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Investigation of the beneficiation of refractory ferromanganese ores "Zhomart" deposits

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ABSTRACT
In order to provide ferroalloy production with high-quality raw materials, the need to develop technologies for processing of low-grade manganese and ferromanganese ores is becoming increasingly important. In view of the change in the quality characteristics of ores, the decrease in manganese content and the ability to beneficiation by traditional methods, it is necessary to consider new approaches and technological solutions. The article presents data from a study on the beneficiation of refractory iron-manganese ore from the Zhomart deposit. The mineralogy, physical and mechanical properties, and granulometric composition of the ore were determined. The results of a study on gravitational beneficiation using a laboratory pulsator with a pneumatic drive and a laboratory 2-chamber diaphragm jigging machine and magnetic beneficiation of ore with a high-intensity magnetic field are presented. Iron-containing concentrate (Fe-45% and Mn-6.5% is mainly represented by hematite mixed with non-metallic minerals quartz and calcite) and iron-manganese concentrate (Mn-21.7% and Fe-21.1% in the form of hematite, Brownite and pyrolusite, also mixed with quartz and calcite). The concentrates are not suitable for smelting manganese-containing ferroalloys but can be used in the process of electrothermal beneficiation with selective carbothermal reduction of iron in an ore-thermal furnace. The smelting products can be manganese cast iron and iron-free, low-phosphorus limiting manganese slag with a high ratio of manganese to iron.

Keywords: Iron-manganese ore, jigging, dry magnetic separation, iron-manganese concentrate

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Introduction

Currently, ferroalloy production in Kazakhstan requires the provision of high-quality manganese concentrates in sufficient quantities with a manganese content of at least 35%. Along with the well-known manganese deposits of the Atasui and Ulytau ore districts: Zhairemskoye, Zhezdy, Kamys, Tur, Karazhal, etc., manganese-poor ores of the iron-manganese deposits Zhomart, Ushkatyn III, Kartobay and others, which are also concentrated in Central Kazakhstan.

A similar situation regarding the provision of ferroalloy production with manganese concentrates is observed in Russia, where it also became necessary to develop technologies for the beneficiation of low-grade manganese ores.

Researchers of the Siberian State Industrial University note that in order to provide the Russian industry with its own raw materials [1], the use of Kuzbass manganese ores with high iron content is of greatest interest, and other studies provide data on the iron beneficiation of the manganese ore of the Kagaydatskoye deposit of Kuzbass [2]. During the study, the ore beneficiation has been performed by washing, gravitation, magnetic separation, and floatation. The sample contained 10.8% of manganese and 18.7% of iron. Positive results on the beneficiation of the test samples were not obtained, since the ore is difficult to enrich, manganese-iron concentrate (19.9% Mn and 12.7% Fe) and iron-bearing concentrate (8.3% Mn and 31.3% Fe) were obtained. Therefore, hydrometallurgical methods of beneficiation of refractory iron-manganese ore were applied [3]. Autoclave stadial leaching was applied using calcium and iron chlorides as a solvent. After successive precipitation and calcination, high-quality manganese (58-60% Mn with a recovery of 90-92%) and iron (48-54% Fe with a recovery of 86-90%) concentrates were obtained.

The results of the hydrometallurgical scheme for processing poor iron-manganese ore are positive and very encouraging [[4], [5], [6]], but the implementation of this technology is difficult, due to the creation of a new hydrometallurgical production at the ore mining site.

Specialists studied alternative pyrometallurgical methods for the beneficiation and processing of ferromanganese ore [[7], [8]], in particular, interesting data are given in [9], where magnetizing roasting of ore crushed with a particle size of −74 µm (mass accounting for 80%) was combined in a fluidized bed at 600°C followed by magnetic separation of the magnetizing roasting product at 1070 Oe. From the ore, 43.5% Fe and 11.4% Mn, iron concentrate 68.3%Fe (96.3% recovery), and manganese concentrate 33.7% Mn (86.8% recovery) were obtained. However, by analogy with hydrometallurgical methods, the implementation of beneficiation schemes with the inclusion of pyrometallurgical processes at the ore mining site is also difficult.

This article presents the results of a study on the beneficiation of iron-manganese ore from the Zhomart deposit, the study has been undertaken to obtain a large-lump concentrate for smelting furnaces, that is, in the so-called sparing beneficiation mode.

Experimental part and discussions of results

The study revealed the following:

- the ore mineralogy with the use of a polarizing microscope in reflected light with a combination X-ray diffraction and fluorescence analysis methods;

- the physical and mechanical properties and grain size distribution on methods described in reference [[10], [11]];

- the tests on the gravity dressing were conducted using the lab based pulsator with pneumatical drive and laboratory bicameral diaphragm jigging machine (more information will be described further in the article test);

- the tests on dry magnetic separation were conducted on a laboratory magnetic analyzer with a high-intensity magnetic field (more information will be described further in the relevant section of the article).

Iron-manganese ore of the "Zhomart" deposit according to X-ray diffraction analysis presented by the following base minerals: barren minerals – 28.9% of silica SiO_2; 17.8% of calcite $Ca(CO_3)$ – and ore minerals – 27.8% of hematite Fe_2O_3; 15.8% of braunite $(Mn_2O_3)_3{\cdot}MnSiO_3$ and 9.6% of manganese superoxide MnO_2 –The diffraction pattern of the ore is demonstrated in Figure 1.

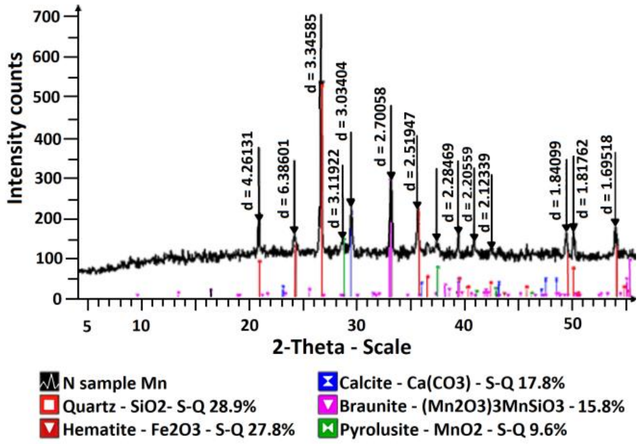

Figure 1 – The diffraction pattern of samples of starting iron-manganese ore

The photo of the exterior form of ore, size fraction from 0 to 50 mm is presented in Figure 2. The sample of iron-manganese ore with a reddish steel and black hue, mostly of a pricked pattern of the hematite and black iron finely banded ore, fine-grained manganese, and to a lesser extent, with a brownish-white color of silica and calcite.

According to the mineralogical analysis performed on Leica DM2500 M polarizing and stereoscopic microscope MBS-1 (MBS, Russia) binocular magnifying glass has been determined that the sample from the "Zhomart" deposit has two types of ores: silica-carbonatic iron oxide (concentrated in iron) and silica-carbonatic manganese oxide (concentrated in manganese):

1) *silica-carbonatic iron oxide* ore contains magnetite and hematite. The original groundmass of hematite is formed in the reduction and replacement processes of magnetite. Tabular grains of the hematite penetrate into magnetite through cracks, within defined areas from the periphery to

the center of magnetite crystals, or completely irregular. Hematite is characterized by small-scale clumps with the irregularly shaped grain size of less than 0.007 mm, sometimes finely dispersed, which form the finest twinning with silica or calcite. In addition to layer-by-layer clumps, string hematite is well-developed, most likely of the second phase, composing a network of coarse-scaled monomineral stringer selections, with a leafy-scaled, tabular grain shape of up to 0.035 mm. Magnetite is represented by irregular nested inclusions, of up to 0.06-0.035 mm, less frequently, idiomorphic crystals, intensely crook-veined with hematite. According to mineralogy, to release iron it is necessary to diminish the ore to fine dimensions of less than 0.071 mm.

Figure 2 – Iron-manganese ore of the "Zhomart" deposit

2) *silica-carbonatic manganese oxide* ore is a cycling between partings of silica-carbonatic composition and braunite- black manganese - pyrolusite aggregates, and also with grainy clumps of friedelite $(Mn,Fe)_8Si_6O_{15}(OH,Cl)_{10}$, red manganese $MnCO_3$, manganese calcite $(Mn,Ca)CO_3$, braunite and pyrolusite:

- braunite is the primary ore mineral that forms close-grained aggregates to a greater extent idiomorphic grains of up to 0.09-0.18 mm. Fine-grained formations of black manganese-pyrolusite composition with power up to 0.014 mm thick develop along the cracks of grain cleavage;

- the friedelite forms fine-grained formations with grain sizes up to 0.08 mm in a close twinning with the red manganese, silica, and calcite with dense insets in microscopic inclusions of the black manganese-pyrolusite composition with the size up to 0.007 mm. Against the background of fine-grained fridelite, cleaved strings and nested clumps with power up to 0.07 mm have been observed, composed of black manganese - pyrolusite aggregates with an allotriomorphic-grained structure.

- cleaved strings with power up to 0.8 mm, the black manganese - pyrolusite composition, performing the wall voids and cracks with the formation of leafy-scaled concretions of pyrolusite with the size up to 0.014 mm are characterized by a fairly wide development. According to mineralogy, in order to release manganese from the second type of ore, it is necessary to diminish the ore to fine dimensions of 0.1-0.5 mm.

The composition of ore according to X-ray fluorescence analysis is given in Figure 3.

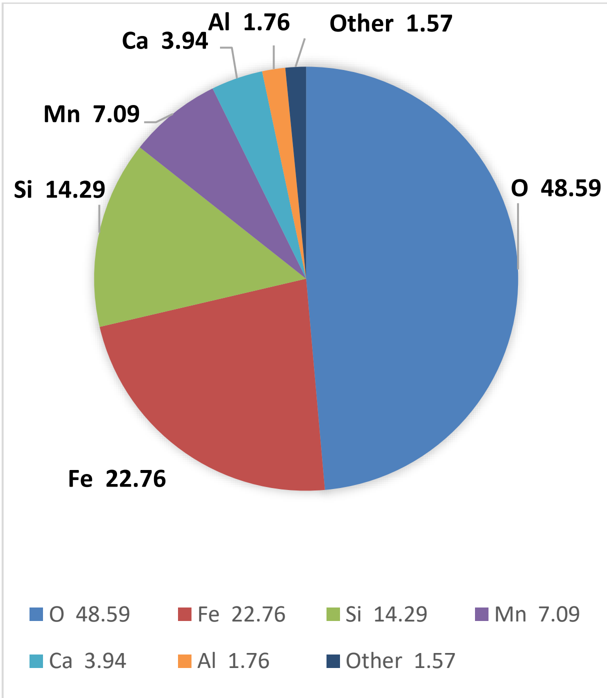

Figure 3 – The results of X-ray fluorescence analysis

According to Figure 3, the manganese, iron, and silicon content are at the level of 7.1%, 22.8%, and 14.3% respectively, in other words, the iron content in the ore is three times more than manganese.

In the process of studying the physical and mechanical properties of iron-manganese ore has been determined that: the true ore density is 3.57 g/cm^3; the bulk ore density (size -50+0.0 mm) is 2.01 g/cm^3; the bulk ore density (size -2.5+0.0 mm) is 1.73 g/cm^3; the ore hardness by M. Protodyakonov - 11.4 (medium hardness ore).

Table 1 – Granulometric analysis of ore sheared to 50 mm

Size, mm	Yield, %	Content, %			Recovery, %		
		Mn	Fe	SiO_2	Mn	Fe	SiO_2
- 50 + 40	8.92	3.03	34.57	27.27	2.80	11.14	8.56
- 40 + 20	28.56	7.91	32.63	22.75	23.42	33.67	22.85
- 20 + 10	14.46	11.41	28.80	27.27	17.11	15.04	13.87
- 10 + 5	10.53	12.34	28.23	27.71	13.47	10.74	10.26
- 5 + 2.5	6.34	13.29	24.44	26.61	8.73	5.60	5.93
- 2.5 + 1.25	4.49	14.11	23.97	26.54	6.57	3.89	4.19
- 1.25 + 0.63	3.66	14.26	23.93	28.11	5.41	3.17	3.62
- 0.63 + 0.315	2.38	10.01	24.25	34.96	2.47	2.09	2.93
- 0.315 + 0.1	4.44	13.81	24.72	29.75	6.35	3.97	4.65
- 0.1 + 0.071	1.12	7.24	21.95	48.30	0.84	0.89	1.90
- 0.071 + 0.0	15.10	8.20	17.96	39.99	12.83	9.80	21.24
Ore	**100.00**	**9.65**	**27.67**	**28.43**	**100.00**	**100.00**	**100.00**

In the course of the ore beneficiation study, a granulometric analysis was carried out (Table 1) to determine the size classes in which iron or manganese are mainly concentrated.

According to the results of granulometric analysis, the weighted average content of manganese and iron composed 9.65% and 27.67% respectively.

Based on the results presented in Table 2, the following may be noted:

- the largest ratio has large size classes -50+40 mm, -40+20 mm, and -20+10 mm, the total ratio consisted of 51.94% and the class -0.071+0.0 mm. The ratio of the subsequent size classes decreases from 10.53% in the -10+5 mm class and up to 1.12% in the -0.1+0.071 mm size class. The ratio of the size class -0.071+0.0 mm reached 15.10%;

- the distribution of manganese content by size classes has been unequal. The highest manganese contents in the range from 10.01% to 14.11% correspond to size classes in the range of -20+0.1 mm. The lowest manganese content in the large class is -50+40 mm and is composed of 3.03%. The content of manganese in the other size classes is in the range of 7.24-8.20%. The extraction of manganese into the size classes practically corresponds to their yields;

- the iron content by size classes is uneven. The highest iron content in the large class is -50+40 mm 34.57% and gradually decreases with decreasing size classes. The lowest iron content in the class with a size of -0.071 +0.0 mm consisted of 17.96%. The indicators of iron extraction in the size classes practically correspond to their yields.

It is known that modern methods of beneficiation of manganese ores are based on the difference in density [12], wettability, and magnetic characteristics of various chemical elements by which it is possible to purify ores from impurity elements. The paper provides data on the jigging of manganese ore in various size classes from 0.63 mm to 50 mm, while the combining concentrate of the jigging contained 40.2% manganese with the extraction of 71.4%.

The authors applied jigging of ore with desliming in the same apparatus as the proposed method a concentrate with a manganese content of 40% was prepared [13].

Based on the data of the granulometric analysis of the ore, as well as to obtain a large-lump concentrate, tests were carried out on the jigging of iron - manganese ore in the size classes of -50+13 mm; -13+2.5 mm and -2.5+0.5 mm.

A laboratory pulsator with a pneumatic drive was used to test the jigging of machine classes with a size of -50+13 mm, -13+2.5 mm. The frequency of pulsations equaled 50 – 70 oscillations per minute, the oscillation amplitude was 80 – 100 mm, the pulsation cycle was sinusoidal (50 – 0 – 50), the diameter of the chamber is 250 mm, the size of the sieve holes is 2.0 mm, the height of the alluvial jig is 250 mm, the flow rate of the screening underflow water is 4-6 m^3/t and the specific load is 8 – 10 $t/(h{\cdot}m^2)$.

The jigging of a size class of -2.5+0.5 mm was carried out in a laboratory bicameral diaphragm jigging machine of the OML TsNIGRI type with the following parameters: pulsation frequency 150 – 390 count/min, the height of the false-bed jig 40 mm prepared in the first camera from iron mineral grains with a density of more than 4000 kg/m^3 and in the second camera from manganese minerals with a

Table 2 – The balance of metals gained from jigging of ore to obtain iron concentrate and middling

Title	Yield, %	Content, %		Recovery, %		Ratio Mn/Fe
		Mn	Fe	Mn	Fe	
Concentrate – chamber 1 -50+13 mm	17.78	5.49	46.28	9.46	32.42	0.12
Concentrate – chamber 1 -13+2.5 mm	5.10	9.21	45.40	4.56	9.12	0.20
Total iron concentrate -50+0.5 mm	**22.88**	**6.32**	**46.08**	**14.02**	**41.54**	**0.14**
Middling –chamber 2 -50+13 mm	15.82	16.19	27.36	24.83	17.06	0.59
Tails -13+2.5 mm	17.28	13.91	18.58	23.31	12.65	0.75
Size class -2.5+0.5 mm	8.98	14.77	23.11	12.86	8.18	0.64
Size class -0.5+0.0 mm	22.28	8.86	20.22	19.16	17.75	0.44
Total middlings -50+0.0 mm	**64.36**	**12.84**	**21.94**	**80.16**	**55.64**	**0.59**
Tails -50+13 mm	12.76	4.70	5.60	5.82	2.82	0.84
Ore -50+0.0 mm	**100.0**	**10.31**	**25.38**	**100.0**	**100.0**	**0.41**

density of more than 3000 kg/m^3 and a size class of 8-10 mm, pulsation amplitude of 6-8 mm, specific productivity of 5-6 t/(h/m^2), consumption of the screening underflow water of 3 m^3/t.

Consolidated indicators on the jigging for all size classes -50+13 mm; -13+2.5 mm and -2.5+0.5 mm with the production of iron concentrate and iron-manganese middling are shown in Table 2.

According to Table 2, it is clearly seen that a size class of less than 50 mm has been obtained after jigging:

- iron concentrate (yield 22.88%) with an iron content of 46.08% and manganese of 6.32% when extracting 41.51% and 14.02%, respectively, based on the mineralogy of the ore, iron is mainly represented by hematite.

- iron - manganese middling (yield 64.36%) with a manganese content of 12.84% and iron 21.94% with the manganese and iron extraction of 80.16%, 55.64% respectively, and which is not suitable for smelting ferroalloys, because a manganese content of at least 35% required.

The author [14] notes that various technological schemes could be applied for the beneficiation of manganese ores, including the combination of gravity and magnetic beneficiation techniques.

In articles [[15],[16],17]], a method for the beneficiation of manganese ore has been provided, which includes magnetic separation of a fine fraction of ore with a size class of less than 3 mm by known technology.

In order to increase the manganese content, tests were conducted on dry magnetic separation of industrial products, which was carried out on a laboratory electromagnetic separator 138T-SEM with a high magnetic field intensity from 660 to 780 kA / m. Previously, the middling was diminish to dimensions of 2.5 mm, followed by classification by a size class of 0.1 mm (Figure 4).

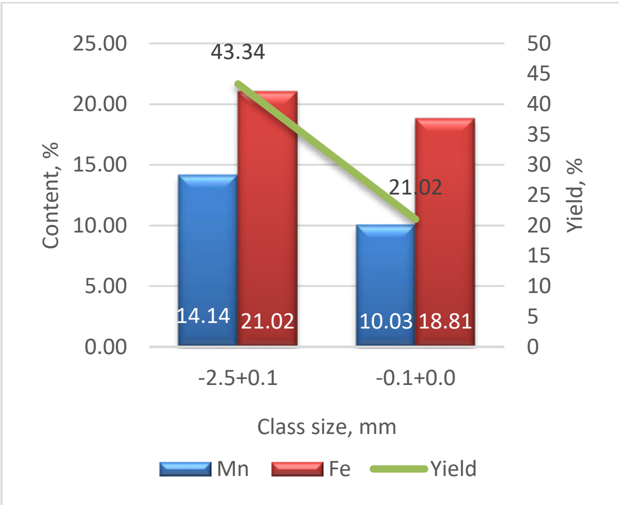

Figure 4 – Classification Results for the middling on jigging

The results for magnetic separation of size class -2.5+0.1 mm of the middling are shown in Table 3.

The total balance of ore processing of the "Zhomart" deposit with the use of jigging and magnetic separation processes to obtain additional iron and iron-manganese concentrate by magnetic separation is demonstrated in Table 4.

Table 3 – The balance of metals of magnetic separartion of the middling on the jigging to obtain iron and iron-manganese concentrate

Title	Yield, % from		Content, %		Recovery from process, %		Ratio Mn/Fe
	process	ore	Mn	Fe	Mn	Fe	
Iron concentrate, 660 kA/m	20.96	9.08	7.07	42.97	10.48	42.84	0.16
Iron-manganese concentrate, 780 kA/m	51.74	22.43	21.73	21.09	79.50	51.93	1.03
Tails, non-magnetic fraction 780 kA/m	27.30	11.83	5.19	4.03	10.02	5.23	1.29
Total middling -2.5+0.1 mm	**100.0**	**43.34**	**14.14**	**21.02**	**100.0**	**100.0**	-

Table 4 – The balance of metals of ore beneficiation of the "Zhomart" deposit with the use of jigging and magnetic separation

Title	Yield, %	Content, %		Recovery, %		Ratio Mn/Fe
		Mn	Fe	Mn	Fe	
Concentrate – chamber 1 -50+13 mm	17.78	5.49	46.28	9.49	33.83	0.12
Concentrate – chamber 1 -13+2.5 mm	5.10	9.21	45.40	4.57	9.52	0.20
Iron concentrate, magnetic fraction 660 kA/m -2.5+0.1 mm	9.08	7.07	42.97	6.24	16.04	0.16
Total iron concentrate -50+0.1 mm	**31.96**	**6.53**	**45.20**	**20.30**	**59.39**	**0.14**
Iron-manganese concentrate, magnetic fraction 780 kA/m -2.5+0.1 mm	**22.43**	**21.73**	**21.09**	**47.40**	**19.45**	**1.03**
Tails -50+13 mm	12.76	4.70	5.60	5.83	2.94	-
Tails, non-magnetic fraction 780 kA/m -2.5+0.1 mm	11.83	5.19	4.03	5.97	1.96	-
Size class -0.1+0.0 mm	21.02	10.03	18.81	20.50	16.26	-
Total tails -50+0.0 mm	**45.61**	**7.28**	**11.28**	**32.30**	**21.16**	-
Ore -50+0.0 mm	**100.0**	**10.28**	**24.32**	**100.0**	**100.0**	-

According to Table 4, it is seen that from the ore of the "Zhomart" deposit, according to the gravitational-magnetic scheme, could be obtained:

- iron concentrate (yield 31.96%) with an iron content of 45.2% and manganese content of 6.53% with the extraction of 59.39% and 20.3% respectively;

- iron - manganese concentrate (yield 22.43%) with the content of manganese 21.73% and iron 21.09% with the extraction of manganese 47.4% and iron 19.45%.

The study results showed that iron concentrate (Fe-45% and Mn-6,5% manganese are mainly represented by hematite mixed with non-metallic minerals, i.e silica and calcite) and iron-manganese concentrate (Mn-21,7% and Fe-21,1% iron presented by hematite, braunite and pyrrolusite also blend with silica and calcite).

Concentrates that could be obtained by ore beneficiation of the "Zhomart" deposit are not considered to be saleable for smelting manganese-containing ferroalloys. Potential use is in the process of electro-thermal phenomena with selective carbothermal reduction of iron in the ore-thermal furnace [[18], [19], [20]]. The smelting products will be manganese cast iron and ironless low-phosphorous marginal manganese slag with a high ratio of manganese to iron.

Conclusions

During the study, iron-manganese concentrate (Fe-45% and Mn-6.5%) and iron-manganese concentrate (Mn-21.7% and Fe-21.1%) were obtained from iron-manganese ore (Mn-10.3% and Fe-24.3%).

This type of ore is difficult to obtain concentrates. It can be seen from the data that in order to obtain concentrates with a sufficient content of the target metal in the beneficiation process, it is necessary to include hydro- or pyrometallurgical processes.

The preference of this beneficiation scheme is determined by the need to reduce the mass of rock for further processing.

Concentrates obtained in the process of beneficiation by means of jigging and magnetic separation of Zhomart deposit ore are not conditioned for smelting manganese-containing ferroalloys, but can be used in the process of electrothermal beneficiation with selective carbothermal reduction of iron in the ore-thermal furnace. Smelting products can be manganese pig iron and iron-free low-phosphorus marginal manganese slag with high manganese to iron ratio.

Conflicts of interest. On behalf of all authors, the corresponding author states that there is no conflict ofinterest

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«Жомарт» кен орнының қиын байытылатын темір-марганец кендерін байыту жұмыстарын зерттеу

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Мақала келді: *23 маусым 2023*
Сараптамадан өтті: *15 шілде 2023*
Қабылданды: *26 шілде 2023*

ТҮЙІНДЕМЕ

Ферроқорытпа өндірісін жоғары сапалы шикізатпен қамтамасыз ету үшін төмен сапалы марганецті және темір-марганецті кендерді байыту технологияларын әзірлеу қажеттілігі күннен-күнге өзекті болуда. Кендердің сапалық сипаттамаларының, пайдалы зат үлесінің төмендеуін және дәстүрлі байыту әдістерімен байытудың өзгерулерін ескере отырып, жаңа тәсілдер мен технологиялық шешімдерді қарастыру қажет. Мақалада «Жомарт» кен орнындағы қиын байытылатын темір-марганец кенін байыту бойынша зерттеу деректері келтірілген. Кеннің минералогиясы, физикалық-механикалық қасиеттері және гранулометриялық құрамы анықталды. Пневматикалық жетегі бар зертханалық пульсаторды және зертханалық 2 камералы диафрагмалық тұндыру аппаратын қолдану арқылы гравитациялық байыту және жоғары қарқынды магнит өрісімен кенді магниттік байыту бойынша зерттеу нәтижелері берілген. Құрамында темір бар концентрат (Fe-45% және Mn-6,5% негізінен металл емес минералдар кварц және кальцит араласқан гематит түрінде) және темір-марганец концентраты (Mn-21,7% және Fe-21,1% гематит, броунит және пирролюзит, сонымен қатар кварц пен кальцитпен араласқан түрінде) алынды. Концентраттар құрамында марганеці бар ферроқорытпаларды балқыту үшін жарамсыз, бірақ оларды кен-термиялық пеште темірді селективті карботермиялық тотықсыздандыру арқылы электротермиялық байыту процесінде қолдануға болады. Балқыту өнімдері ретінде марганецтің темірге жоғары қатынасы бар марганецті шойын және темірсіз аз фосфорлы марганец шлактары болуы мүмкін.

Түйін сөздер: темір-марганецті кен, тұндыру, құрғақ магниттік сепарация, темір-марганецті концентрат

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Исследование обогащения упорных железомарганцевых руд месторождения «Жомарт»

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АННОТАЦИЯ
С целью обеспечения ферросплавное производство качественным сырьем все более актуальным становится необходимость разработки технологий обогащения бедных марганцевых и железомарганцевых руд. Ввиду изменения качественных характеристик руд, снижения содержания и обогатимости традиционными методами обогащения, необходимо рассматривать новые подходы и технологические решения. В статье приведены данные исследования по обогащению труднообогатимой железо-марганцевой руды месторождения «Жомарт». Определена минералогия, физико-механические свойства и гранулометрический состав руды. Приведены результаты исследования по гравитационному обогащению с использованием лабораторного пульсатора с пневматическим приводом и лабораторной 2-х камерной диафрагмовой отсадочной машины и магнитному обогащению руды с высокоинтенсивным магнитным полем. Получены железосодержащий концентрат (Fe-45% и Mn-6,5% в основном представлен гематитом в смеси с нерудными минералами кварцем и кальцитом) и железо – марганцевый концентрат (Mn-21,7% и Fe-21,1% в виде гематита, браунита и пирролюзита также в смеси с кварцем и кальцитом). Концентраты не являются кондиционными для выплавки марганец содержащих ферросплавов, но могут быть использованы в процессе электротермического обогащения с селективным карботермическим восстановлением железа в рудотермической печи. Продуктами плавки могут являться марганцовистый чугун и безжелезистый малофосфористый предельный марганцевый шлак с высоким отношением марганца к железу.

Ключевые слова: железомарганцевая руда, отсадка, сухая магнитная сепарация, железомарганцевый концентрат

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