Contrast range examination of rich iron ore from Mikhailovskoe deposit and evaluation of possibility of its preliminary concentration via physical methods

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The paper presents the review of the main technologies for concentration of rich iron ores and factors having influence on selection of the technology and concentration parameters. The most important technological parameters at the leading concentration plants (both abroad and in Russia), which are processing rich iron ores, are observed. It is shown that even ores with Fe content more than 65 % are subjected to concentration abroad. At present time, only 15 % of iron ores in CIS can be directed to metallurgical processing without concentration, 65 % of iron ores are concentrated via simple routes, but 20 % of iron ores require use of combined concentration methods. The aim of this work was study of substantial composition of large-lump hematite ore at Mikhailovskoe deposit and determination of possible technological pre-concentration methods for rise of Fe content in sinter ore up to 53-55 %. Examination of mineral composition of grab and bulk samples displayed that oxidized ferriferous quartzites are characterized by thin-layered texture with alteration of ore-free layers and interlayers, which are enriched by hematite. Coarseness less than 2 mm for more than 45 % of material proved presence of essential amount of slightly structured mineral differences and high oxidation degree. The experiments on determination of possibility of technological preliminary concentration of large-piece rich hematite ore were carried out using gravitation, X-ray absorption (XRT) and electromagnetic (EM) methods, dry magnetic separation in weak and strong field. It was shown that preliminary concentration of large-piece rich hematite ore from Mikhailovskoe deposit is impossible due to the features of mineral composition (wide range of porosity of ore lumps, Fe content outside the ranges of XRT method use, presence of essential amount of martite with relict magnetite nuclei etc.).
Key words: rich iron ore, mineral composition, hematite, magnetite, fraction composition, contrast range of physical properties, preliminary concentration, lump gravitation concentration, X-ray absorption separation, electromagnetic method, dry magnetic separation.
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Introduction

Iron ore deposits of industrial scale are very various in their genesis. They are known in endogenic, exogenic and metamorphogenic rock complexes. The main types of iron ores are presented by ferriferous quartzites and hornfeles (with alternating magnetite-hematite and silicon layers), skarn ores (characterized by presence of granates, pyroxenes and epidote); Fe is presented in these ores by magnetite as well as hematite, martite and by pyrite (often cobalt-containing). Square and linear weathering crusts, which are developing along areas and squares of development of ferriferous quartzites and presented by rich iron ores, are connected with these areas and squares. Such ores are presented at Mikhailovskoe deposit. Totally the part of deposits with ferriferous quartzites and polygenic rich iron ores, which are developing from these deposits, constitutes about 71 % of explored reserves and more than 74 % of production of commercial ores worldwide. In Russia, the part of ores from these types of deposits makes about 68 % in reserves and more than 65 % in commercial ores production.

At present time, the problem of efficiency rise for the processing technology of rich hematite ore becomes actual due to definite reduction of reserves of rich magnetite ores as well as deterioration of their quality, variation of the structure of prices for raw materials and energy carriers, establishment of more strict requirements to the quality of blast furnace ore and sinter ore during processing at metallurgical stage.

The aim of this work is examination of substantial composition and technological properties of lump rich hematite ore from Mikhailovskoe deposit and determination of possible technological methods for rise of Fe content in sinter ore up to 53-55 %, with maximal possible output of commercial product and Fe recovery.

Review of concentration technologies for rich iron ores

Selection of the concentration technology for iron ores is determined by mineral composition of the ore part with texture and structure features.

The following deposits make the raw material base of the Russian iron ore concentration plants:

- sedimentary-metamorphic deposits of ferriferous quartzites (59 % of mining and concentrating works operate with such raw materials);
- contact-metasomatic deposits (23 %);
- sediment brown iron ore deposits (12 %);
- magmatic titanium-magnetite deposits (6 %).

Iron ore deposits of industrial scale are very various. As it was mentioned above, they are known in endogenic, exogenic and metamorphogenic rock complexes [1-3].

The most important ore minerals are magnetite, magnesiomagnetite, titanium magnetite, hematite, hydrohematite, goethite, hydrogoethite, siderite, ferriferous chlorites (chamosite, thuringite etc.).

Fe content in industrial ores is measured within the wide range from 16 to 66 (68) %. There are rich ores (Fe_{tot} content exceeds 50 %), raw ores (Fe_{tot} content is 50-25 %) and depleted ores (Fe_{tot} content is less than 25 %).

All kinds of hematite and hematite-martite ores can be conditionally divided by three groups for their Fe content: depleted ores (up to 40 % Fe), average quality ores (40-50 % Fe) and rich ores (above 50 % Fe). All these kinds of ores are oxidized ones. Development of concentration technologies for rich ores is stipulated by essential reserves of such ores and their accompanying mining during development of other kinds of ores. Essential reserves of such ores ore located in Krivoy Rog iron ore basin (Ukraine) and in Russia, where the main part of iron ore reserves (59 %) is concentrated in Kursk magnetic anomaly (KMA). Mikhailovskiy and Lebedinskiy mining and concentrating plants, which are incorporated in “Metalloinvest” company, occupy the leading places in iron ore mining and concentrate production [1-5].

Depth of concentration and technological parameters of ore processing are determined by its substantial composition, character of impregnation of mineral components, contrast range characteristics and efficiency of applying separation processes [3, 6—8].

Rich hematite ores from Krivoy Rog and KMA, containing 60—63 % of Fe, 6—8 % of silica, 0.045—0.84 % of sulfur and 0.02—0.09 % of phosphorus, which are developed by underground mining, are used without concentration after crushing and separation. Hematite rich ores, containing even 60-65 % of Fe, are subjected abroad to washing: coarse classes in screens with consequent concentration in jigging machines and fine classes — in classifiers; then fine ore classes are subjected to concentration via flotation or magnetic separation in high-intensive or high-gradient separators [9-11]. Rich ores with coarse-layered texture (e.g. ores from South Africa and Australia) after crushing, separation and washing are subjected to concentration in heavy suspensions (in drum separators and heavy-medium hydrocyclones) in order to decrease silica content from 10-15 to 3-5 %. To provide concentration of easy ores (specularites), spiral separators are used (e.g., at the “Mount Right” plant).

When processing hematite ores with medium quality, the combination of several concentration methods, taking into account the features of substantial ore composition, is usually used. So, concentration in heavy suspensions is used in processing of diluted ores with coarse impregnations (e.g. at the plants “St. Nicolas”, “La Perla” etc.); jigging is used in concentration of acinose ores (e.g. at the plants “Steep Rock”, “Picarras” etc.). The concentration route of banded hematite ores at the plant “Welbeck” includes concentration of coarse classes in heavy suspensions (in drum separators and heavy-medium hydrocyclones) and concentration of fine classes in jet concentrators (Reichert cones). Fine impregnated ores are in spiral separators, while ores of -0.5 mm class are concentrated subjected to concentration via magnetic separation in strong field, with finishing of obtained concentrate in electric separators [10].

About 15 % of total amount of the explored iron ore reserves in CIS is presented by ores that can be used industrially without concentration, 65 % - by ores that are concentrated or planned to be concentrated via simple routes, and 20 % - by ores that require use of complex concentration methods [1].

Until present time, maximal industrial importance is noted for magnetite ores, which can be easily concentrated via magnetic separation [12].

Depending on the features of substantial composition, concentration of magnetite, hematite, brown iron and siderite ores is carried out according to the combined magnetic-gravitational and magnetic-flotation-gravitational routes. So, apatite-magnetite ores of Kovdor deposit are subjected to concentration via the combined magnetic-flotation-gravitational technology with obtaining iron ore, baddeleyite and apatite concentrates [13].

Use of gravitation concentration methods in processing of weak magnetic iron ores

Gravitation concentration method was widely distributed at the enterprises which process oxidized and complex iron ores. This method is used both on the primary concentration stage and in order to obtain high-quality commercial products and recovery of accompanying valuable components from them.

Several CIS concentration plants operated with hematite recovery. For this purpose they used diaphragm jigs of MOD type (Olenegorskiy mining and concentrating works) and air-pulse jigs of OPS, OPM and OMR-1 types (Lisakovkiy mining and concentrating works, for hydrogoethite oolite ores with Fe mass part 40.6 % (in ore) and 43.6 % (in concentrate), recovery is 69.9 %). Concentration of brown iron ores (with Fe mass part 46 %) at the concentration plant of Kamysh-Burunskiy mining and concentrating works was also carried out using OMR-1 jigs with Fe recovery 77.9 % and achieving of the mass part in concentrate equal to 49.5 %. When concentrating wash ores at Magnitogorsk Iron and Steel Works, the gravitation and magnetic route was used, it includes ore preliminary concentration in jigs with coarseness -12+3 mm and -3+0 mm and consequent magnetic separation. Oxidized ores from Krivoy Rog basin were concentrated via jigging, with crushing down to coarseness -10+0 mm and consequent additional comminution of tailings down to coarseness -3+0 mm and additional concentration also in jigs [10, 12–14].

Pneumatic machines of "Batak" (Germany) and "Takub" (Japan) were widely distributed in foreign practice during concentration of both classified and non-classified oxidized iron ores with coarseness -10+0 mm. These machines are equipped with the developed automatic technological systems, what provides achievement of high technological parameters and productivity up to 450 tph.

Several foreign concentration plants use heavy medium separation for narrow coarseness classes (120-50, 50-20, 20-4 mm) during processing of oxidized iron ores in wheel and drum separators of "Humboldt", "Wedag", "Tesca" companies with productivity from 50 to 300 tph, as well as 2- and 3-product heavy medium hydrocyclones [15].

To provide gravitation concentration of hematite ores from Pilbara deposit (Western Australia), with average Fe mass part 53-55 % and concentration for coarseness class less than 1 mm, and several other deposits, the jigs of "Alljig" company and high-productive gravitation separators "Allflux" of "Allmineral" company (Germany), with separation in fluidized bed are successfully used [16].

Study of substantial composition of rich ore

The studies of contrast range evaluation and possibility of preliminary concentration of ruch ore from Mikhalovskoe deposit were carried out with 7 probes, 5 of them were presented by grab samples of different kinds of ores with coarseness -60+30 mm and 2 bulk samples with ore coarseness -60+0 mm and -100+0 mm, which were taken at the crushing and screening plant of the works. All

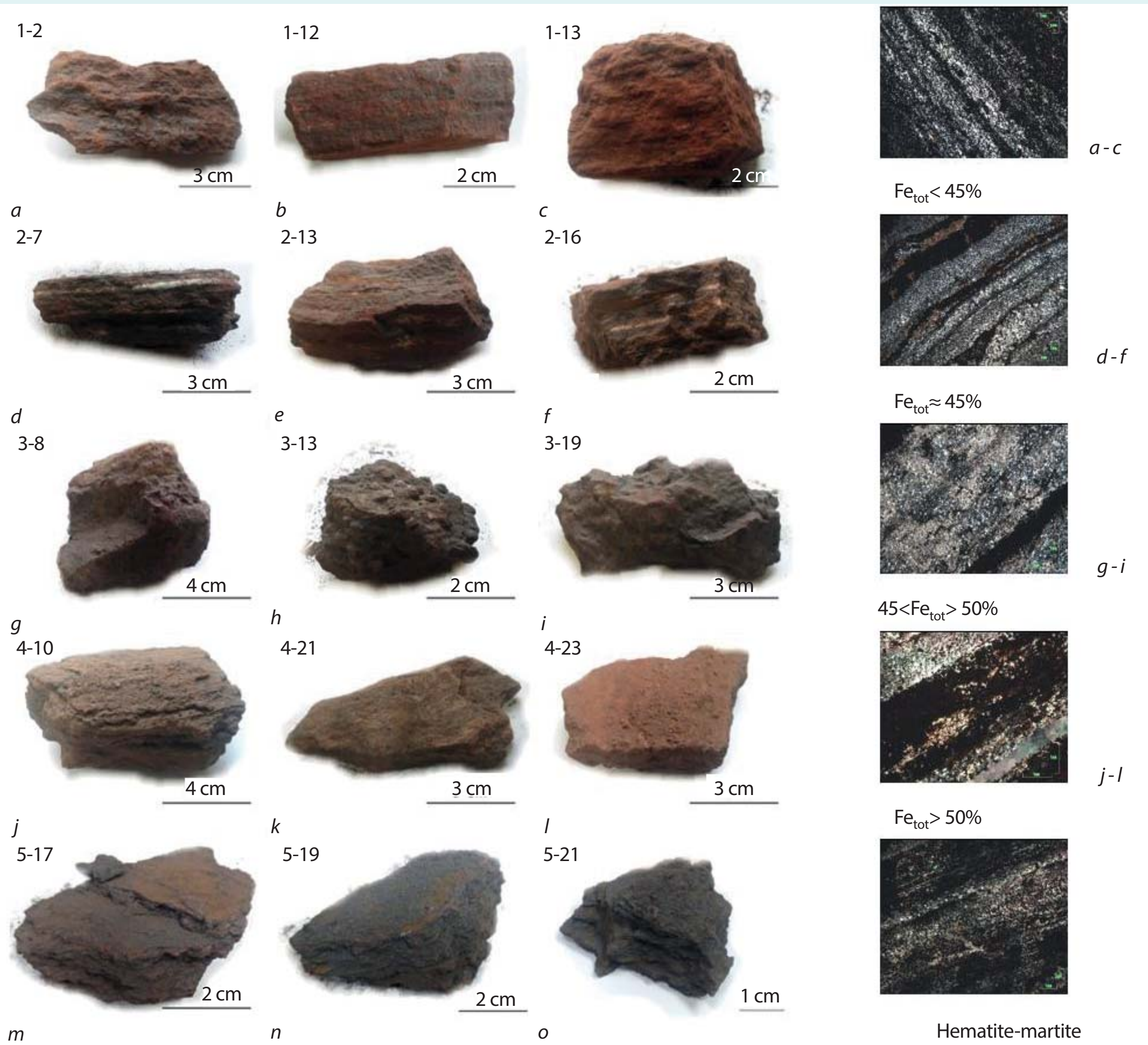


Fig. 1. The samples which were randomly taken from grab samples

probes characterize rich ore from the Central quarry of Mikhalovskoe deposit. Enclosing ores are absent at this site.

All probes were examined via the methods of microscope mineralogical analysis, optical and electron microscope using micro-probe. It was established that ore material is related to oxidized-hematite type; textures are characterized as fine-laminated, fine-layered, structures are fine- and thin-impregnated ones. Fe is presented by hematite, magnetite, goethite, hydroxides.

Incomplete random collection of samples, which were taken from grab samples, are shown on the **Fig. 1**. The example of determination of “3-19” designation: 3 is the number of probe, 19 is the number of probe piece.

Analysis of the results of examination of mineral composition of grab samples of rich ore allowed to make the following conclusions:

1. Grab samples are presented by oxidized ferriferous quartzites, which are characterized by thin-layered texture with alternation of ore-free layers and interlayers, that are enriched by hematite in different degree.

2. The most dense probes 1 and 2 ($\beta_{Fe_{tot}}$ < 45 % and $\beta_{Fe_{tot}}$, ≈5 %) are characterized by predominance of quartzite interlayers. The probe 3 with medium density (45 % < $\beta_{Fe_{tot}}$ < 50 %) has substantial part of quartzite with carbonate predominance. The probes 4 and 5 with minimal density ($\beta_{Fe_{tot}}$ > 50 % and hematite-martite) have small quartzite content in comparison with content of carbonates.

3. Fe content in ore minerals (hematite, siderite, hydrogoethite) is lowered in comparison with stoichiometric content, mainly due to hydro-goethite impurities with lowered content of Fe and quartzite in hematite, and minerals of gangue rocks (quartzite, phyllite-clayed) in siderite, what leads to difficulties in obtaining of high-quality concentrates.

4. It was established based on the results of examination of granulometric composition, that more than 45 % of material has coarseness less than 1 mm; it testifies on substantial amount of slightly structured mineral differences and high oxidation degree of rich hematite ore from the Central quarry of Mikhalovskoe deposit.

To examine ore contrast range, the ranges of quality values of ore pieces were determined for content of the valuable component (Fe) from the point of view of evaluation of rich ore availability for concentration via physical methods. The massif of initial data was formed using the random sampling method. 100 samples from the material

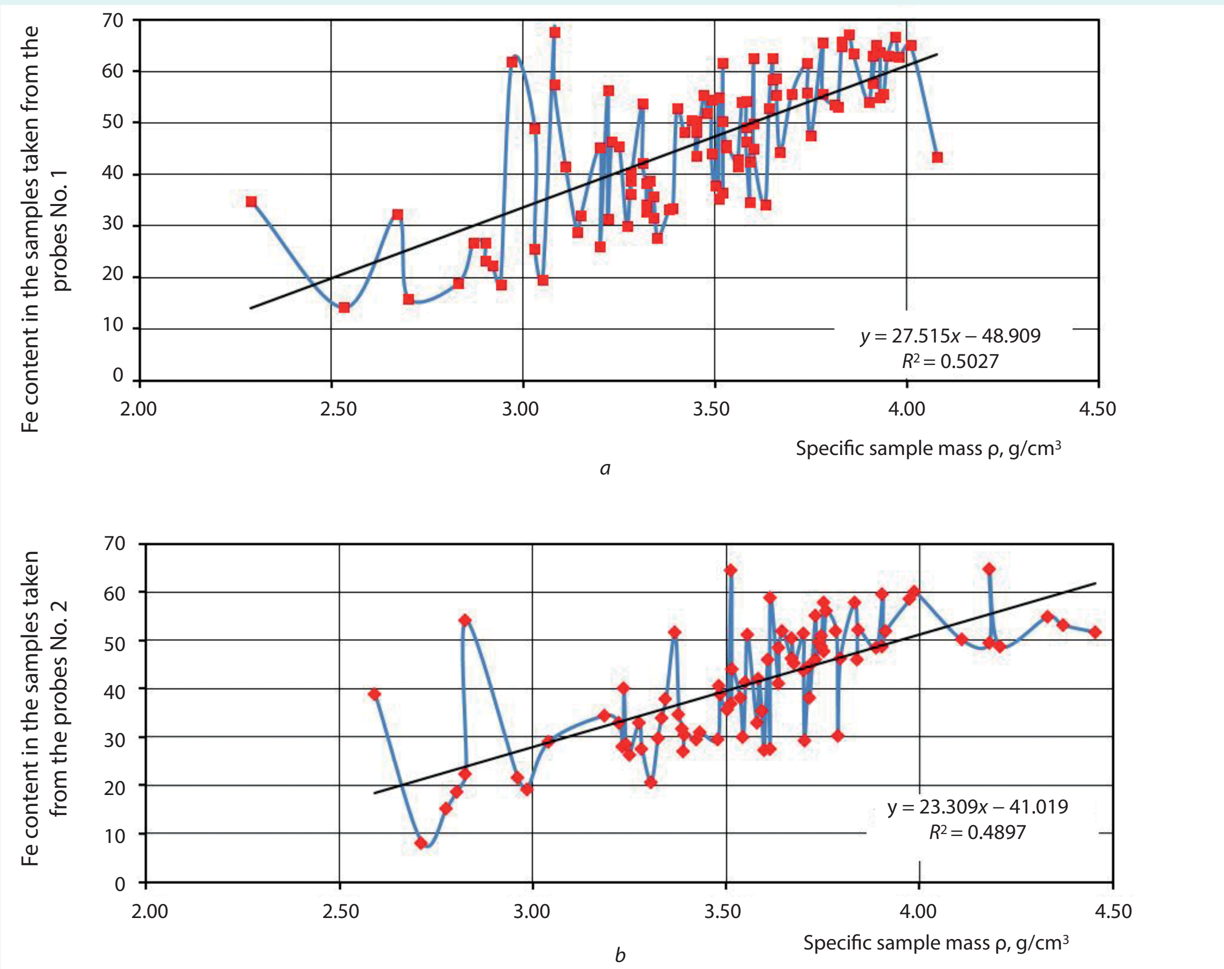


Fig. 2. Fe content in the samples taken from the probes No. 1 and No. 2, depending on sample specific weight: *A* - probe No. 1, *B* - probe No. 2

of bulk probe No. 1 and 85 samples from the material of bulk probe No. 2 were selected. Coarseness of ore samples was 60(100)+10 mm.

The aim of selection was to establish possibility of gravitation, radiometric and magnetic concentration of piece part of material in bulk probe with Fe content more than 45 %. For this purpose, the experiments for determination of correlation between specific weight, contrast range during X-ray absorption separation, magnetic properties of ore pieces and content of valuable components in these pieces were carried out.

Study of principal possibility of gravitation concentration for material with coarseness + 10 mm

To evaluate principal possibility of gravitation concentration, mass and apparent density of the samples were measured. Visual control of the samples of bulk probe displayed that ore pieces are essentially differ from each other by their macroscopic parameters (texture and structure features, colour, porosity etc.).

When measuring density via weight comparison in air and in water, emission of air bubbles was noted for significant number of samples, what testifies about presence of opened pores. In other words, actual density of these samples differs seriously from apparent density, what is confirmed by presence of pieces with apparent density less than 2.7 g/cm^3 (what is lower than density of gangue rock.

It was established that interaction between specific mass of samples and Fe content for the bulk probe No. 1 (100 samples) is not determined definitely (see **Fig. 2*A***). Dispersion of apparent density values of ore pieces varies from 2.29 to 4.08. The equation of trend line is $\beta_{Fe} = 27.515\rho - 48.90$, for approximation accuracy value $R^2 = 0.5027$.

Interaction between specific mass of samples and Fe content for 85 pieces (taken from the probe No. 2), also is not determined definitely (see Fig. 2*B*).

Fig. 3. X-ray absorption separator COM Tertiary XRT 1200/D in the testing center of "BM Bergbautechnik" JSC

Conclusions about evaluation of possibility of gravitation concentration of rich lump ore

Essential dispersion of the obtained data and, consequently, average coefficient of correlation between specific mass and Fe mass part shows that reaching of acceptable technological and economical parameters of gravitation concentration is hardly probable for material with coarseness -60(100)+10 mm.

It is explained by presence of essential amount of porous pieces in a probe, which were formed as a result of hypergenesis process, including "washing-off" of significant amount of carbonates (calcite, siderite etc.). Then measured density of pieces became essentially lower than true density. So, the samples with apparent density 2.3-2.6 g/cm^3 are resented in probes; it is lower than density of calcite and quartzite, and Fe mass part in these samples makes 35-39 %.

Study of principal possibility of ore preliminary concentration with coarseness +10 mm via X-ray absorption (XRT) method

Determination of contrast range properties in order to study possibility of concentration by Fe content via X-ray absorption using broad-band X-ray tube (XRT method) was carried out in the testing center of "Thrane Teknikk" JSC (at present time "BM Bergbautechnik" JSC).

X-ray absorption method is characterized as penetrating technique, i.e. it allows to determine pieces with concealed ore minerals (closed attachments), otherwise to X-ray fluorescent method. XRT method also does not require special material preparation to separation (surface cleaning for removal of picked slime and dusty fractions).

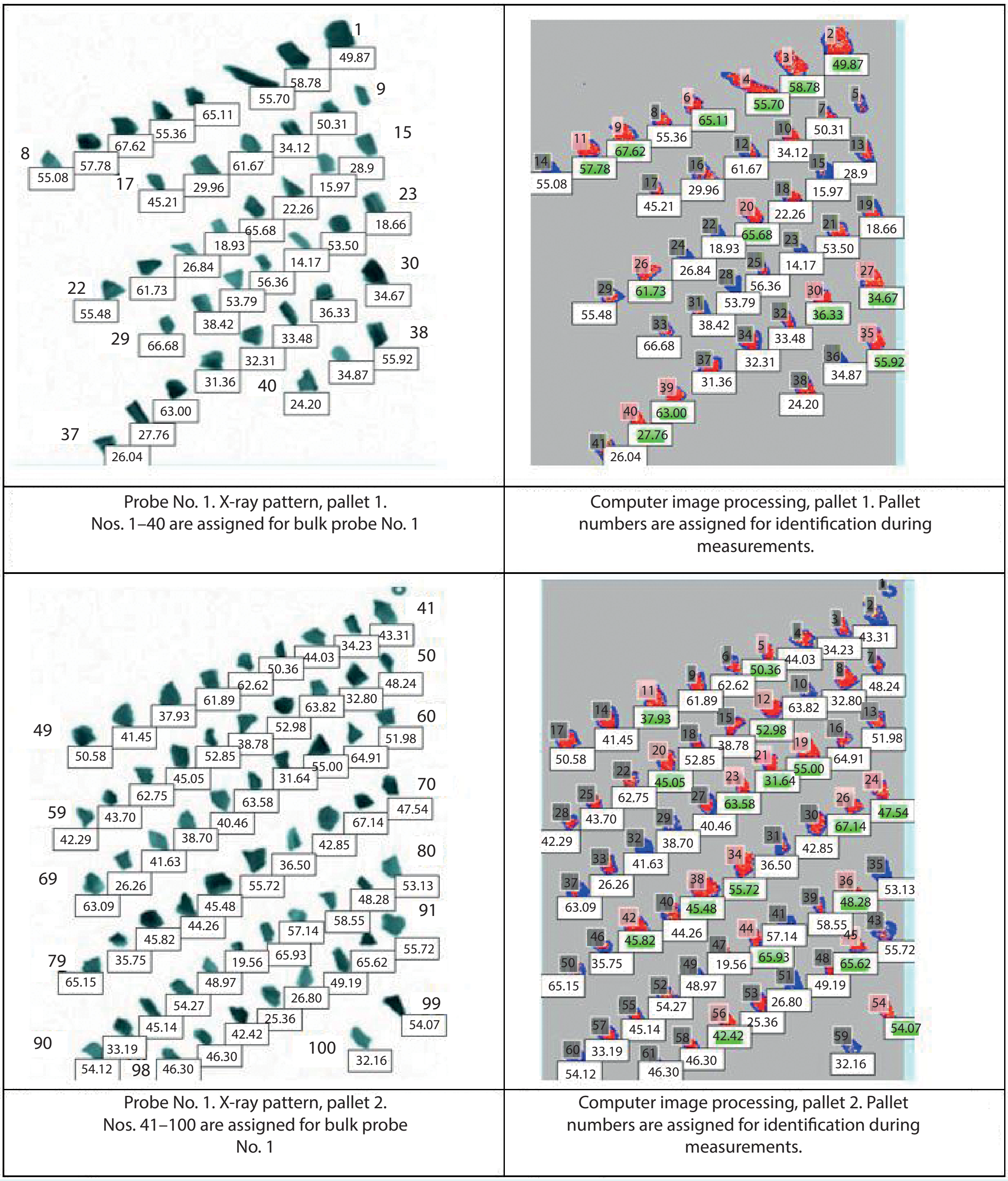
Testing of application possibility for XRT method was conducted in the separator COM Tertiary XRT 1200/D [17] (**Fig. 3**). This separator is characterized by the fact that two different radiation detectors are used in TOMRA separators for optimization of measuring conditions for pieces with various coarseness and for lowering the influence of material density on the signal level. One detector operates with low energy channel (materials with low atomic numbers – gangue rock) and other - with high energy channel (materials with big atomic numbers).

Two pallets of samples, which are stuck on polyethylene substrate, were prepared for preliminary examination of principal evaluation of possibility of the probe No. 1 separation via XRT method (**Fig. 4**, the first pallet includes the samples Nos. 1-40, the second – Nos. 41-100).

The samples with the following running numbers are directed in "conditional concentrate" of separation, which is determined by relation of colours in the image after processing by special program:

- 2, 3, 4, 6, 9, 11, 20, 26, 40, 39, 30, 27, 35 – on the X-ray pattern of the pallet 1 after computer processing;
- 5, 11, 20, 12, 8, 23, 21, 19, 24, 26, 34, 38, 42, 36, 44, 56, 45, 54 35 – on the X-ray pattern of the pallet 2 after computer processing.

Comparison of images of the pieces of "conditional concentrate" and "conditional tailings" with corresponding values of Fe content displayed dispersion of content



Probe No. 1. X-ray pattern, pallet 1. Nos. 1–40 are assigned for bulk probe No. 1

Computer image processing, pallet 1. Pallet numbers are assigned for identification during measurements.

Probe No. 1. X-ray pattern, pallet 2. Nos. 41–100 are assigned for bulk probe No. 1

Computer image processing, pallet 2. Pallet numbers are assigned for identification during measurements.

Fig. 4. X-ray patterns and image of samples of the bulk probe No. 1 after computer image processing. Fe content in the sample is noted under the sample image. Fe content values in "conditional concentrate" are underlined by green colour. The rest samples are considered as "conditional tailings" of separation

values from 27.76 to 67.14 % in "conditional concentrate" and from 18.66 to 66.88 % in "conditional tailings". Thus, concentration of presented ore probe via XRT method is impossible.

The same researches were carried out for 85 samples of the bulk probe No. 2.

Average probe content in the probe was 40.97 % with range from 8.11 to 64.72 %. Part of the data, which were obtained during this experiment, are presented in the **Table 1** as an example.

The XRT boundary based on the sum «Dark+ High» for Fe (%) was taken as the separation parameter. **Table 2** and **Fig. 5** include the results of calculation of the concentrate output, Fe recovery and content, as well as process efficiency during grouping of the examined pieces for the different values of the XRT boundary (pitch 10 %).

It can be concluded from analysis of the obtained results and from the conclusion of “Thrane Teknikk” JSC specialists, that the Fe probe in XRT test is non-contrast (M=0.25). The calcium content test showed, that calcium probe is medium-contrast (M=0.88); however, it is useless to adjust the separator for obtaining iron ore concentrate according to this feature, owing to the fact that Fe atomic weight is essentially larger than calcium atomic weight, and β_{Fe}/β_{Ca} relationship is varying within wide range (from 3 to 60).

Table 1. **Collection of the results of the bulk probe No. 2 examination for concentration ability via X-ray absorption method**

No. of sample	Содержание		XRT parameter sim 7075H15*		
	Ca	Fe			
	m/m%	m/m%	Dark	High	Low
1	1.120	60.050	6.29	65.62	17.05
2	1.490	35.480	0.00	31.86	48.12
3	2.420	18.730	0.00	0.00	93.97
4	10.890	38.000	0.11	20.04	49.92
5	0.253	15.270	0.00	0.35	80.20
7	4.980	41.250	13.22	64.83	12.65
40	7.510	42.030	61.51	5.47	20.43
59	1.500	58.730	0.00	53.51	29.96
60	13.130	8.110	0.00	0.00	95.72
84	8.900	48.450	0.00	18.16	48.40
85	0.264	64.720	0.00	65.41	21.00

* Image colour after computer processing:
Dark – mainly red; High – significant part is red; Low – mainly blue.

Study of possibility of ore preliminary concentration with coarseness +10 mm via electromagnetic (EM) method

EM method is based on variation of the factor of merit (Q) of induction coil (i.e. relation of its inductive resistance to its active resistance) due to influence of magnetic susceptibility and conductivity of samples, which were located in the center of coil. The measurement is conducted by the value of signal amplitude (M) and the value of phase shift (Ф) [18].

Deviations of phase and amplitude values from zero were measured at the specialized Q-meter of «Commodas Ultrasort» in the testing center of “Thrane Teknikk” JSC. In other words, variation of the factor of merit of measuring induction coil was examined, while this coil was made as tracks on printed board with alternating location of 85 samples (taken from the bulk probe No. 2) in the center of coil.

Apparent response was registered for only 15 samples from 85 (**Table 3** and **Fig. 6**). Mass Fe part in these 15 samples was within the range 20.66-59.55 %.

The correlation coefficients for signal value and phase were calculated without taking into account other 70 samples; they are equal to -0.61 and -0.64 respectively. If other samples are taken into account, the correlation coefficients make -0.19381 и -0.27747 (very weak negative correlation).

Table 2. **Parameters of separation of the samples, which were taken from the bulk probe No. 2, via X-ray absorption method (calculation by Fe)**

Fe	XRT boundary Dark+High, %	Fraction			Tailings			Concentrate			Concentration degree
No. of fraction		Output	Content	Recovery	Output	Content	Recovery	Output	Content	Recovery	
		γ,%	β, %	ε, %	γ, %	β, %	ε, %	γ, %	β, %	ε, %	
1	10.0	14.1	26.0	9.0	14.1	26.0	9.0	85,9	43.4	91.0	1.06
2	20.0	9.4	34.3	7.9	23.5	29.3	16.8	76,5	44.5	83.2	1.09
3	30.0	11.8	35.7	10.3	35.3	31.4	27.1	64,7	46.1	72.9	1.13
4	40.0	10.6	43.5	11.2	45.9	34.2	38.3	54,1	46.6	61.7	1.14
6	50.0	15.3	43.7	16.3	61.2	36.6	54.7	38,8	47.8	45.3	1.17
7	60.0	18.8	49.8	22.9	80.0	39.7	77.6	20,0	45.9	22.4	1.12
8	70.0	12.9	45.2	14.3	92.9	40,.5	91.9	7.1	47.2	8.1	1.15
9	80.0	5.9	49.3	7.1	98.8	41,0	98.9	1.2	36.9	1.1	0.90
10	100	1.2	36.9	1.1	100	40.9	100	-	-	-	
		100		100							

Comments: correlation by Fe 0.60; contrast range (M) 0.25; Separation feature (S) 0.17; efficiency of separation feature 0.66.

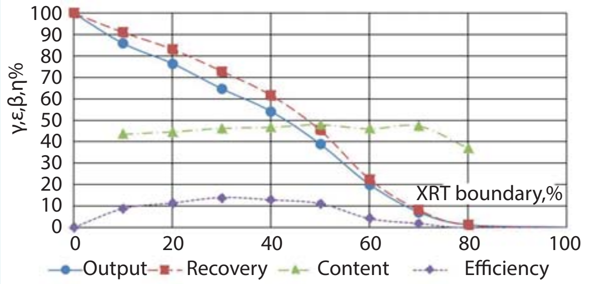


Fig. 5. Dependence of grading parameters for lump rich ore on XRT boundary value by Fe:
γ – output of "conditional concentrate"; ε – Fe recovery in "conditional concentrate"; β – Fe content in "conditional concentrate"; η – separation efficiency by Hancock-Luiken

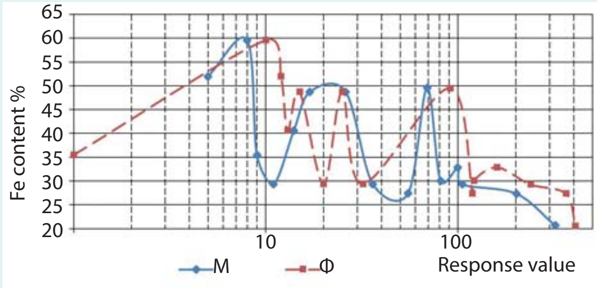


Fig. 6. Relationship between Fe content in the sample and response value by amplitude (M) and phase (Φ)

Table 3. **Results of testing of grab samples, which were taken from the bulk probe No. 2**

No.	2	11	21	22	24	28	29	33	34	48	58	70	75	81	83
M	9	14	26	5	55	8	105	201	11	17	81	36	69	100	320
Φ	1	13	25	12	119	10	238	365	20	15	121	32	91	160	410
β_{Fe}, %	35.48	40.59	48.74	51.93	27.41	59.55	29.31	27.35	29.39	48.73	30.1	29.43	49.51	32.87	20.66

Thus, electromagnetic method (EM method) is not efficient for separation of the examined probe of rich ore from Mikhailovskoe deposit. Table 3 includes data only for 15 samples from 85, which displayed apparent deviation of amplitude (M) and phase (Φ).

Conclusions about study of possibility of X-ray absorption and electromagnetic separation of lump ore

Study of possibility of lump grading via X-ray absorption (XRT) and electromagnetic (EM) methods didn't lead to positive results.

It is explained by diversity of form or ore pieces (from blast furnace bottom to lumpy) and features of ore composition. Absorption of X-ray radiation depends on piece thickness and Fe mass part in this piece. Absorption of radiation by more thick piece will be higher that by piece with smaller thickness (for equal mass parts). Additionally, X-ray absorption methods provide stable operation for metal content on the level of first percents. Analysis of the obtained results shows that recovery of ore with coarseness more than 30 mm in a separate fraction leads to possibility of its separation by Fe mass part about 20-30 %. More large pieces evidently can be extracted only at smaller content (about 10-15 %). Absence of serious correlation in the EM method is explained by different relationship in magnetite and hematite samples for equal total Fe mass part, taking into account that magnetic susceptibility and conductivity of magnetite in comparison with hematite is larger by 200-1,200 and 100-10,000 times respectively. Size of conducting particles, which are isolated from each other by dielectric particles (such as quartzite, alumosilicates etc.), has also effect on general ore conductivity.

Determination of possibility of dry magnetic separation of bulk probes

The experiments on determination of possibility of dry magnetic separation of bulk probes were carried out in the laboratory of ERGA Scientific and production corporation.

Separation for magnetic field induction values on the drum surface 0.18; 0.32; 0.48; 0.75 Tl was conducted on the drum separator with magnetic mixing; drum diameter was 600 mm, rotation frequency was 35 min^{-1} (**Fig. 7*a***).

Separation for magnetic field induction value on the drum surface 0.9 Tl was conducted on the drum separator without magnetic mixing; drum diameter was 200 mm, rotation frequency was 80 min^{-1} (Fig. 7*b*).

Separation for magnetic field induction value on the drum surface 1.1 Tl was conducted on the roll-belt separator; drum diameter was 110 mm, rotation frequency was 80 min^{-1} (Fig. 7*c*).

The numbered samples, which were taken from bulk probes No, 1 (100 samples) and No. 2 (85 samples) were transferred consequently to the drum section, starting from the induction value 0.18 Tl. Non-magnetic fraction was transferred to the section with large induction value or to the following separator (see the experiment route on the **Fig. 8**). The samples, which were included in all magnetic fractions and the last non-magnetic fraction, were weighed and forwarded to analysis of Fe mass part.

a. Drum separator with magnetic mixing *b.* Drum separator without magnetic mixing *c.* Roll-belt separator

Fig. 7. Laboratorial dry-type separators with magnetic systems from the alloy Nd-Fe-B, developed by ERGA Scientific and production corporation

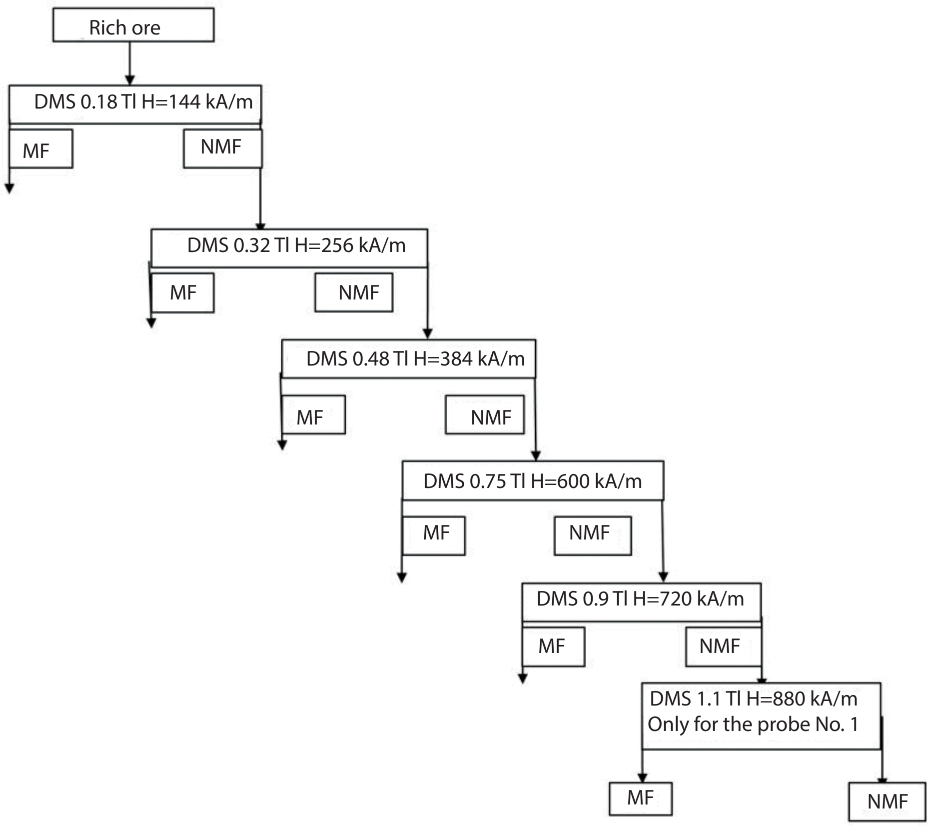


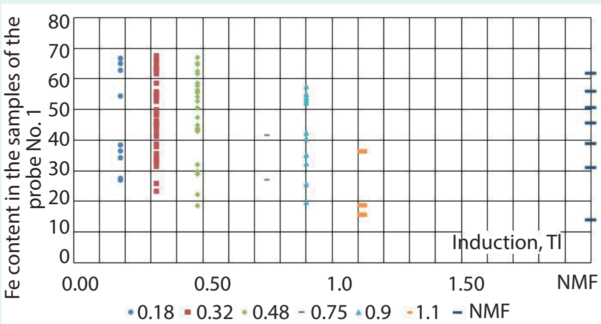
Fig. 8. The route of experiment conduction on magnetic separation of lump ore probes No. 1 and No. 2; the last operation (B = 1.1. Tl) is excluded for the probe No. 2 due to nonconformity between size of samples and technical parameters of separator*
*Notes: MF - magnetic fraction; NMF - non-magnetic fraction.

The experimental results on lump ore concentration are presented in the **Table 4** and on the **Fig. 9**.

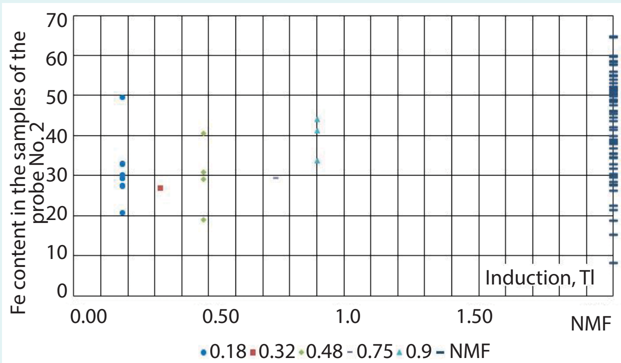
The relationship between concentration parameters of the grab samples, which are taken from the probe No. 1, and magnetic field is shown on the **Fig. 10**. Concentration efficiency does not exceed 2.14 %. The results of magnetic fractioning of the samples, which are taken from the probe No. 2, are not satisfactory. Concentration efficiency for the

Table 4. **Metal balance during the experiments on concentration of grab samples from bulk probes No. 1 and No. 2**

Induction	Output		Content		Recovery		Efficiency	
B, Tl	$\gamma_{part.}$, %	γ_{total}, %	$\beta_{p\ Fe}$, %	$\beta_{t\ Fe}$, %	$\varepsilon_{p\ Fe}$, %	$\varepsilon_{t\ Fe}$, %	η_p, %	η_t, %
Probe No. 1								
0.18	6.71	6.71	43.68	43.68	6.35	6.35	-0.66	-0.66
0.32	44.36	51.06	47.03	46.59	45.22	51.57	0.86	0.51
0.48	27.27	78.33	48.90	47.40	28.91	80.47	1.64	2.14
0.75	1.29	79.62	34.46	47.19	0.96	81.44	-0.33	1.82
0.90	9.56	89.18	42.15	46.65	8.74	90.17	-0.83	0.99
1.10	2.12	91.30	26.36	46.18	1.21	91.38	-0.91	0.08
Total, MF	91.30		46.18		91.38		0.08	
NMF	8.70	8.70	45.70	45.70	8.62	8.62	-0.08	-0.08
Initial	100.00		46.13		100.00	100.00	0.00	0.00
Probe No. 2								
0.18	8.51	8.51	30.48	30.48	6.33	6.33	-3.69	-3.69
0.32	0.58	9.09	26.94	30.26	0.38	6.71	-0.20	-2.37
0.48	3.42	12.51	28.80	29.86	2.41	9.12	-1.02	-3.39
0.75	1.16	13.66	29.39	29.82	0.83	9.95	-0.33	-3.72
0.90	3.00	**16.66**	41.16	31.86	3.01	**12.96**	0.01	-3.70
Total, MF	**16.66**		**31.86**		**12.96**		-3.70	
NMF	**83.34**	83.34	**42.79**	42.79	**87.04**	**87.04**	3.70	3.70
Initial	100.00		**40.97**		100.00	0.00	0.00	0.00



a



b

Fig. 9. Distribution of Fe content on magnetic fractions (for samples):
a — samples from the bulk probe No. 1; *b* - samples from the bulk probe No. 2

samples of the probe No. 2 is negative (Fe concentration is larger in non-magnetic fraction) and does not exceed -3.7 %.

Conclusions about study of possibility of dry magnetic separation of lump ore probes

Dry magnetic separation of bulk probes (both No. 1 and No. 2) didn't lead to positive results. When conducting separation of the probe No. 1, the correlation coefficient made +0.4 (weak positive), ore is low contrast; when conducting separation of the probe No. 2, the correlation coefficient made -0.19 (very weak negative), ore is non-contrast.

It is caused by presence of some amount of magnetite in all types of ores; this magnetite is presented both by individual grains, as well as in composition of martite and in aggregates. Magnetic susceptibility of magnetite (χ_{magn}) is within the range (3.4—5)·10^{-4} m^3/kg for the field intensity created by magnetic systems of applied separators. Magnetic susceptibility of hematite (χ_{hem}) and martite (χ_{mart}) is within the ranges (60-380)·10^{-8} m^3/kg and (250—880)·10^{-8} m^3/kg respectively. Magnetic susceptibility can reduce to 30·10^{-8} m^3/kg and lower for hematite particles with coarseness less than 50 μm, in the case of hematite replacement by siderite [19]. Thus, χ_{magn}/χ_{hem} > 200, i.e. slight oscillations of the mass part of magnetite have extremely strong influence on behaviour of particles of hematite, hematite-martite and martite ores during magnetic separation processes.

Conclusion

The results of conducted complex of researches on examination of contrast range of rich iron ore from Mikhailovskoe deposit and evaluation of possibility of its

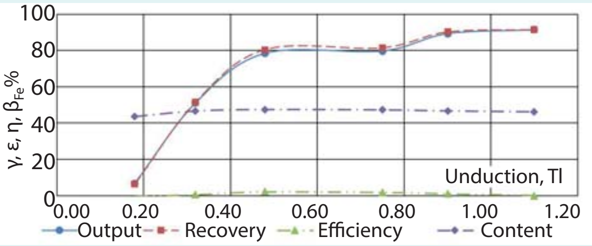


Fig. 10. The relationship between concentration parameters of the grab samples, which are taken from the probe No. 1, and magnetic field:
γ – output of magnetic fraction; ε – Fe recovery in magnetic fraction; η – separation efficiency by Hancock-Luiken; β_{Fe} – Fe content in magnetic fraction

preliminary concentration via physical methods allowed to make the following conclusions.

1. All fractions of rich lump ore with coarseness -60(100)+10 mm are either non-contrast, or low contrast, due to the features of its substantial composition. It testifies on impossibility of preliminary concentration of rich ore from Mikhailovskoe deposit via physical methods (such as gravitation, X-ray absorption and magnetic).

2. Study of concentration possibility via gravitation methods (i.e. based on specific mass of pieces) of lump ore didn't lead to positive results. Essential dispersion of parameters and, respectively, low correlation between specific mass and Fe mass part shows that achievement of acceptable technological and economical parameters is low possible; it is explained by presence of significant amount of porous pieces in a probe.

3. Examination of possibility of lump grading via X-ray absorption (XRT) and electromagnetic (EM) methods displayed absence of positive results. Correlation coefficient between absorption of X-ray radiation and Fe mass part is about +0.25 (weak positive), while correlation coefficient between variation of amplitude and phase in a Q-meter, and Fe mass part is -0.19381 and -0.27747 respectively. It makes impossible to achieve acceptable technological and economical parameters, what is explained by diversity of forms of ore pieces and features of ore substantial composition. Absorption of X-ray radiation depends on a piece thickness and Fe mass part in it. Absorption of radiation by a piece with larger thickness will exceed absorption of radiation by a piece with smaller thickness, for equal mass parts. Additionally, X-ray absorption separation method provides stable operation for metal content at the level of first percents. Absence of apparent correlation for EM method is explained by different mass part in the samples of ferromagnetic (magnetic) for equal mass part of total Fe.

4. Dry magnetic separation of bulk probes also displayed unsatisfactory results. Study of mineral composition of rich ore probes showed substantial dispersion of ore magnetic properties, depending on magnetite content in this ore both as individual particles (free or incorporated in aggregates), or as relicts in martite composition. As soon as magnetic susceptibility of hematite is lower than magnetic susceptibility of magnetite by several orders, aggregates of magnetite with gangue rock, which contain the first percents of magnetite, will be extracted in magnetic fraction together with hematite grains during separation in strong field; it will inevitably lead to ore impoverishment and impossibility of obtaining of high-quality concentrate. Efficiency of ore magnetic separation in strong field will be low in the case when ore includes aggregates of magnetite and martite with gangue rock.

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