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Obtaining manganese pellets from manganese-containing technogenic waste

S.S. Temirova, G.Zh. Abdykirova, A.A. Biryukova, D.Y. Fischer*
Institute of Metallurgy and Ore Beneficiation, Almaty, Kazakhstan
**Corresponding author: fischerdametken@gmail.com*

Abstract. Recycling manganese-rich industrial residues is a significant technological and environmental challenge in mining regions because it lowers long-term waste accumulation and provides a valuable supplementary feedstock for ferroalloy production. This study thoroughly examined fine-grained manganese sludge from the Ushkatyn-3 deposit (JSC «Zhayremsky GOK») using particle size analysis, X-ray fluorescence spectroscopy, X-ray diffraction, ICP-AES, and differential thermal analysis. Nearly all of the original technogenic material, which contained 15.0-18.3% Mn, was composed of barite, quartz, bixbyite, calcite, and braunite. Based on the identified granulometric and mineralogical properties, a gravity-magnetic beneficiation flowsheet was created. Sequential treatment using jigging, concentration tables, and high-intensity magnetic separation produced a finely dispersed manganese concentrate with a Mn content of 34.9-35.2% and a recovery of roughly 61%. Pelletizing mixtures containing calcium oxide, natural iron-bearing diatomite, and, in certain compositions, coke was made using the resultant concentrate. The formation of green pellets during granulation in an Eirich mixer-granulator has been examined in relation to binder content and particle-size distribution. The thermal behavior of the composite mixture was examined using TGA-DTA/DSC and quadrupole mass spectrometry, which revealed dehydration, carbonate breakdown, and polymorphic transformations of manganese phases over the temperature range of 200-1160°C. Because it offers adequate phase consolidation without partial melting, the sintering process proved that 1170°C is the optimal firing temperature. The formation of ferrobustamite ($CaFe_2Si_2O_4$), hausmannite (Mn_3O_4), and jacobsite ($MnFe_2O_4$) was verified by X-ray diffraction analysis of the fired pellets. This is the ferrosilicon calcium binding phase, which strengthens the agglomerates' structural integrity. The sintered pellets' high mechanical strength (up to 33.8 kg per pellet), apparent density of 1.45-1.91 g/cm³, and open porosity of 27-35% attest to their suitability as feedstock for ferromanganese alloy production. The developed beneficiation and agglomeration method represent an effective way to convert low-grade manganese sludge into useful metallurgical raw materials. The proposed technology reduces the environmental impact of tailings ponds and opens a viable path to the sustainable use of manganese-containing industrial waste.

Keywords: *manganese-containing waste, technological scheme, manganese concentrate, manganese pellets, strength*.

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1. Introduction

The processing of manganese ores produces significant volumes of finely dispersed manganese-containing raw materials [1]. The use of mineral formations of technogenic origin, including finely dispersed crushing products, residues after enrichment, and slags from metallurgical processes, opens up new opportunities for the effective development of the raw material base and reduction of natural resource use by involving secondary resources in the technological cycle. This approach not only significantly reduces the costs associated with traditional mineral extraction but also contributes to solving pressing environmental issues related to the disposal of industrial waste and reducing the anthropogenic impact on the environment [2-5].

Research is being conducted on the enrichment of low-quality iron-manganese raw materials using flotation and magnetic separation processes [6-9].

Study [6] provides data on the processing of ore material containing 17% pyrolusite, 78% calcite, and 4% quartz. In the first stage, using gravity enrichment on separation equipment, a pyrolusite concentrate was obtained, characterized by a specific manganese oxide content of 20%.

Subsequent application of high-intensity magnetic separation increased the MnO content to 44.3% with a total element recovery of 61.3%. Studies have been conducted on the enrichment of fine-grained manganese ore with a low manganese content [8]. Classification followed by a two-stage process of high-intensity magnetic separation (1.7 and 1.1 T) made it possible to obtain an iron-manganese concentrate with a Mn content of 37% and a recovery rate of 48%.

The possibility of gravitational and magnetic enrichment of aged manganese sludge has been studied [10]. Using a 3.0-0.63 mm class screening process and 0.63-0.071 mm class magnetic separation, a concentrate with a manganese content of 38.25% was obtained.

For use in metallurgical processes for smelting finely dispersed concentrates obtained by enriching manganese-containing sludge, they must be agglomerated into pellets and briquettes. The strength characteristics, melting and reducing properties of manganese pellets have been studied depending on the nature of the fluxing materials, carbon content, ratio of acidic and basic oxides, and heat treatment conditions [11-17]. As a rule, substandard concentrate of the fine fraction is used for pellet production. Various types of binders are added to the charge to ensure strength characteristics.

Work [18, 19] presents the results of pellet formation using bentonite as a binder. The resulting pellets were dried and then fired at a temperature of 1300°C. According to the assessment, the physical and mechanical properties of the pellets met the requirements for ferroalloy production.

A method for producing composite pellets for silicomanganese production, consisting of manganese ore, iron ore, fine coke, and ferromanganese slag without additional binders, is described [18]. The physical properties of the pellets obtained, such as cracking and reducibility, were significantly improved compared to the original lump manganese ore.

The results of the study [19] confirmed the effectiveness of the thermohydrotreatment method in autoclave conditions for strengthening fluxed manganese material. It was found that the initial (raw) pellets had a strength of about 3.55 kg/pellet, while after autoclave treatment, this figure increased to 40-60 kg/pellet. The samples obtained demonstrated thermal stability and retained their structural integrity under rapid thermal exposure up to 1000°C, which indicates their suitability for smelting carbon ferromanganese.

Thus, it has been established that autoclave-hardened manganese pellets formed from finely dispersed concentrates are characterized by high strength, uniformity in particle size and chemical composition, and are capable of effective carbon reduction under metallurgical process conditions.

In recent years, researchers have shown growing interest in the use of fine-grained manganese residues that remain after ore beneficiation and metallurgical operations. These materials are difficult to handle because of their small particle size and uneven mineral composition, and for that reason they cannot be directly fed into pyrometallurgical processes. This makes the question of how to agglomerate them into a stable, uniform product an important practical issue.

Another point that requires attention is the choice of additives introduced into the pellet mixture. Fluxes, carbon materials, and various silicate components influence the reactions that occur during firing and determine which binding phases eventually form. Several publications report that natural aluminosilicates, clay-rich residues, and diatomite can promote the formation of calcium–silicate and related phases, which improve the strength of pellets under reducing conditions typical of ferroalloy production [20-23].

At the same time, manganese-bearing waste from specific deposits in Kazakhstan has not been investigated in detail. Differences in mineralogical composition, particle shape, impurity content, and moisture content require adjustments to separation stages and pelletizing methods. Therefore, additional research is needed to determine methods for producing agglomerated materials that meet the requirements of metallurgical processing.

The aim of this work was to develop methods for enriching finely dispersed manganese-containing raw materials and obtaining pellets suitable for smelting into ferromanganese alloys based on manganese concentrate.

2. Materials and methods

A sample manganese sludge with a size of -5+0 mm was taken at the Ushkatyn-3 deposit (JSC «Zhayremsky GOK») with a mass of 200 kg. The manganese content in the average sludge sample was 15.04% (15.96%), and the iron content was 6.03% (5.97%).

The following materials were used in the study: manganese concentrate obtained by enriching manganese-containing sludge, diatomite from the Zhalpak deposit, calcium oxide, and coke.

The chemical composition of the raw materials and processed products was determined by analysis using inductively coupled plasma atomic emission spectrometry (ICP-AES) on an Optima 8000 DV (ICP, PerkinElmer, Norwalk, CT, USA), and X-ray fluorescence data was obtained using a Venus 200 wave dispersion spectrometer from PANalytical (Netherlands).

X-ray phase data were obtained on a D8 Advance diffractometer (Bruker AXS GmbH, Karlsruhe, Germany) with a cobalt anode, radiation, Cu. Differential thermal analysis of the mixture for pellet production was performed on a TG-DTA/DSC synchronous thermal analyzer and a STA 449 F3 Jupiter® quadrupole mass spectrometer (NETZSCH, Germany).

The particle size distribution of manganese-containing technogenic raw materials from the Ushkatyn-3 deposit was studied on a sample with a size of -5.0 + 0 mm.

Sieve analysis was performed by sequentially sieving the test sample through a standard set of laboratory sieves, followed by determination of the mass fraction of material retained on each sieve, calculated based on the mass of the initial sample. To evaluate the size distribution of particles in the slurry sample, sieves with mesh sizes of 2.0, 1.0, 0.5, 0.315, 0.16, and 0.1 mm were used. Sieving was performed using a mechanical vibrating analyzer.

3. Results and discussion

The particle size distribution of the material under study is presented in Table 1. The content of manganese, iron, and silicon was determined in the sieve analysis products.

Table 1. Results of sieve analysis of a sample of sludge fraction (–5.0+0) mm from the Ushkatyn-3 deposit

Class, mm	Yield, %	Element content, %		Element distribution, %	
		Mn	Fe	Mn	Fe
+2.0	22.17	16.10	5.10	22.37	18.91
-2.0+1.0	22.44	15.01	5.21	21.08	19.56
-1.0+0.5	24.32	15.92	6.24	24.26	25.38
-0.5+0.315	9.02	16.12	6.81	9.11	10.27
-0.315+0.16	14.25	16.34	7.02	14.58	16.68
-0.16+0.1	3.95	18.30	8.22	4.53	5.43
-0.1+0.0	3.85	16.88	5.86	4.07	3.77
Total	100.0	15.96	5.97	100.0	100.0

The results of the granulometric analysis of manganese-containing sludge from the Ushkatyn-3 deposit (Figures 2 and 3) show that the largest mass is represented by the +0.5 mm size class and accounts for 68.93%, while the other size classes vary from 3.85% to 14.25%. The content and distribution of manganese and iron in different size classes of manganese-containing sludge are shown in Figures 2 and 3. It is shown that the manganese content in different fractions differs insignificantly and ranges from 15.0 to 18.3%. Most of the manganese is concentrated in fractions larger than 0.5 mm.

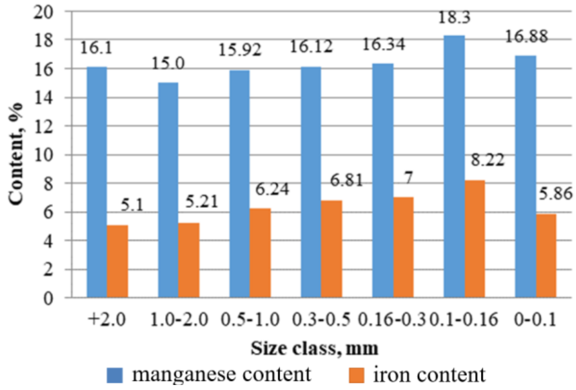

Figure 2. Manganese and iron content in different size classes of manganese-containing sludge

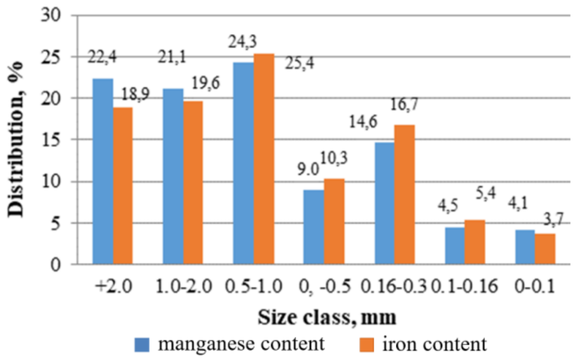

Figure 3. Distribution of manganese and iron in different size classes of manganese-containing sludge

Along with studying the particle size distribution, X-ray fluorescence and X-ray phase analyses of the sample were performed (Table 2 and 3).

Table 2. Results of X-ray fluorescence analysis of a sample of manganese-containing sludge from the Ushkatyn-3 deposit

Components	Component content, %	Components	Component content, %
O	44.12	K	0.273
Mn	16.78	Ca	16.21
Fe	5.52	Ti	0.149
Na	0.301	As	0.036
Mg	0.795	Cu	0.015
Al	1.41	Zn	0.067
Si	6.89	Pb	0.239
P	0.025	Sr	0.127
Cl	0.041	Ba	6.437
S	0.701	Pb	0.002

Table 3. Results of X-ray phase analysis of a sample of manganese- containing sludge

Compound name	Formula	S-Q, %
Calcite	$Ca(_{CO_3})$	41.2
Quartz	SiO_2	13.0
Brownite	$Mn_7 O_8 (SiO_4)$	10.1
Bixbyite	$FeMnO_3$	9.85
Barite	$BaSO_4$	6.59
Pigeonite	$Mg_{0.69} Fe_{0.23} Ca_{0.08} SiO_3$	6.58
Dikit	$Al_2 Si_2 O_5 (OH)_4$	5.57
Hematite	$Fe_{1.957} O_3$	4.59

X-ray phase analysis of manganese-containing sludge showed that the main manganese-containing minerals are braunite $Mn_7O_8(SiO_4)$ and bixbite, while the rock-forming minerals are calcite, quartz, and barite (Table 3).

Manganese ore enrichment is mainly carried out by flotation. To carry out flotation, the difference in density between manganese minerals and waste rock must be at least 400 kg/m^3. Since the density of most manganese minerals is 3200-3800 kg/m^3, and that of waste rock does not exceed 2800 kg/m^3, this operation can be carried out.

A study of the processes of gravitational enrichment of manganese-containing sludge was carried out, resulting in a finely dispersed concentrate with an increased manganese content. A 50.0 kg sample of sludge was screened using sieves of different particle sizes: 2.5, 1.25, and 0.071 mm.

Beneficiation of sludge with particle sizes of -2.5+1.25 and -1.25+0.071 mm was carried out in a jigging machine. The optimal operating parameters are: bed size (manganese grains) – 10-8 mm, bed height – 30-40 mm, pulsation frequency – 350 oscillations/min, oscillation amplitude – 8 mm enrichment of the -0.071+0 mm size class was carried out on concentration tables under the following conditions: table stroke – 14 mm, number of deck oscillations per minute – 240, deck inclination – 35 degrees.

A technological scheme for the gravitational beneficiation of manganese sludge has been developed, allowing the production of a concentrate with a manganese content of 28.5% and iron content of 7.25%. At the same time, the extraction of these components was achieved at a level of 62.01% and 39.85%, respectively (Figure 4).

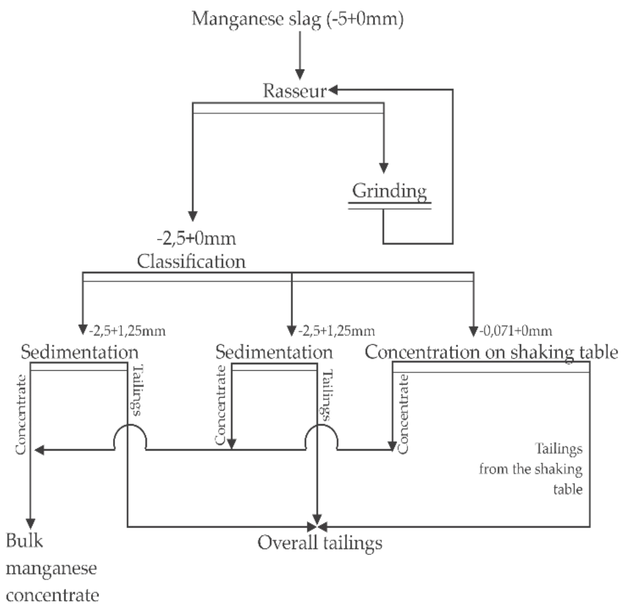

Figure 4. Schematic diagram of gravity enrichment of manganese-containing sludge

The combined manganese concentrate from the tailings and concentration table was separated using a SMP-PR-02 laboratory magnetic separator (manufactured in Ukraine) at a magnetic field strength of 900 mT.

As a result of applying the gravity-magnetic enrichment scheme, a manganese concentrates with a manganese content of 34.9% and iron content of 7.9% was obtained; the extraction rates were 61% and 39%, respectively. The optimal technological parameters for the formation of «raw» pellets from a composite mixture including manganese concentrate, special coke, iron-containing varieties of diatomite, and lime were established. The chemical composition of the starting components is shown in Table 4.

Table 4. Chemical composition of the starting materials

Source material	Oxide content, mass %									
	Mn	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	BaO	K_2O	Na_2O	other	ppm
Manganese concentration	34.9	10.31	1.83	14.82	6.86	1.31	7.68	0.17	0.90	5.56	-
Diatomite	-	63.94	8.03	10.30	8.06	9.61	-	-	-	0.6	-
Lime	-	0.23	0.05	0.09	76.32	1.80	-	-	-	0.54	20.97

Manganese concentrate-based pellets were obtained by pelletizing on a laboratory automated mixer-granulator manufactured by Eirich (Figure 5 and 6). Granulation process parameters: steel drum rotation speed – 170 rpm, drum angle – 30(o), drum rotation relative to the swirler – counterclockwise.

Figure 5. Eirich mixer-granulator

Figure 6. Samples of manganese pellets

Experiments were conducted to obtain pellets based on two compositions with different fractional compositions of manganese concentrate: 1) content of fractions 0.5-0.16 mm – 61.3%; 0.16-0.071 mm – 34.0%; less than 0.071 mm – 4.7%; 2). The particle size distribution of the material under study is as follows:

– the 0.5-0.16 mm fraction accounts for 39.8%;

– fraction 0.16-0.071 mm – 31.2%;

– particles smaller than 0.071 mm account for 29.0%. Kazakh diatomite containing iron oxides (Zhalpak deposit) was used as a binder in the mixture for producing manganese pellets. The chemical composition of diatomite is as follows, in mass %: SiO_2 – 63.94; Al_2O_3 – 8.03; Fe_2O_3 – 10.30; CaO – 8.06; MgO – 9.61; others – 0.6.

Diatomite is a natural material, the main component of which is quartz (69.4%), also containing goethite, barium-manganese, magnesium, calcium-aluminum, and barium silicates (Figure 7).

To obtain pellets, 500 g of the raw material mixture was poured into the mixer-granulator. The mixture was mixed for 30 seconds at a maximum vortex speed of 2000 rpm. When small granules appeared, the vortex speed was reduced to 1000 rpm, followed by powdering of the mixture.

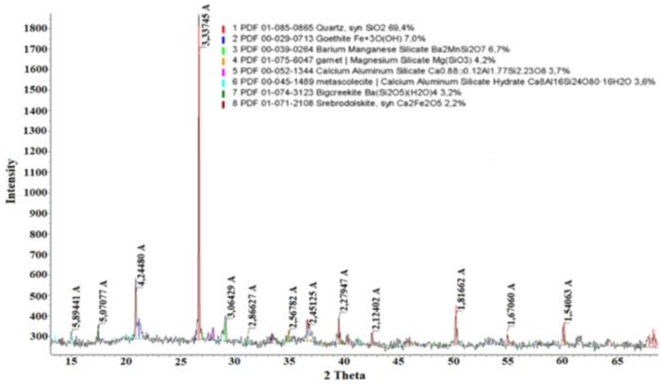

Figure 7. Diffractogram of a diatomite sample

To obtain pellets, 500 g of the raw mixture was poured into the mixer-granulator. The mixture was mixed for 30 seconds at a maximum agitator speed of 2000 rpm. When small granules appeared, the speed of the swirler was reduced to 1000 rpm, followed by powder coating of the mass. After 1 minute, the remaining part of the binder component was added, and the moistened mass was powder coated, reducing the speed of the swirler to 700 rpm. After one minute, the speed of the swirler was reduced to 500 rpm, then to 300 rpm. After continuing granulation at this speed for 3 minutes, the process was completed and the raw pellets were unloaded.

It was found that pellets based on a charge with a high content of fine manganese concentrate (less than 0.071 mm) have high strength characteristics.

To establish the patterns of structural and phase transformations occurring during the heat treatment of manganese pellets, a differential thermal analysis was performed on a mixture with the following composition, in mass %: manganese concentrate – 85, diatomite – 10, calcium oxide – 5 (Figure 8).

In the temperature range of 200-550°C, endothermic effects were observed with extrema at 281.8°C and 495.8°C. They are accompanied by a decrease in the weight of the sample, which indicates the dehydration of iron hydroxides. The combination of an endothermic effect with an extreme at 587.4°C and an inflection point on the DTA curve at 708.2°C may be associated with the decomposition of $(Fe,Mn)CO_{(3)}$ .An intense endothermic effect with an extreme at 836.5ºC reflects the decomposition of calcite. The endothermic effect with maximum development at 1168.9ºC can be attributed to the polymorphic transformation of brownite $3Mn_{(2)}O_{(3)}(Mn,Mg,Ca)SiO_{(3)}$. At 1191ºC, crystallization of the fayalite phase 2FeO·SiO(2) phase. The exothermic effect at 979.8ºC is probably associated with the crystallization of ferroboostite $(CaFe_{(2)}Si_{(2)}O_{(6)})$.

The sintering range of experimental manganese-containing pellets was studied, which was 1160-1200°C, with an optimal pellet firing temperature of 1170°C.

As the firing temperature increases, the strength of the samples increases, but at a temperature of 1200°C, signs of melting are observed.

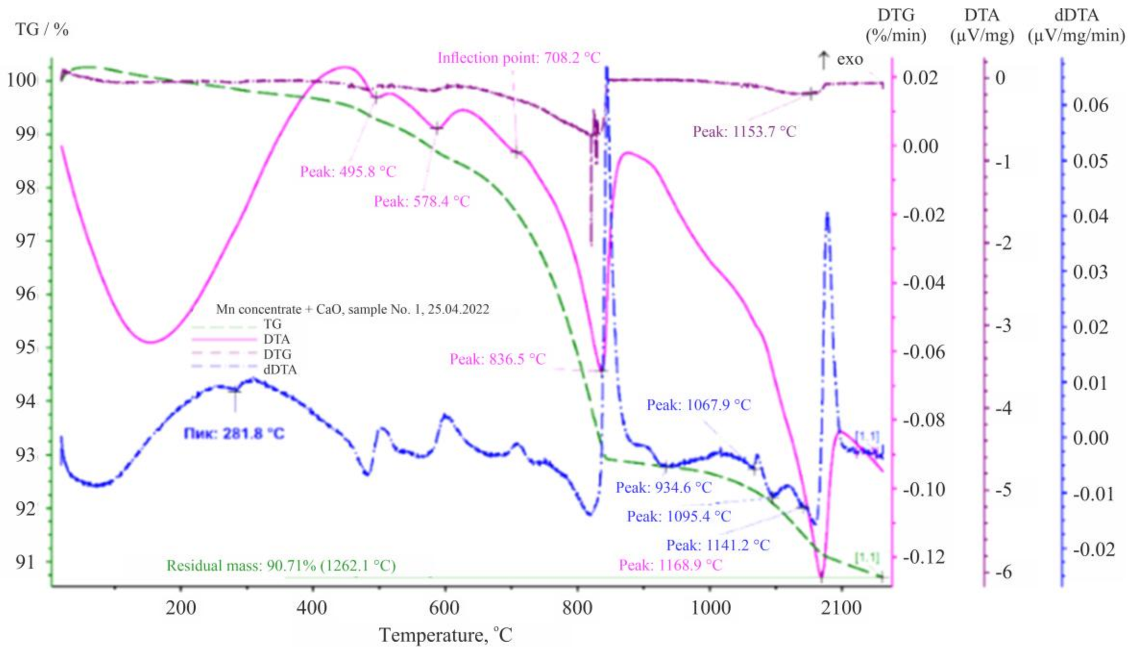

Figure 8. Derivatogram of the charge consisting of manganese concentrate, diatomite, and calcium oxide

X-ray phase analysis of fired compositions based on manganese concentrate with additives revealed that manganese in the pellet structure is present in the form of jacobsite ($MnFe_2O_4$) and hausmannite (Mn_3O_4) phases. The binding part of the structure contains cwalcium and iron silicate – ferrobustamite ($CaFe_2Si_2O_6$), which contributes to the strengthening of pellets and increases their mechanical strength.

The physical and mechanical properties of manganese pellets were determined. For the optimal particle size distribution, pellets were produced using two compositions. In the first composition, the pellet mixture consisted of manganese concentrate (85 wt.%), diatomite (10 wt.%), and calcium oxide (5 wt.%). In the second composition, the charge consisted of manganese concentrate (78 wt.%), diatomite (11 wt.%), calcium oxide (6 wt.%), and coke (5 wt.%).

The pellets exhibited the following properties: open porosity of 27.3% and 34.5%, apparent density of 1.91 and 1.45 g/cm³, and water absorption of 12.5% and 19.2%, respectively. The compressive strength of pellets based on the manganese concentrate–diatomite–CaO mixture was 33.80 kg/pellet, while the addition of coke reduced the strength to 23.28 kg/pellet.

4. Conclusions

A technological scheme has been developed for the beneficiation of finely dispersed manganese-containing raw materials with obtaining a concentrate with a Mn content of 35.2%. The optimal technological parameters for forming pellets from a mixture including manganese concentrate, special coke, diatomite, and lime have been established. By firing at a temperature of 1170°C, it was found that manganese in the obtained pellets is present mainly in the form of jacobsite ($MnFe_2O_4$) and hausmannite (Mn_3O_4), and a phase of ferrobustamite phase, which contributes to the increased strength of the products.

The compressive strength of the formed pellets was 33.8 kg/pellet, which indicates their sufficient mechanical strength. The obtained pellets meet the requirements for raw materials for smelting ferromanganese alloys and can be effectively used in ferroalloy production.

Author contributions

Conceptualization: SST, GZA; Data curation: SST, GZA; Formal analysis: SST, GZA, AAB; Funding acquisition: SST; Investigation: SST; Methodology: SST, AAB; Project administration: SST, AAB; Resources: SST, GZA; Software: DYF, SST; Supervision: SST, GZA; Validation: SST; Visualization: DYF; Writing – original draft: SST, DYF; Writing – review & editing: SST, DYF. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Марганец бар техногендік қалдықтардан марганец түйіршіктерін алу

С.С. Темирова, Г.Ж. Абдыкирова, А.А. Бирюкова, Д.Е. Фишер*

Металлургия және кен байыту инстиуты, Алматы, Қазақстан

**Корреспонденция үшін автор:* fischerdametken@gmail.com

Аңдатпа. Марганецке бай өнеркәсіптік қалдықтарды қайта өңдеу таукен өндірісі аймақтарында маңызды технологиялық және экологиялық қиындық тудырады, себебі ол ұзақ мерзімді қалдықтардың жиналуын азайтады және ферроқорытпа өндірісі үшін құнды қосымша шикізат болып табылады. Бұл зерттеуде Үшқатын-3 кен орнынан («Жайрем ГОК» АҚ) алынған ұсақ түйіршікті марганец шламы бөлшектердің мөлшерін талдау, рентгендік флуоресценциялық спектроскопия, рентгендік дифракция, ICP-AES және дифференциалды термиялық талдау әдістерін қолдана отырып мұқият зерттелді. 15.0-18.3% Mn құрайтын бастапқы техногендік материалдың барлығы дерлік барит, кварц, биксбиит, кальцит және брауниттен тұрды. Анықталған гранулометриялық және минералогиялық қасиеттерге сүйене отырып, гравитациялық-магниттік байыту ағындық схемасы жасалды. Джиггинг, концентрация кестелері және жоғары қарқынды магниттік бөлуді қолдана отырып, тізбекті өңдеу нәтижесінде Mn мөлшері 34.9-35.2% және қалпына келтіруі шамамен 61% болатын ұсақ дисперсті марганец концентраты алынды. Алынған концентратты пайдаланып, кальций оксиді, табиғи темірі бар диатомит және кейбір құрамдарда кокс бар түйіршіктеу қоспалары жасалды. Эйрих араластырғыш-грануляторында түйіршіктеу кезінде жасыл түйіршіктердің пайда болуы байланыстырушы заттың құрамы мен бөлшектердің мөлшерінің таралуына байланысты зерттелді. Композиттік қоспаның термиялық мінез-құлқы TGA-DTA/DSC және квадрупольді масс-спектрометрияны қолдану арқылы зерттелді, бұл 200-1160°C температура диапазонында марганец фазаларының дегидратациясын, карбонаттың ыдырауын және полиморфты түрленулерін анықтады. Жартылай балқымай, жеткілікті фазалық конденсацияны қамтамасыз ететіндіктен, күйдіру процесі 1170°C оңтайлы күйдіру температурасы екенін дәлелдеді. Ферробустамиттің ($CaFe_2Si_2O_4$), гаусманниттің (Mn_3O_4) және якобситтің ($MnFe_2O_4$) пайда болуы күйдірілген түйіршіктердің рентгендік дифракциялық талдауы арқылы расталды. Бұл агломераттардың құрылымдық тұтастығын нығайтатын ферросилиций кальцийін байланыстыру фазасы. Бітелген түйіршіктердің жоғары механикалық беріктігі (бір түйіршікте 33.8 кг-ға дейін), көрінетін тығыздығы 1.45-1.91 г/см³ және ашық кеуектілігі 27-35% олардың ферромарганец қорытпасын өндіруге арналған шикізат ретінде жарамдылығын растайды. Әзірленген байыту және агломерация әдісі төмен сұрыпты марганец шламын пайдалы металлургиялық шикізатқа айналдырудың тиімді тәсілін білдіреді. Ұсынылған технология қалдық қоймаларының қоршаған ортаға әсерін азайтады және марганец бар өнеркәсіптік қалдықтарды тұрақты пайдалануға жол ашады.

Негізгі сөздер: *құрамында марганец бар қалдықтар, технологиялық сұлба, марганец концентраты, марганец түйіршіктері, беріктігі.*

Получение марганцевых окатышей из марганецсодержащих техногенных отходов

С.С. Темирова, Г.Ж. Абдыкирова, А.А. Бирюкова, Д.Е. Фишер*

Институт металлургии и обогащения, Алматы, Казахстан

**Автор для корреспонденции:* fischerdametken@gmail.com

Аннотация. Переработка богатых марганцем промышленных отходов представляет собой серьезную технологическую и экологическую проблему в горнодобывающих регионах, поскольку она снижает долгосрочное накопление отходов и обеспечивает ценное дополнительное сырье для производства ферросплавов. В данном исследовании был проведен тщательный анализ мелкозернистого марганцевого шлама с месторождения Ушкатын-3 (АО «Жайремский ГОК») с использованием гранулометрического анализа, рентгенофлуоресцентной спектроскопии, рентгеновской дифракции, ИСП-АЭС и дифференциального термического анализа. Практически весь исходный техногенный материал, содержащий 15.0-18.3% Mn, состоял из барита, кварца, биксбиита, кальцита и браунита. На основе выявленных гранулометрических и минералогических свойств была разработана технологическая схема гравитационно-магнитного обогащения. Последовательная обработка с использованием отсадочных машин, концентрационных столов и высокоинтенсивной магнитной сепарации позволила получить мелкодисперсный марганцевый концентрат с содержанием Mn 34.9-35.2% и выходом примерно 61%. Из полученного концентрата были изготовлены гранулированные смеси, содержащие оксид кальция, природный железосодержащий диатомит и, в некоторых составах, кокс. Исследовано образование зеленых гранул в процессе гранулирования в смесителе-грануляторе Eirich в зависимости от содержания связующего и гранулометрического состава. Термическое поведение композитной смеси было изучено с помощью ТГА-ДТА/ДСК и квадрупольной масс-спектрометрии, которые выявили дегидратацию, разрушение карбонатов и полиморфные превращения марганцевых фаз в диапазоне температур 200-1160°C. Поскольку процесс спекания обеспечивает адекватную консолидацию фаз без частичного плавления, было доказано, что оптимальной температурой обжига является 1170°C. Рентгенодифракционный анализ обожженных гранул подтвердил образование ферробустамита ($CaFe_2Si_2O_4$), гаусманнита (Mn_3O_4) и якобсита ($MnFe_2O_4$). Это фаза, связывающая ферросилиций и кальций, которая укрепляет структурную целостность агломератов. Высокая механическая прочность спеченных гранул (до 33.8 кг на гранулу), кажущаяся плотность 1.45-1.91 г/см³ и открытая пористость 27-35% свидетельствуют об их пригодности в качестве сырья для производства ферромарганцевых сплавов. Разработанный метод обогащения и агломерации представляет собой эффективный способ преобразования низкосортного марганцевого шлама в полезное металлургическое сырье. Предлагаемая технология снижает воздействие хвостохранилищ на окружающую среду и открывает перспективный путь к устойчивому использованию промышленных отходов, содержащих марганец.

Ключевые слова: *марганецсодержащие отходы, технологическая схема, марганцевый концентрат, марганцевые окатыши, прочность.*

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