high-intensive magnetic fields. Technological scheme for concentration of oxidized ferriferous quartzites was developed. This scheme allows to produce high-quality magnetite concentrate, hematite concentrate and mixed hematite – magnetite concentrate.
Key words: iron ore raw material, IsaMill grinding technology, magnetic hydrocyclone, classifying, magnetic separation, high-gradient magnetic separation, oxidized ferriferous quartzites.
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Introduction

Mineral and raw material complex plays the most important, even decisive role in the most countries for providing sustainable development of the global economics. And iron as a raw material can really be considered as the base of modern industry. It is difficult to mention such area of activity, where iron or its alloys were not used [1-6].

The most part of iron ores in Russia is presented by magnetite quartzites and is characterized by relatively low Fe content, thereby such ores are subjected to mandatory concentration. It allows to increase substantially economical efficiency of further processing both of iron ores and any other kinds of mineral resources [7-16].

Russia has serious amount of oxidized ferriferous quartzites (OFQ), which are essential reserve of iron ores. These ores are principally more complicated object for concentration in comparison with magnetite quartzites. To provide OFQ concentration, stadial concentration using magnetic, gravitation, flotation and other methods, as well as their combination, are used [12-16].

It seems prospective to use simultaneous effect of different physical fields on the base of superposition principle for concentration, e.g., simultaneous effect of gravitation and magnetic fields. Particles of magnetite, hematite and quartzite differ substantially by density and by magnetic sensitivity, thereby the effect of magnetic field will strengthen the effect of gravitation one.

It should be mentioned that practically all iron ores subjected to concentration are finely disseminated ones. It is required to include fine grinding in ore preparation process for their concentration; this process is conventionally used within closed circuit with classifying in hydrocyclones.

Based on these "prerequisites", this paper was devoted to study of the technology using magnetic separation in weak and strong fields after fine grinding with application of magnetic hydrocyclone in the classifying cycle.

Hydrocyclones are widely used in many industries. They are characterized by simple construction, relatively low cost, high productivity [17, 18]. Hydrocyclone with magnetic system was firstly developed and used in the USSR. Pulp in such hydrocyclone passes through magnetic system, magnetite

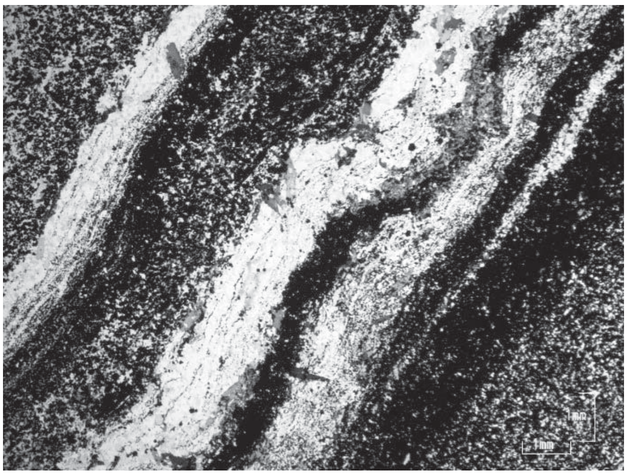
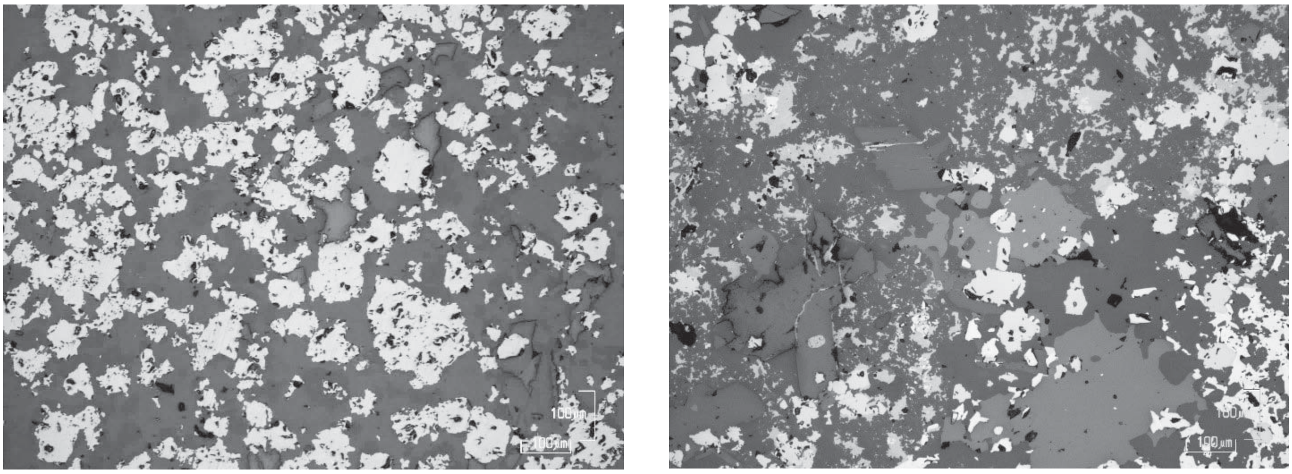
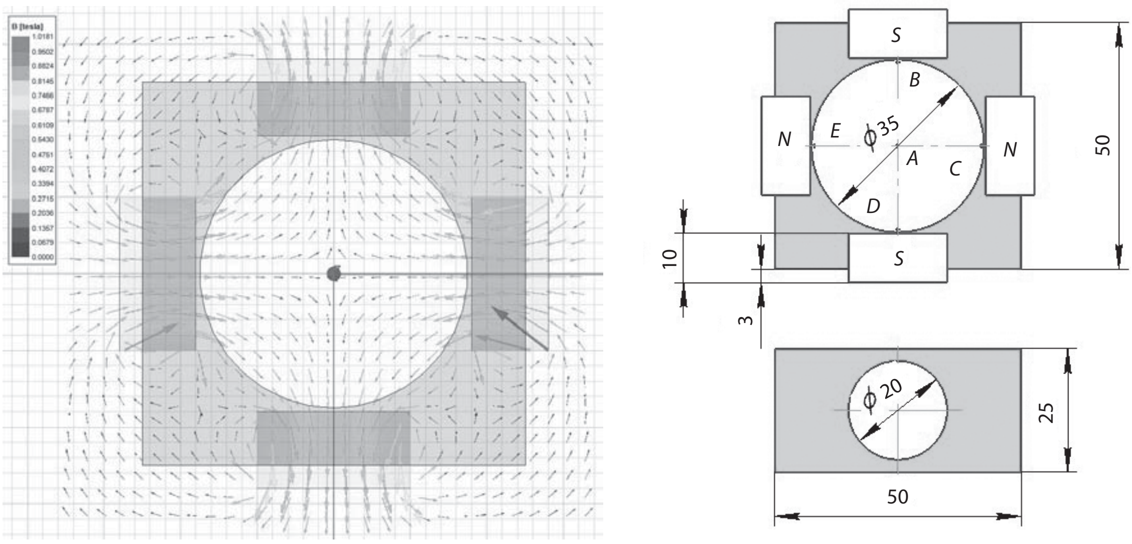


Fig. 1. Ferriferous quartzites (fine-lamellar texture)



a *b*

Fig. 2. Interlayers in ferriferous quartzites:
a – carbonate-celadonite-magnetite-quartzite; *b* – hematite-magnetite-hydrogoethite-carbonate-celadonite-quartzite



a *b*

Fig. 3. Magnetic system: *a* – model of magnetic system; *b* – parameters of magnetic system

particles are magnetized and form floccules, which move in sands more completely than separate particles [19-21].

Study of possibility of OFQ concentration efficiency rise at Mikhailovskoe deposit, using magnetic hydrocyclone, was the aim of this investigation.

Analysis of examination results for substantial composition of the studied sample allowed to characterize OFQ from Mikhailovskoe deposit by concentration capacity degree as rather hardly concentrating for all separation processes. It is explained by the fact that OFQ are fine-grained, very abrasive and high-strength. Small and fine dissemination as well as relatively high strength of ores causes necessity of grinding during several stages. It finalizes in increased processing expenses [22].

Represented sample of oxidized ferriferous quartzites from Mikhailovskoe deposit is the object of investigations.

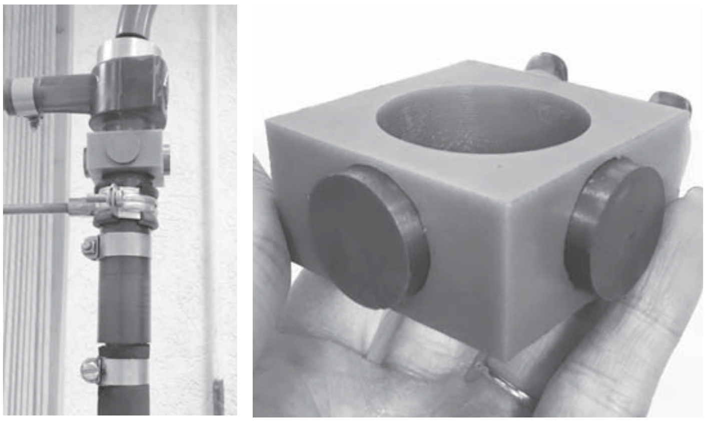
Experimental part

Chemical, mineral and granulometric composition of the sample was determined preliminarily. Visual and optical methods, X-ray spectral microanalysis, computer-aided analysis, chemical analysis and sieve analysis were used for examination of sample substantial composition.

Optical method was applied with use of polarization microscope ECLIPSE LV100-POL, optical stereomicroscope SMZ-1500 with digital photo-micrographic system DS-5M-L1 and stereomicroscope SMZ-645.

The complex MLA 650 (FEI Company) equipped with scanning electron microscope FEI Quanta 650 SEM was used for determination of the sample chemical composition.

As a result of the sample examination, it was determined that ore texture is characterized as fine-laminated with alternation of quartzite-hematite-magnetite and quartzite interlayers, as well as celadonites, carbonates (**Fig. 1**). Content of iron oxides varied within the range 15-85 %.



a *b*

Fig. 4. Hydrocyclone unit:
a – hydrocyclone with mounted magnetic system;
b – magnetic system

Hematite and magnetite are the main ore minerals in the sample; also hydrogoethite and other iron hydroxides are presented in the sample.

Magnetite is presented in quartzite-hematite-magnetite, carbonate-celadonite-magnetite-quartzite and magnetite-hydrogoethite-hematite-carbonate-celadonite-quartzite interlayers (see **Fig. 2**). Iron part in magnetite makes 69-71 %.

Hematite is characterized by isometric and elongated-lamellar shape with size 0.03-0.15 mm. Iron part in hematite makes 67-70 % and SiO_2 – up to 1.75 %.

Hydrogoethite is presented as impregnations of different sizes: from 3 to 120 μm. Iron part in hydrogoethite makes 58-63 % and SiO_2 – up to 1.47 %.

The main rock-forming minerals in OFQ are quartzite, celadonite, carbonates and phosphates.

Mass parts of the main components of the initial sample are the following: Fe_{total} 48.4 %; $Fe_{magnetic}$ 3.12 %; SiO_2 26.0 %; P_2O_5 0.07 %; S_{total} 0.3 %.

Study of OFQ sample concentration capacity. Represented OFQ sample with grain size P_{80} = 1307.2 μm was ground during two stages. The first stage included grinding to grain size P_{80} > 100 μm in a ball mill of MShL-40ML type. The second stage continued grinding in the mill IsaMill M4 (Glencore Techology) to grain size P_{80} = 13.8 μm [23, 24].

It was established on the base of studying the technical literature sources that two types of magnetic hydrocyclones are known: devices with radial field, more known abroad as Fricker hydrocyclones (1) and hydrocyclones with external field, so-called Watson hydrocyclones (2). It was also found out that location of external magnetic system on hydrocyclone cylinder part is considered as the optimal technical solution.

Magnetic system which is mounted on a hydrocyclone was designed using computer software ANSYS Maxwell for simulation of electromagnetic fields. As a result of simulation, the optimal values of magnetic induction (which are sufficient for effective extraction of strongly magnetic materials) and location of permanent magnets were determined. The following values of magnetic induction were obtained: 0.05 T in the field center and 0.1 T on its sides. Optimal distances between the magnets were also determined, they made 35 mm. The original construction of magnetic hydrocyclone GTs-M was fabricated on the base of simulation results. Permanent magnets made from Nd–Fe–B alloy were used as a magnetic field source. To provide the required size of construction, these magnets were inserted in magnetically permeable material (plastic). The computer model of such magnetic system and its parameters are presented on the **Fig. 3** [25-27].

Magnetic system was mounted on the cylinder part of hydrocyclone RWK 42L. This hydrocyclone operated together with hydrocyclone unit of AKW Laborant ZLF 50-CH type manufactured by the company Apparate und Verfahren GmbH (Germany).

The series of experiments was conducted in the framework of experimental studies, both with and without use of magnetic system.

Used hydrocyclone had the diameter of its cylinder part 35 mm. Hydrocyclone unit AKW-Laborant is equipped with automatic system which was mounted on the tube for initial feed in hydrocyclone. This system provides measuring of such current pulp parameters as temperature, consumption and density.

Hydrocyclone of AKW A+W type was fabricated from polyurethane and has modular construction. It consists of cylinder and conic parts, branch pipes for sands and drain.

Fig. 4 shows the magnetic system and hydrocyclone with this system mounted.

The conducted serial experiments included the following operations: classifying of ground ore in hydrocyclone without mounted magnetic system (with use of sand nozzles with diameters 3, 4. 5 and 6 mm) and classifying of ground ore in hydrocyclone with mounted magnetic system (with use of sand nozzles with diameters 3, 4. 5 and 6 mm). The results of classifying experiments are presented in the **Table 1**.

To choose the most efficient classifying process, experimental data were processed using the methods of mathematical statistics. Obtained data were compared via Student and Fisher criteria as well as dispersion analysis. As a result, it was determined that conditions of hydrocyclone operation with diameter of sand nozzle 4 mm and mounted magnetic system are the most efficient. It can be seen from the obtained results that use of magnetic system allows to increase technological parameters of total Fe content up to 52.7 % (enlargement by 4.3 %).

Despite this relatively small enlargement of Fe content and extraction in sands, this effect is achieved practically without additional expenses, because permanent magnets don't consume energy. Additionally, ferromagnetic particles are magnetized in hydrocyclone and it has positive effect on their extraction during consequent wet magnetic separation (WMS).

Later, several experiments on magnetic separation of classifying products in magnetic fields with different intensity were conducted.

Table 1. **Classifying results**

Diameter of sand nozzle, mm	Presence of magnetic system	Name of product	Output, %	Content of Fe_{total}, %	Extraction of Fe_{total}, %
3	No	Sands	79.11	50.33	82.25
		Drain	20.89	41.12	17.75
		Initial	100.00	48.40	100.00
	Yes	Sands	78.91	51.44	83.86
		Drain	21.09	37.03	16.14
		Initial	100.00	48.40	100.00
4	No	Sands	78.63	50.92	82.69
		Drain	21.37	39.22	17.31
		Initial	100.00	48.40	100.00
	Yes	Sands	78.81	52.70	85.81
		Drain	21.19	32.41	14.19
		Initial	100.00	48.40	100.00
5	No	Sands	79.81	50.46	83.21
		Drain	20.19	40.26	16.79
		Initial	100.00	48.40	100.00
	Yes	Sands	79.13	51.49	84.14
		Drain	20.87	36.79	15.86
		Initial	100.00	48.40	100.00
6	No	Sands	79.09	50.31	82.16
		Drain	20.91	41.31	17.84
		Initial	100.00	48.40	100.00
	Yes	Sands	78.53	50.66	82.19
		Drain	21.47	40.16	17.81
		Initial	100.00	48.40	100.00

The further examination of OFQ concentration concluded in study of the effect of magnetic concentration in strong and weak magnetic fields on technological parameters.

WMS experiments were carried out on the drum separator EBM 32/20 with induction 0.13 T and single-pass bath procedure; high-gradient separation was realized on SLon 100 separator (core matrix with core diameter 1 mm, magnetic field induction 1.2 T, pulsation 250 min-1) [25, 28].

Several variants of technological scheme were tested. As a result, the scheme displayed on the **Fig. 5** was chosen; technological balance of its OFQ concentration products is presented in the **Table 2**.

The 1st grinding stage was realized within the framework of open cycle, providing sufficient grain size for consequent grinding in the 2nsd stage mill IsaMill. This mill is equipped with internal classifiers and does not need in use of closed circuit of grinding.

It is evident that obtained concentrates should be pelletized before their metallurgical processing [29, 30].

Conclusion

Use of magnetic hydrocyclone in the classifying cycle made it possible to increase Fe total mass part in classifying sands from 48.4 % to 52.7 % with extraction 85.81 %; it means that this technology is prospective for applying in iron ore concentration schemes.

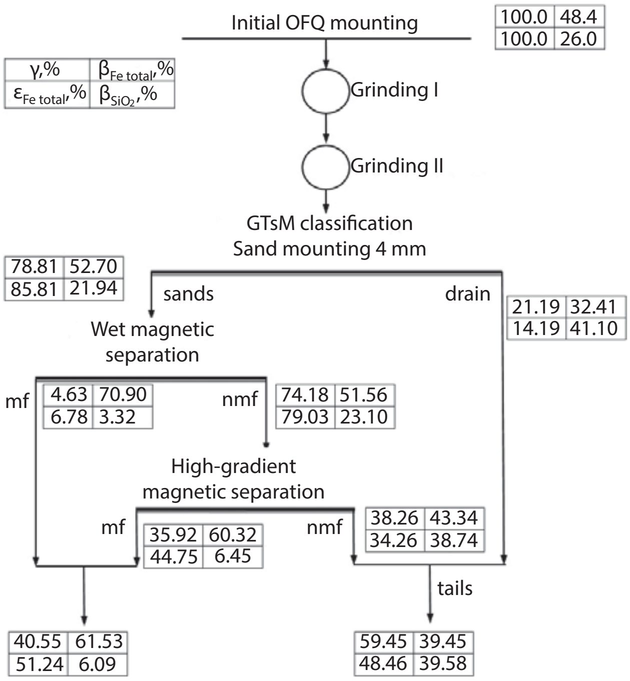


Fig. 5. Qualitative and quantitative scheme of OFQ magnetic separation:
mf – magnetic fraction, nmf – non-magnetic fraction

Table 2. **Technological balance of OFQ concentration**

Name of operations and products	γ_p, %	β_p, %	ε_p, %
GTs-M classifying			
Input:			
Ground product	100.00	48.40	100.00
Totally:	100.00	48.40	100.00
Output:			
Sands	78.81	52.70	85.81
Drain	21.19	32.41	14.19
Total hydrocyclone feed:	100.00	48.40	100.00
Wet magnetic separation (WMS)			
Input:			
Sands	78.81	52.70	85.81
Totally:	78.81	52.70	85.81
Output:			
WMS magnetic fraction	4.63	70.90	6.78
WMS non-magnetic fraction	74.18	51.56	79.03
Total WMS feed:	78.81	52.70	85.81
High-gradient magnetic separation (HGMS)			
Input:			
WMS non-magnetic fraction	74.18	51.56	79.03
Totally:	74.18	51.56	79.03
Output:			
HGMS magnetic fraction	35.92	60.32	44.77
HGMS non-magnetic fraction	38.26	43.34	34.26
Total HGMS feed:	74.18	51.56	79.03
United magnetic concentrate	40.55	61.53	51.55
United tails	59.45	39.45	48.45

As a result of conducted investigations, the technological scheme for OFQ magnetic concentration was developed; it allows to obtain:

- high-quality magnetite concentrate ($\beta_{Fe\ total}$ = 70.9 %, β_{SiO2} = 3.32 %, γ = 4.63 %, $\varepsilon_{Fe\ total}$ = 6.78 %);
- hematite concentrate ($\beta_{Fe\ total}$ = 60.32 %, β_{SiO_2} = 6.45 %, γ = 35.92 %, $\varepsilon_{Fe\ total}$ = 44.77 %);
- summarized magnetite-hematite concentrate ($\beta_{Fe\ total}$ = 61.53 %, β_{SiO_2} = 6.09 %, γ = 40.55 %, $\varepsilon_{Fe\ total}$ = 51.24 %).

Obtained hematite concentrate and summarized magnetite-hematite concentrate meet the requirements of TU 07.10.10-008-00186849-2016 “Iron ore concentrate with Fe mass part less than 63 %”, they can be used e.g. in blast furnace practice.

High-quality magnetite concentrate meets the requirements of TU 07.10.10-006-00186803-2016 “Iron ore concentrate with Fe mass part more than 69.5 %”, it can be used also in iron direct reduction process.

Use of magnetic hydrocyclone allows to rise concentration economical efficiency for oxidized ferriferous quartzites owing to preliminary concentration of initial raw materials in a cheap and high-productive magnetic hydrocyclone. This technology involves OFQ in processing and leads to increase of Fe extraction coefficient by 10.92 % from developing initial ore at Mikhailovskoe deposit.

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