DOI 10.1007/s11015-023-01549-6

Metallurgist, Vol. 67, Nos. 5-6, September, 2023 (Russian Original Nos. 5-6, May–June, 2023)

MELTING FERROCHROME USING CHROME-ORE BRIQUETTES

A. K. Zhunusov,[1] L. B. Tolymbekova,[2] P. O. Bykov,[3] and O. V. Zayakin[4]

UDC 669.168

Results are provided for experimental-industrial tests of high-carbon ferrochrome smelting with partial replacement of the basic chromium ore with chromium ore briquettes produced by OJSC Donskoi Ore Mining and Processing Plant in an amount of 20–40% of the chromium ore raw material supplied to TNC Kazchrome JSC Aksu Ferroalloys Plant (Kazakhstan). These tests show that use of chromium ore briquettes has a number of technological advantages. When using briquettes instead of ore, there is a reduction in electricity consumption from 7201 to 6184 kWh/ton, and chromium extraction increases from 80.3 to 85.3%. Use of briquettes solves the problem of involving substandard chromium ore raw materials in production and improving technical and economic performance of the furnace.

Keywords: chrome ore, high-carbon ferrochrome, briquettes, ferroalloys, pilot smelting.

Technology for producing highly alloyed ferrochrome in ore reduction electric furnaces presents a series of requirements for charge materials, in particular the raw material fractional composition: use of materials with a size less than 10 mm leads to reduction in technical and economic indices for this operation connected with significant dust entrainment and disruption of the furnace passage.

The problem of chromium ore fine faction formation and its involvement in ferroalloy production has been important over many years. Chromium ore in the form of fine fractions (– 10 mm) in an amount of 20–50% of the overall volume of recovery falling into a dump leads to losses and an increase in lump ore cost [1–3].

Under DON Mining Enrichment Combine (Khromtau, Kazakhstan) conditions, being the main supplier of chrome ore for Kazakhstan ferroalloy plants, the proportion of fine factions of this raw material is up to 60–70%, and the proportion of ore in powder and dust form reaches 30% [4, 5]. Use of fine ore fractions as charge material in electric furnaces is not effective. In this case melting will be characterized by intense dust entrainment which leads to irreversible losses, unstable furnace operation, and reduction in technical and economic indices, and contamination of the environment. Therefore for normal operation of electric furnaces melting ferroalloys there is use of lump material (briquettes, pellets, agglomerates) [6].

Of lumping methods for fine ore before melting ferroalloys in ore reduction furnaces within many countries there is development of all methods, i.e., lump formation, briquetting, and agglomeration of fine ore fractions [6, 7]. Many researchers [14] demonstrate that use of briquettes and other lump materials during melting ferroalloys leads to a reduction in reducing agent consumption and an increase in furnace productivity. In [15] use of chromium ore briquettes during test melting of ferrochrome shows a reduction in electrical energy consumption by 2.4% and an increase in furnace productivity by 3.7%.

[1] Non-commercial Joint Stock Company “Toraigyrov University”, Pavlodar, Republic of Kazakhstan; e-mail: zhunusov_ab@mail.ru.

[2] Non-commercial Joint Stock Company “Toraigyrov University”, Pavlodar, Republic of Kazakhstan; e-mail: lyazat-t@mail.ru.

[3] Non-commercial Joint Stock Company “Toraigyrov University”, Pavlodar, Republic of Kazakhstan; e-mail: bykov_petr@mail.ru.

[4] Institute of Metallurgy of Ural Branch of the Russian Academy of sciences, Ekaterinburg, Russia; e-mail: zferro@mail.ru.

Translated from Metallurg, Vol. 67, No. 5, pp. 39–44, May, 2023. Original article submitted November 24, 2022, after modification February 26, 2023, received for publishing April 15, 2023.

 0026-0894/23/0506-0606

Results have also been provided in [16] for laboratory studies, industrial test experience, and industrial use of extrusion briquettes (bricks) based on technogenic and natural materials and fuel for producing ferroalloys. The possibility has been demonstrated of achieving marked saving of electrical energy, a reduction in coke consumption, and an increase in the degree of extraction of the main components during operation with a briquetted charge.

In the Aksu Ferroalloy Plant (AFP, Kazakhstan) test industrial melting has been conducted aimed at establishing the possibility of using chromium ore briquettes in large and powerful ore reduction furnaces with a power of 63 MW with the aim of using sub-standard chromium raw material in production, and improvement of technical and economic indices for furnace operation, During performance of tests there was use of a batch of chromium ore briquettes of the Don Mining and Enrichment Combine (Don GOK, Khromtau) for melting high-carbon ferrochrome that was performed in ferroalloy workshop No. 6 of AFP in furnace No. 62.

Chromium ore briquette chemical composition, wt.%: 52.4 Cr_2O_3, 6.0 SiO_2, 17.2 MgO, 0.4 CaO, 12.8 FeO, 7.9 Al_2O_3, 0.003 S, 0.01 P.

Before the start of test ahead of charging briquettes into furnace bunkers a batch of briquettes was selected and screening was performed. The yield of fines < 10 mm was on average 36.8%.

Physicomechanical properties of chromium ore briquettes:

– moisture, % – 4.40;

– strength in compression, MPa (kg/cm^2) – 18.0 (180);

– strength, % – 28;

– briquette size, mm – 10 × 50 × 40);

– weight fraction of fines 0–10 mm, %.

Charge composition within a test “charge”, kg:

– chromium briquettes – 200–300;

– chromium ore (fraction 5–80 mm) – 700;

– Zarinsk coke (Russia) – 215;

– quartzite screenings – 60;

– coke screenings 20–30.

Test melts were conducted in five stages. The first stage melting a basic charge by the technology adopted in the workshop.

In the second stage furnace power, according to an approved program, should be maintained at the level of 50 MW. The amount of fine fraction 0–5 mm in chromium briquettes was 30–40% after screening a selected batch. Low strength led to their subsequent breakdown during passage of charge supply tracts, furnace containers, and pipelines. Charge collapse was observed with a sharp increase in pressure beneath the furnace arch, the amount of charge discharges increased in the arch beneath electrodes, and it was often necessary to clean inclined gas conduits. For the first few days there was no difficulty in delivery of molten products. Subsequently furnace operation became unstable both with respect to the electrical regime and also for “taphole” operation. Continuous charge falls led to unstable seating of electrodes and variation of the current load. Entry of large amounts of “cold charge” into the furnace melt reduced its temperature and change slag composition. Cases were observed of incomplete emergence of slag from a furnace. Apparently access of a considerable amount of fine charge affected the electrical conductivity of melt within a furnace and caused loss of current load within electrodes. In order to maintain the current load from 1 to 2.5 tons of coke were loaded above electrodes. In this case the coke charge increased from 210 to 235 kg for one "charge". Some of the coke with uneven charge entry was slagged and hardly participated in the reduction process, i.e., there was formation of excess reducing agent in a furnace. Therefore, the coke charge started to decrease, but taphole operation continued to deteriorate: slag was delivered "cold".

Therefore, the second test stage with chromium briquettes was characterized by unstable furnace operation with respect to current load and with respect "taphole" operation.

Over the extent of the third furnace testing stage operation was also unstable. Different proportions of coke were introduced above electrodes. In order to increase the current load there was an increase coke charge from 215 to 225 Kg for on charge. For slag removal thirty charges were made without flux and the amount of quartzite screenings was reduced from 60 to 55 kg for one charge. In this case there was burning outlet opening as a result of reduction in the ferrochrome carbon content since alloy previously was delivered containing 7.355 carbon. Therefore, all three furnace operating were unsatisfactory.

The fourth test stage was characterized by more stable furnace operation compared with the preceding stages. A solution was adopted that all briquettes fed to furnace No. 6 were subjected to complete screening, i.e., screening of fraction 0–10 mm. Over the extent of the whole test stage here was evaluation of the melting temperature regime. For this purpose measurements were made for each discharge by a Promin' pyrometer of metal and slag temperature, delivered from a furnace. Depending upon furnace production the temperature index was within the limits of 1600–1680°C for high-carbon ferrochrome, and 1720–1780°C for the final slag.

Comparison with operation on a basic charge (first stage) showed that after introducing into a charge composition chromium ore briquettes the furnace temperature regime did not undergo marked changes with respect to slag and metal temperature within a furnace.

In the fifth stage, as also in the fourth stage, all batches of briquettes were screened within the charge preparation workshop (CPW). After screening briquettes and exclusion of fine faction (0–10 mm) gradually technology was developed for using chromium ore briquettes during melting high-carbon ferrochrome in furnace No. 62 with a power of 63 MW·A.

It is seen from Table 1 that in the industrial testing time within period 5 the best furnace operating technical and economic indices were achieved. In the first (basic), second and third stages briquettes were fed unscreened, and supplied together with fines. As noted above, briquettes had weak strength. Due to low briquette strength the fine fraction in all batches was up to 30–40%. However, in spite of an increase in fine fraction, from the second stage an increase in active furnace power and an increase in daily furnace production were observed. It is seen from Fig. 1 that with an increase in active furnace power from 39.7 to 55.6 MW there is an increase in daily furnace production compared with the main period (first stage) from 130 to 191.4 tons within the fifth period. Specific electrical energy consumption decreased compared with the main period from 7201 to 6184 kW·h/ton. Chromium extraction for the test period with chromium ore briquettes compared with the basic material increased from 80.3 to 85.3%.

In the fifth test melt period the furnace condition remained satisfactory. Then the proportion of briquettes in a charge was increased to 1206 kg for 1 ton of ferrochrome and this remained up to the end of testing melts. Production of furnace No. 62 in the concluding testing stages was characterized by steady furnace mouth operation with uniform gas separation. A charge entered uniformly with rare slides and discharges, and electrodes moved in a normal production regime.

Organizationally and technologically melts of high-carbon ferrochrome using chromium ore briquettes did not differ considerably from basic technology. They operated with steady capacity-longitudinal compensation (CLC) and per shift there were 2–3 deliveries of melt and slag. In all of the testing time with use of chromium ore briquettes 244 test melts were conducted and about 7200 tons of high-carbon ferrochrome were obtained.

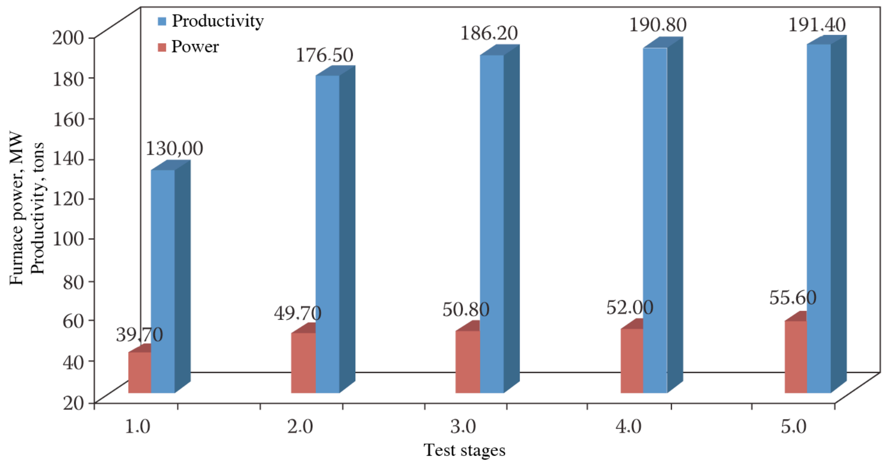

Fig. 1. Power and daily productivity during test for assimilation of total furnace RK3-63 furnace capacity (No. 62 of workshop No. 6, using a chromium ore briquette charge.

Table 1
Furnace No. 62 Operating Indices

Indices	Stage 1 (basic melting)	Stage 2	Stage 3	Stage 4	Stage 5
Actual power, kW	39797	49718	50884	52066	55623
Furnace productivity, ton/day	130.03	176.50	186.24	190.83	191.4
Basic material and electrical energy consumption, kg/m					
Chromium ore (50% Cr_2O_3)	3642	2376	2317	2315	2247
Chromium briquettes (50% Cr_2O_3)	–	1127	1171	1179	1206
Total, ore materials	3642	3582	3486	3445	3425
Coke	785	827	806	802	780
Krasnogor anthracite	148	–	–	–	–
Coke screenings	100	127	90	80	70
Total reducing agent (converted to coke)	770	900	850	800	750
Electrode weight	37.9	49.6	39.9	36.8	33.1
Quartzite screenings	165	200	180	170	165
Returned waste	496	–	–	–	–
Metal concentrate	168	–	–	–	–
Electrical energy consumption, kW·h/ton	7201	6786	6656	6539	6184
Extracted chromium, %	80.3	81.6	83.9	84.9	85.3

Table 2
Metal Chemical Composition for Main Period and Industrial Testing of High-Carbon Ferrochrome Melting

Test period, stages	Amount of briquettes, kg	Ferrochrome chemical composition, %					
		Cr	C	S	Si	P	Mn
1	–	68.84	7.99	0.036	0.92	0.023	0.15
2	1127	68.75	7.83	0.037	0.95	0.023	0.15
3	1171	68.97	8.28	0.038	0.50	0.022	0.16
4	1179	68.68	8.25	0.034	0.87	0.027	0.17
5	1206	68.74	8.40	0.032	0.79	0.027	0.16

The operating conditions of furnace No. 62 are provided in Table 1.

It is seen from Table 2 that during operation of furnace No. 62 using different amounts of chromium ore briquettes the chemical composition of a melt is high-carbon ferrochrome, and with the exception of carbon content the composition did not differ from alloy obtained in the main melting period. With addition of chromium ore briquettes to charge material composition a significant increase in the amount of carbon was observed in the molten ferrochrome from 7.99 to 8.40%. An increase in the amount of carbon within alloys is connected with metal carburization since in the test period from the second stage the amount of coke was increased from 785 to 827 kg/ton due to and observed lack of coke. Consequently, the low strength of test ore briquettes led to breakage of the "ore layer" and melted ferrochrome refined with respect to carbon.

A disadvantage of the reducing agent was observed from second stage during metal delivery. Melt was delivered slowly, it was cold, and viscous, and it contained unreduced ore. In the third melting stage in order to adjust the furnace path there was a reduction in flux and reducing agent added, it is seen from Table 1 that in the subsequent stages the amount of reducing agent and flux continued to decrease.

Metallurgical properties of chromium ores are mainly determined by the composition of the ore-forming chromium spinelid. As a result of a high amount of magnesium within chromium ore briquettes (see above) the phase composition of spinelid increases the proportion of magnesium chromite spinel $MgO \cdot Cr_2O_3$, reduced in the high temperature region [15, 17]. This has an unfavorable effect on reduction processes occurring within a ferroalloy furnace during test melts of high-carbon ferrochrome of the second and third stages. Slag composition is mainly determined by the chromium ore composition. It is seen from Table 3 that with an increase in the proportion of chromium ore briquettes during test melts there is an increase in the magnesium oxide content (from 28 to 41%) and a reduction in aluminum oxide (from 26 to 17%), whereas the silicon dioxide content remains at the required level (from 29–33.4%). This is confirmed by the dynamics for change in final electrothermal high-carbon ferrochrome slag composition, presented in Table 2, from which it is seen that the MgO/Al_2O_3 ratio increases in the second stage to 2.25 and in the third stage to 2.37.

A reduction in the MgO/Al_2O_3 ratio is observed in the fourth and fifth test melt stages. It is possible to explain the reduction in MgO/Al_2O_3 ratio by the fact that in the fourth and fifth test melt stages considering the abovementioned phase composition the amount of fluxes (quartzite screenings) started to be reduced. In conducting test melts in the second and third stages excess fluxes were observe, and therefore the amount of fluxes was reduced gradually from 200 kg/ton in the second stage to 106 kg/ton in the fifth period. Therefore in the fifth period it returned the basic amount of fluxes.

Table 3
High-Carbon Ferrochrome Slag Chemical Composition for Test Period

Melting periods	Component content, wt.%						MgO/Al_2O_3
	SiO_2	MgO	Al_2O_3	CaO	FeO	Cr_2O_3	
stage 1	33.4	28.0	26.1	1.14	1.73	6.5	1.07
	31.0	36.4	24.1	1.02	1.26	4.5	1.51
stage 2	36.0	38.2	18.7	2.5	0.78	4.1	2.04
	35.9	38.5	17.1	2.9	1.6	6.8	2.25
stage 3	37.4	40.4	17.0	3.3	0.61	3.7	2.37
	36.0	41.0	18.0	1.26	0.20	4.8	2.27
stage 4	29.9	28.1	24.9	1.05	1.47	6.14	1.12
	29.3	30.3	22.1	1.13	1.25	5.17	1.35
stage 5	29.5	29.4	24.5	1.83	1.04	4.73	1.20
	29.2	28.3	25.6	1.46	1.02	4.57	1.10

Use of chromium ore briquettes in producing chromium ferroalloys makes it possible to draw on metallurgical conversion of high-magnesia chromite materials containing 17–22% MgO with concentrations of 7-9% Al_2O_3. It is well known from [4, 18] that a certain alloy composition with respect to chromium and carbon content corresponds to the determined slag composition. An increase in magnesium concentration in slag leads to an increase in chromium loss with slag. A significant amount of chromium may be lost in the form of metal phase. This is connected with deterioration of physicochemical properties of the high-magnesia slags formed. As authors in [19–21] conform, with an increase in MgO in slag there is an increase viscosity and electrical conductivity. However, test experience demonstrated the expediency of using high-magnesia chromium ore briquettes.

In order to use this material it is necessary previously to screen briquettes, i.e., to exclude fine fractions 0–10 mm and it is expedient to use fluxes to avoid undesirable problems in the production process. With use of flux, i.e., quartzite screenings in the second stage of testing, an excess of flux was observed, which was characterized by a reduction in slag melting temperature. Metal emerges from the furnace "cold" in view of its inadequate heating, and due to readily melting slag this metal is "bounced" into a ladle, increasing the carbon content in alloy in view of the low temperature of the process, and reduction of chromium oxides proceeds to carbides with an increase in carbon content (Table 2). Excess flux is also confirmed by data in Table 3, from which it is seen that the slag silica content is high. In the second stage silica in slag increases to 35-9–36.0%, and in the third stage to 37.4%.

By analyzing data in Table 3 it may be proposed that during performance of test melts (2nd and 3rd melting stages) a diffusion nature is observed for slowdown in the chromium ore briquette reduction reaction. This phenomenon may be explained as follows: the main flux component (quartzite screenings) is silica, and also alumina. Silica accelerates the reduction of silicon and chromium oxides. With frontal reduction of iron and chromium oxides by carbon around grains of chromium ore chromium spinelid and briquettes there is formation of a metal-slag shell. Its thickness depends upon the ore structure, temperature, time, and degree of reduction [22]. This shell is a metal-slag barrier for development of reduction through the depth of chromium ore grains. It is seen from Table 3 that within the slag chemical composition of high-carbon ferrochrome a reduction in SiO_2, MgO, and Al_2O_3 is observed within slags in the fourth and fifth stages. This is connected with the fact that silica and alumina, contained within the quartzite screenings composition, during reduction are dissolved in refractory and viscous slag-forming oxides, i.e., products developing with reduction of chromium spinelid. As a result of this at a contact surface there is formation of readily melting and liquid-mobile slags. These slags readily breakdown a slag diffusion barrier and expose the surface of chromium spinelid nuclei for new contact between iron and chromium oxides with carbon.

Therefore, silica, contained with quartzite screenings, reducing a diffusion barrier formed with frontal reduction of ore grains, facilitates more complete and intense reduction of iron and chromium oxides.

CONCLUSION

Test-industrial experience has demonstrated that solution of the problem of processing high-magnesia chromite raw material should be aimed at finding the optimum slag regime, with expansion of questions of ore preparation of fines using the same high-magnesia ores with selection of the optimum fluxing materials. Use of different fluxing additives will have a favorable effect on final slag properties, improving their physicomechanical properties, and thereby facilitating reduction of chromium from oxides melts.

In spite of low strength, use of chromium briquettes after screening a test batch of briquettes in the fourth and fifth stages made it possible to increase furnace productivity from 186.2 to 191.4 tons, to reduce the specific electrical energy consumption from 7201 to 6184 kW·h/ton compared with the main period, to reduce the amount of chromium ore used, and to decrease the amount of reducing agent. Also during development of the production regime for melting ferrochrome furnace power of 55 MW was only reached in the fifth stage of testing.

In order to reduce energy expended in the melting process for high-carbon ferrochrome it is expedient to conduct preliminary raw material preparation (with performance of complete screening of fraction 0–10 mm), using for this purpose chromium ore briquettes with flux additives in the quartzite screenings in an optimum amount facilitating more complete and intense reduction of chromium and iron oxides.

Therefore, test industrial melts have demonstrated the expediency of using chromium ore briquettes in large and powerful ore reduction furnaces with power of 63 MW.

REFERENCES

1. L. P. Gal'perin, O. V. Zayakin, and Ya. I. Ostrovskii, "Features of production of high-carbon ferrochrome from chromium ore raw material of different forms," *Stal'*, No. 11, 47–49 (2003).
2. V. I. Zhuchkov, L. P. Gal'perin, and V. B. Kashin, "Chromium-containing raw material lump formation," *Élekrometallurgiya*, No. 9, 35-42 (2003).
3. *Russian Raw Material Complex. Chromium Ores. Information Analytical Center "Mineral"* [Electronic source] Access regime http: // www.mineral.ru /Facts/Russia/161/549/3_06_cr.pdf. (Referral date 26.01.2023).
4. E. É. Abdulabekov, V. I. Grinenko, and D. D, Izbembetov, "production of chromite pellets for melting high-carbon ferrochrome," *Stal'*, No. 5, 39–41 (2003).
5. O. V. Zayakin, L. I. Leont'ev, and V. I. Afanas'ev, "Production aspects of suing of lean chromium-containing ores," in: Coll. Sci.-Pract. Conf. "Prospects of Developing Metallurgy and Engineering Using Improved Fundamental Research in NIOKR" [in Russian], IMET UrO RaAN, Ekaterinburg (2013), pp. 118–122.
6. A. Zhunusov, L. Tolymbekova, Ye. Abdulabekov, Zh. Zholdubayeva , and P. Bykov, "Agglomeration of manganese ores and manganese containing wastes of Kazakhstan," *Metallurgija*, No. 60 (1–2), 101–103 (2021).
7. J. Pal, D. Bandyopadhyay, D. P. Singh, and S. Ghosh, "A comparative study for smelting of chromite ore, pellets, briquettes and sinter," *Mineral Processing and Extractive Metallurgy*, **117**, No. 3, 129–136 (2008); DOI: 10.1179/174328508X283469.

8. V. I. Grinenko, P. S. Petlyukh, T. D. Takenov, et al., "Assimilation of melting technology for high-carbon ferrochrome using briquetted fine chromite ore," *Stal'*, No. 12, 28–30 (2001).
9. A. Magdziarz, M. Kuźnia, M. Bembenek, et al., "Briquetting of EAF dust for its utilization in metallurgical processes," *Chemical and Process Engin.*, **36**, No. 2, 263–271 (2015).
10. I. Yu. Ryvkin, A. Ya. Eremin, E. M. Litvin, and V. I. Babanin, "Briquetting fine-grained and finely dispersed materials with binder," *Koks i Khimiya.*, No. 10, 36–43 (2000).
11. A. Ya. Eremin and V. I. Babanin, "Change in physicomechanical properties of mixtures of fine-grained materials with binders in preparation and compaction stages during briquetting," *Koks i Khimiya.*, **4**, 17–26 (2003).
12. L. Khoroshavin, "Metallurgical briquettes of a new generation reduce metal melting duration," *Ural. Rynok Metallov,* No. 7, 39–42 (2006).
13. V. V. Ozhogin, A. A. Tomash, and I. A. Kovalevskii, "Briquetting as a correct method for lumping metallurgical raw material," *Metall. Protsess. Oborud.,* No. 2, 54–58 (2005).
14. A. V. Sivtsov, D. K. Egiazar'yan, O. Yu. Sheshukov, et al., "Methods for controlling parameters of electric arc characteristics and use in evaluating the efficiency of using briquetted metallized scale for steel smelting," *Metallurg,* No. 1, 16–22 (2022).
15. E. Zh. Shabanov, D. D. Izbembetov, S. O. Baisanov, et al., "Production technology for high-carbon ferrochrome using single charge briquettes," *Izv. Vuz. Chern. Met.,* No. 61(9), 695–701 (2018).
16. A. M. Bizhanov, I. F. Kurunov, N. M. Durov, et al., "Briquette extrusion (bricks) for producing ferroalloys," *Metallurg.,* No. 12, 52–57 (2012).
17. V. I. Grinenko, O. I. Polyakov, and M. I. Gasik, *Kazalhstan Chromium* [in Russian], Metallurgiya, Moscow (2001).
18. M. Sh. Kats, V. P. Trabina, and P. P. Aganichev, "Study of reducing capacity of high-magnesia chromium ores of the Aktyubinsk deposit," *Stal'*, No. 10, 911–912 (1974).
19. V. I. Grinenko, P. S. Petlyukh, T. T. Takanov, et al., "Assimilation of electrothermal technology for high-carbon ferrochrome using pellets of chromium ore fines in AO Ferrokhrom," *Prom. Kazakhstana,* No. 4, 74–76 (2000).
20. I. S. Ostrovtseva, "Effect of slag composition and properties of carbon ferrochrome on degree of chromium extraction," in: *Chromium Ferroalloys* [in Russian], Metallurgiya, Moscow (1986), pp. 48–53.
21. N. L. Zhilo, I. S. Ostretsova, V. G. Mizin, et al., "Physicochemical properties of carbon ferrochrome slags," *Stal',* No. 3, 35–39 (1983).
22. Kh. N. Kadarmetov, "Control of metal-slag barrier during reduction of chromium ore with carbon," *Proizvod. Ferrosplavov,* No. 6, 5–13 (1978).