

Article

Pilot Tests of Pre-Reduction in Chromium Raw Materials from Donskoy Ore Mining and Processing Plant and Melting of High-Carbon Ferrochromium

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Abstract: Experiments were conducted to pilot the initial reduction in chromium raw materials using the innovative Hoganäs technology in a tunnel furnace. To simulate the process, a gas-fired bogie hearth furnace was employed. Technological containers made of silicon carbide crucibles were utilized. Sixteen different combinations of ore and coal mixtures were employed for the initial reduction process. Their total mass was more than 20 tons. Their heat treatment was performed at different temperatures and durations. During the pilot tests, the possibility of achieving chromium metallization was confirmed. Thus, it explains the application of a pre-reduction instead of the sintering or charge heating before the ferrochromium melting, i.e., the power consumption is minimized during the final remelting of the product in DC furnaces. The pilot melting of three batches of the pre-reduced chromium raw materials with various chromium metallization degrees has been tested in the ore-smelting furnace at Zh. Abishev Chemical–Metallurgical Institute (Karaganda). The capacity was 0.2 MVA. To evaluate the technical and economic efficiency of remelting pre-reduced chromium raw materials in commercial DC furnaces, a specific batch of primary ingredients for producing high-carbon ferrochromium, including chromite ore, coke, and quartz flux, was successfully melted in a segregated phase. As a result of the study, it was found that the specific energy consumption for melting high-carbon ferrochromium in the pilot furnace depends on the chromium metallization degree. The researchers tested a range of chromium metallization degrees from 0 to 65% and determined the corresponding specific energy consumption for each degree. Using the data obtained from the study, the researchers were able to assess the melting indexes of high-carbon ferrochromium in a larger 72 MW furnace. They found that by using a pre-reduced product with a chromium metallization degree of 65%, it was possible to reduce the specific energy consumption by half, to around 3.4 MW·h per ton of chromium. Overall, this study highlights the importance of considering the chromium metallization degree when determining the specific energy consumption for melting high-carbon ferrochromium. By optimizing the metallization degree, significant energy savings can be achieved, leading to more efficient and sustainable production processes.

Keywords: pre-reduction; ferrochromium; Hoganäs; bogie hearth furnace; metallization degree; ore-smelting furnace; direct current furnace



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1. Introduction

Throughout the production of ferrochromium in ore-smelting furnaces using chromium raw materials, approximately 50% of the heat utilized for melting is expended on endothermic reactions involved in metal reduction. Due to the high temperature necessary for

liquid-phase chromium reduction within the ore-smelting furnace, electricity has been deemed a reasonable heat source. However, electricity currently stands as the most expensive widely-used heat source in the industry per unit of heat energy [1,2].

The ore-smelting furnace itself is a complex and costly unit, with an increase in capacity leading to significant economic benefits. It has been observed that the utilization of a metalized product, derived from enriching metal concentrates in slag and varying in quality within the charge of the ore-smelting furnace, results in decreased specific energy consumption for melting ferroalloys, alongside an increased furnace capacity. Consequently, the introduction of partially or fully reduced material into the ore-smelting furnace for remelting purposes will reduce specific energy consumption for ferrochromium melting and enhance its capacity [3–13].

The objective of this simulation was to determine the impact of preheating and pre-reduction on power consumption for melting high-carbon ferrochromium sourced from different raw materials using the ore-smelting furnace and direct current furnace. It is noteworthy that during the preheating, sintering, and pre-reduction in the charge, the material loaded into the furnace reached a temperature of 800 °C. Figure 1 illustrates the other initial values. South African chromites and Kazakhstan chromites significantly differ in terms of chromium/iron ratio and basic slag-forming oxides. It is important to highlight that the chromium oxide content in Kazakhstan chromite amounts to 59%. Hence, this concentrate produced from a section of ores from the Vostok-chromium deposit occurrence exhibits specificity.

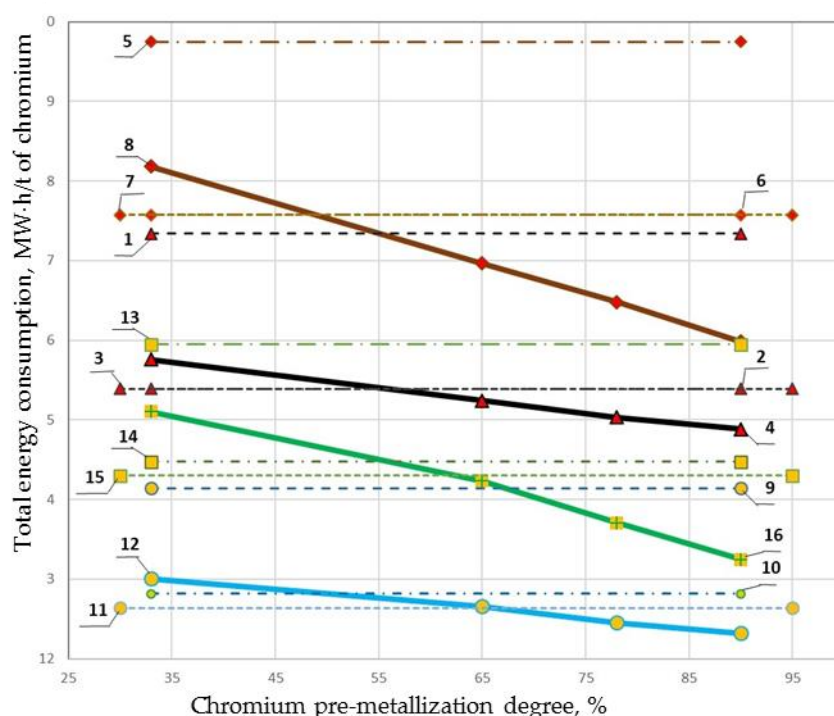


Figure 1. The total energy consumption for melting high-carbon ferrochromium through pre-reduction is influenced by the level of chromium pre-metallization in both the ore-smelting furnace and DC furnace. Reprinted with permission from ref. [14]. 2022 Springer Nature.

Table 1 results in the calculation of the power consumption as described in [14]. Materials used in [14] have been supplemented by our calculated data on the total power consumption, including the power consumption with a coefficient of efficiency of 40%. The schemes of the metallurgical coke used as reducing agent and fuel for the annealing and sintering processes have been supplemented by the power consumption for coking in accordance with the data described in [15–21].

Table 1. The calculated power consumption for various process schemes of the melting of the high-carbon ferrochromium (MW·h/t of chromium).

No	Origin	Furnace Type	Process Scheme	Heating (by Waste, Gas)	Power Consumption, MW·h/t of Chromium			Total Power Consumption including a Coefficient of Efficiency from the Source, MW·h/t of Chromium	Total Power Consumption including a Coefficient of Efficiency from the Source, MW·h/t of Alloy
					Pre-Reduction	Melting	Supplementary		
1	South African chromites	Ore-smelting furnace	Standards	26 °C	-	6.58	0.84	17.3399	7.984
2			With charge heating	T of carrier gas 850 °C	-	6.02	0.945	16.02	8.05
3			With sintering	-	-	6.1	1005	16.2	8.1
4			Pre-reduction by 32.98%	-	3.31	4.98	-	15.76	7.66
			Pre-reduction by 64.8%		5.49	3.90	-	15.24	7.34
			Pre-reduction by 79.2%		6.58	3.38	-	15.03	7.20
			Pre-reduction by 90%		7.81	2.83	-	14.89	7.09
5		DC furnace	Standard	25 °C	-	7.90	-	19.75	10.00
6			With charge heating	T of carrier gas 800 °C	-	7.03	-	17.58	8.90
7			With sintering	-	-	7.03	-	17.58	8.90
8			Pre-reduction by 32.98%	-	3.31	5.95	-	18.19	8.84
			Pre-reduction by 64.8%		5.49	4.59	-	16.97	8.17
			Pre-reduction by 79.2%		6.58	3.96	-	16.48	7.90
			Pre-reduction by 90%		7.81	3.27	-	15.99	7.59
9	Kazakhstan chromites	Ore-smelting furnace	Standard	25 °C	-	5.32	0.83915	14.14	9.48
10			With charge heating	T of carrier gas 800 °C	-	4.79	0.83915	12.81	8.59
11			With sintering	-	-	4.72	0.83915	12.64	8.47
12			Pre-reduction by 32.98%	-	2.23	4.31	-	13.01	8.72
			Pre-reduction by 64.8%		4.16	3.40	-	12.66	8.40
			Pre-reduction by 79.2%		5.18	2.91	-	12.46	8.21
			Pre-reduction by 90%		6.37	2.38	-	12.32	8.06
13		DC furnace	Standard	25 °C	-	6.38	-	15.95	11.18
14			With charge heating	T of carrier gas 800 °C	-	5.79	-	14.48	10.13
15			With sintering	-	-	5.72	-	14.30	10.00
16			Pre-reduction by 32.98%	-	2.23	5.15	-	15.11	10.12
			Pre-reduction by 64.8%		4.16	4.03	-	14.24	9.43
			Pre-reduction by 79.2%		5.18	3.41	-	13.71	9.04
			Pre-reduction by 90%		6.37	2.75	-	13.25	8.66

According to the information presented in Table 1, it is evident that the utilization of a pre-reduction process for chromium raw materials in ore-smelting and DC furnaces results in the most efficient power consumption. Specifically, schemes incorporating South African and Kazakhstan chromites displayed the lowest total power consumption, with a chromium reduction rate exceeding 65%. The scheme with pre-reduction in the case of Kazakhstan chromites in ore-smelting furnaces has demonstrated that power consumption is lower than at the chromium metallization degree of 78%.

The scheme of DC furnace with using South African chromites has showed the lowest energy consumption during the application of chromium raw materials with a metallization degree of 65%. It has been observed from 3.47% compared with the sintering and charge heating to 14% with the standard process scheme.

It should be noted that the calculation was conducted for Kazakhstan chromites which contain 59.2% chromium oxide, as specified in [14].

In practical terms, the majority of chromium raw materials utilized in the production of ferro-chromium in Kazakhstan and Russia typically contain chromium oxide levels of up to 52%. As a result, the calculation outcomes differ. The characteristics of Kazakhstan chromites closely resemble those of South African chromites. Consequently, they are primarily used for the ore-smelting furnace and DC furnace, where a lower grade ore is suitable.

Figure 1 demonstrates the relationship between the overall power consumption and the degree of pre-reduction in the material for all investigated process schemes, based on the data presented in [14].

Where 1—South African chromites in ore-smelting furnace, standard; 2—South African chromites in ore-smelting furnace, with charge heating; 3—South African chromites in ore-smelting furnace, with sintering; 4—South African chromites in ore-smelting furnace, pre-reduction; 5—South African chromites in DC furnace, standard; 6—South African chromites in DC furnace, with charge heating; 7—South African chromites in DC furnace, with sintering; 8—South African chromites in DC furnace, pre-reduction; 9—Kazakhstan chromites in ore-smelting furnace, standard; 10—Kazakhstan chromites in ore-smelting furnace, with charge heating; 11—Kazakhstan chromites in ore-smelting furnace, with sintering; 12—Kazakhstan chromites in ore-smelting furnace, pre-reduction; 13—Kazakhstan chromites in DC furnace, standard; 14—Kazakhstan chromites in DC furnace, with charge heating; 15—Kazakhstan chromites in DC furnace, with sintering; and 16—Kazakhstan chromites in DC furnace, pre-reduction.

The dotted lines represent the total power consumption of standard technology, sintering schemes, and charge heating in order to accurately determine the degree of pre-reduction in the product. The power consumption for chromium production is the same for all these methods. The total power consumption for chromium pre-reduction in ore-smelting furnaces and DC furnaces is lower compared to sintering schemes and charge heating methods once a certain pre-reduction degree is reached. Figure 2 shows that the maximum pre-reduction degree for melting high-carbon ferrochromium can be achieved with the lowest power consumption.

In order to minimize energy consumption in ferro chromium production, the pre-reduction degree of chromium before remelting in ore-smelting furnaces and DC furnaces should be high, at least 50% or above. Otherwise, the process schemes involving sintering (for ore fines) and heating (for lump ore) will result in lower energy efficiency.

Currently, the industrial implementation of chromium pre-reduction is carried out in South Africa and China using the Premus process. This process involves pelletizing crushed chromium raw materials (Cr_2O_3 —37.1%, $\text{Cr}/\text{Fe} = 2.5$) and anthracite, followed by annealing the pelletized mixture on a fire grate and pre-reduction in the calcined pellets in a rotary tube furnace. Crushed anthracite is used as fuel.

The hot semi-product obtained is then placed into an electric furnace, where chromium and iron are further reduced by coke. This process results in the production of chromium charges with a chromium content of 52–55%. According to published data, the iron

metallization degree reaches approximately 90%, while the chromium reduction degree is around 50% during the solid-phase reduction stage. However, compared to traditional technology, the specific energy consumption per ton of ferrochromium decreases from 4.1 to 2.4 MW·h/t and coke consumption is reduced by 60%.

Different ratios of chromium to iron in various chromite types must be considered when selecting the pre-reduction technology. Figure 2 illustrates the relationship between chromium reduction degree and iron reduction degree for Kazakhstan chromites based on data described in [7].

The Figure 2 shows that the chromium reduction degree for Kazakhstan chromite with an iron reduction degree of 90% is only 30–40%, which is lower than the percentage mentioned in [10] based on experience with the Premus process. This suggests that Kazakhstan solid chromites are less effectively reduced compared to South African chromites. Based on the lower iron content of Kazakhstan chromites compared to South African chromites, more stringent reduction conditions would be required to achieve the comparable pre-reduction rates for pre-reduction in South African chromites [14].

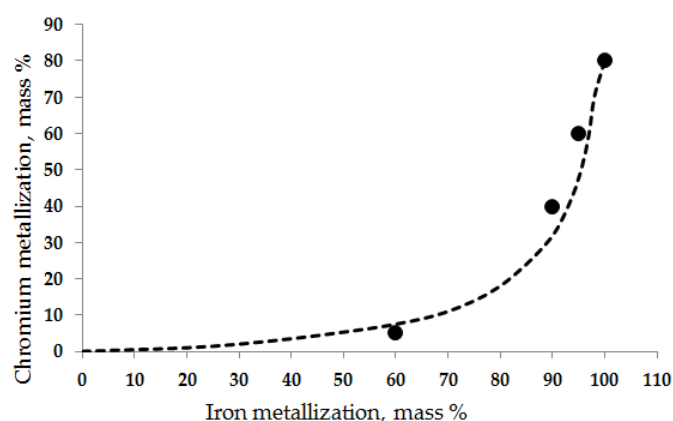


Figure 2. The calculated ratio between the metallization of Fe and Cr during the preliminary reduction in Kazakhstani chromites. Reprinted with permission from ref. [14]. 2022 Springer Nature.

Additionally, the use of alternative methods for pre-reduction, such as closed-space reactors, should be explored to avoid the formation of carbon dioxide. These alternative methods could potentially provide a more suitable environment for the reduction process, leading to higher chromium reduction degrees in the briquettes.

Further studies should also investigate the potential effects of varying parameters such as temperature, pressure, and composition of the reducing agents on the pre-reduction process. This would contribute to a better understanding of the Fe and Cr metallization ratios and their influence on the reduction degree of chromium in Kazakhstan chromites.

In 2014, the fourth melting shop at Aktobe ferroalloy plant was built and equipped with DC furnaces. It is focused on processing the ore fines without pelletizing. Due to the lack of the stringent requirements for the size of raw materials in DC furnace, the pre-reduced product without pelletizing can be processed. Therefore, for the 4th melting shop at Aktobe ferroalloy plant, the preferred pre-reduction technique should first provide the maximum chromium metallization degree. The existing and potential technologies of pre-reduction in chromium raw materials have been analyzed at the ERG Research and Engineering Center LLP. As a result, the Hoganas technology of the solid-phase reduction in a tunnel furnace compared with other methods has the following advantages:

- The long heat treatment time can increase the overall process duration and potentially reduce production efficiency;
- The high consumption of crucibles made of silicon carbide can lead to increased costs and potentially impact the economics of the process;
- The process may require additional equipment or modifications to existing equipment to accommodate the application of ore fines without pelletizing;

- The elimination of contact between the charge and oxidizing gases may require careful control and monitoring to ensure the desired reduction rate is achieved;
- The opposite-flow of material and gases may require design considerations to optimize thermal efficiency and minimize heat loss;
- The CO reheating process may require additional energy inputs and potentially increase operational costs.

2. Materials and Methods

The pilot tests aimed to evaluate the laboratory indexes of the pre-reduction process of chromium raw materials. The tests were conducted at the experimental shop in Kazogne-upor factory, located in Rudny, Kazakhstan (All ore materials from the city of ERG Co., Khromtau, Kazakhstan).

The chromium raw materials used in the tests were as follows:

- Chromium concentrate of 0–3 mm fraction;
- Chromium ore of 0–1 mm fraction, obtained by sieving from the 0–10 mm ore fraction;
- Dust from the gas cleaning of the ore drying furnace.

To act as a reducing agent, the following carbon-containing materials were used:

- Shubarkol coal of 0–10 mm fraction;
- Shubarkol special coke of 0–5 mm fraction;
- Anthracite of 0–15 mm fraction.

All the ore materials used in the tests remained unchanged. The three types of reducing agents were applied in two size classes, namely 0–0.2 mm and +0.2–1 mm. These size classes were obtained by grinding the materials and subsequent sieving. Chemical and technical analysis of charge materials are given in Tables 2 and 3.

Table 2. Chemical content of ore material, wt.%.

Ore	Cr ₂ O ₃	FeO	SiO ₂	MgO	Al ₂ O ₃	CaO	P	S	C.L.*	W
Concentrate	51.78	13.3	6.35	19.22	7.51	0.011	0.002	0.087	1.49	0.25
Ore	52.1	12.48	6.53	19.73	6.73	0.11	0.0037	0.026	1.84	0.45
Dust	49.02	9.10	11.20	19.95	5.78	0.39	0.012	0.0175	-	0.60

Where: C.L.*—Calcination losses.

Table 3. Technical analysis of carbonaceous reducing agents, wt.%.

Materials *	S	P	W	A	V
Shubarkol coal	0.38	0.0139	14.20	4.30	44.10
Special coke	0.40	0.0348	19.10	11.40	8.20
Anthracite	0.20	0.02	10.05	3.20	9.50

*—A—ash, V—volatile, S—sulfur, P—phosphorus on dry weight basis, W—moisture on working mass.

The main purpose of these tests was to investigate the effect of temperature and hold time on the reduction process of chromium oxide in the ore–coal mixture. The variation range of the parameters was determined based on the results of laboratory and enlarged laboratory tests. The tests were conducted using a high-temperature chamber of a bogie hearth furnace. The furnace had an arch-shaped vault and a working lining made of corundum-mullite refractory. Natural gas was used as fuel and there were six gas burners in the furnace.

During the tests, 10 crucibles with different compositions of the ore–coal mixture were used. Each crucible was loaded with an average of 310 kg of the mixture without compaction. The height of the column of the mixture in the crucible was 1200 mm and the diameter was 450 mm. A silicon carbide lid was used to cover each loaded crucible.

The temperature during the tests was monitored using two tungsten-rhenium thermocouples and a pyrometer through observation holes in the furnace. The temperature was

adjusted by changing the feed rate of the natural gas and air supply to each burner. The gas/air ratio was also adjusted accordingly.

Overall, the tests aimed to study the reduction process of chromium oxide in the ore–coal mixture under different temperature and hold time conditions. The loading and placement of the crucibles simulated a separate trolley in an industrial furnace.

The analysis of the selected samples included measuring the total chromium content, metallic chromium content, and carbon content. This was performed to assess the degree of chromium reduction during the unloading of the crucibles. Samples were taken from different layers of the crucible, including the top, middle, and bottom layers. These samples were also collected from each quarter part of the crucible's height and both the center and periphery of the horizontal section of each level.

To determine the weighted average degree of chromium metallization for each crucible assembly, two parallel samples were taken from the average material of one assembly. The selected samples were then analyzed to measure the total chromium content, metallic chromium content, and carbon content. This analysis would provide information on the degree of reduction in chromium during the heat treatment process.

This analysis is crucial in assessing the success of the heat treatment process and ensuring that the desired degree of chromium reduction is achieved. It helps in understanding the behavior of the material during the heat treatment process and enables adjustments to be made if needed. The chromium reduction degree has been calculated by the formula:

$$\alpha = Cr_{\text{metal}} \times 100\% / Cr_{\text{total}} \quad (1)$$

The information from Table 4 shows the average results of the pre-reduction of chromium raw materials at two different holding times: 35 h and 45 h. The values obtained represent the reduction degree of chromium in two parallel averaged samples. In addition to the average values, the arithmetic mean and standard deviation were also determined for all combinations of the reduced product. These combinations varied in composition, temperature, and holding time during the annealing process [14].

The comparison of the obtained reduction degrees in the two samples allows for an analysis of the effect of holding time on the pre-reduction of chromium raw materials. Further analysis may be conducted to assess the influence of composition and temperature on the reduction process.

Table 4. Average degree of metallization of chrome raw materials. Reprinted with permission from ref. [14]. 2022 Springer Nature.

Temperature of Holding Time	Holding Time, h	
	35	45
1300 °C	40 (+/−8)%	50 (+/−10)%
1350 °C	50 (+/−10)%	60 (+/−10)%
1380 °C	60 (+/−5)%	no test

Based on the test results, it has been found that the use of aspiration dust for pre-reduction is not recommended as it leads to sintering and increased carry-over of dust during heat treatment. Similarly, the use of reducing agents of size 0.2 mm is also undesirable as they tend to segregate in the crucible assembly during reduction.

However, for other ore materials, regardless of their grain composition, the difference in pre-reduction indexes at temperatures of 1350 °C and above is within the margin of error. Therefore, 1 mm or 2 mm screenings obtained by sieving ore fractions of 0–10 mm are recommended for pre-reduction.

The best results for chromium metallization were observed when using Shubarkol coal as a reducing agent. However, mixtures with this coal tend to segregate during heat treatment. The effect of reducing agent size on chromium metallization is minimal at

temperatures of 1350 °C and above and therefore coal with a particle size of 1 mm or 2 mm should be used to simplify charge material preparation.

Thus, achieving the required pre-reduction degree of chromium raw materials of more than 60% is possible with a mixture holding time of 45 h at 1350 °C and 35 h at 1380 °C as illustrated in Figure 2. Therefore, it energetically justifies the application of pre-reduction in comparison with the sintering or heating of raw materials.

The research mentioned in reference [22] shows that using pre-reduced raw materials during the melting process of chromium alloys has several benefits. It leads to a decrease in the specific consumption of electricity and coke, an increase in the capacity of the ore-smelting furnace, and ultimately a reduction in the cost of the finished product. These findings suggest that utilizing a pre-reduction process for South African concentrates prior to melting them for charge-chromium in ore-smelting furnace is a viable and cost-effective approach for producing high-carbon ferrochromium.

The paper of [14] has described a comparative assessment of the power consumption of ferrochromium melting using some process schemes, including charge heating and sintering or pre-reduction with subsequent remelting in an ore-smelting furnace and direct current furnace. Two South African and Kazakhstan ores have been assessed. Based on the results of the assessment [14], the direct energy consumption to melt the high-carbon ferrochromium in DC furnace from 90% pre-reduced Kazakhstan raw materials at a temperature of 800 °C is reduced from 6.4 to 2.8 MW·h/t of chromium. Chromium oxide content in Kazakhstan ore was 59.2%. It is not typical for the practice of melting the high-carbon ferrochromium in Kazakhstan (usually up to 52%). Therefore, it will influence on the actual melting rates of the high-carbon ferrochromium and increase the specific consumption of electricity [23–26].

Four DC furnaces with a 72 MW capacity are each currently in operation at Aktobe ferroalloy plant. They are designed to melt the high-carbon ferrochromium from ore fines. They can be used to remelt the pre-reduced raw materials.

The use of the data in [14] to predict the remelting rates of pre-reduced raw materials in the DC furnace at the Aktobe ferroalloy plant is not quite correct due to the above-mentioned reason according to the chromium oxide content in the raw material adopted for calculations. The results of the pilot tests showed that the pre-reduced product had varying degrees of chromium metallization. The total weight of the product from the 60 crucibles was 13.44 tons. The weighted average metallization degree for each batch is presented in Table 5.

Table 5. Mass and weighted average chromium metallization degree in pre-reduced material.

Batch by Metallization Degree	Total Weight of Batch, kg	Weighted Average Metallization Degree, %
minimum degree	4582	39.40
medium degree	5038	53.73
maximum degree	3816	65.08

During the remelting process of the pre-reduced product, a similar amount of quartzite as in the base period was added to the charge, along with a small amount of coke to prevent oxidation of the metals. The amount of coke added to the charge was determined experimentally based on the chromium content in the slag, which was maintained at 5%.

It is worth noting that the composition of the pre-reduced product varied depending on the type of chromium raw materials used. The concentrate of the 0–3 mm fraction and the 0–1 mm ore sieve of the 0–10 mm fraction had similar compositions and ratios of the main components. However, the aspiration dust from the bag filters of the ore-smelting furnace had a noticeably different composition, with a lower content of oxides of chromium, iron, and aluminum but a higher content of oxides of silicon and magnesium [27–31].

Overall, these pilot tests aimed to assess the remelting indexes of the pre-reduced product in the DC furnaces at the Aktobe ferroalloy plant. The results of these tests would

provide valuable insights into the energy consumption and efficiency of the DC furnaces when using pre-reduced products.

In order to remelt such a quantity of pre-reduced product, the pilot ore-smelting furnace has been used at Zh. Abishev Chemical–Metallurgical Institute (Karaganda, Kazakhstan). These molds are connected to a water cooling system to rapidly cool the melt and solidify it into desired shapes. The cascade design allows for continuous production as one mold is filled while others are being cooled. The cooled molds can then be opened and the solidified metal shapes can be removed. This setup ensures efficient and consistent production of castings from the furnace.

Figure 3 provides a general view of the pilot furnace during the pilot tests. It likely shows the setup of the furnace, including its structure, components, and any additional equipment used during the tests. This figure may also depict the size and location of the furnace within the experimental setup.



Figure 3. Ore smelting furnace with a capacity of 200 kVA: (a) view of the furnace top and (b) release of metal into a cascade of molds. Reprinted with permission from ref. [15]. 2023 Springer Nature.

On the other hand, Figure 4 displays the melting products resulting from the pilot tests. It could show the material that has been melted, such as metals or minerals, and any changes in their physical properties. The figure may also showcase the state of the melted substances, such as their viscosity or color, providing insights into the effectiveness of the pilot furnace in achieving the desired melting outcomes.



Figure 4. Products of smelting high-carbon ferrochrome in a pilot furnace: (a) metal and slag ingots in a mold and (b) metal after cooling.

During each stage, various parameters such as power consumption, melting rate, and the quality of the final product were monitored and analyzed. The goal of these pilot tests was to evaluate the feasibility and efficiency of using pre-reduced products in the melting process of high-carbon ferrochromium.

In the first stage, the traditional charge was used and the focus was on developing optimal furnace operation modes to achieve the desired melting results. The data collected during this stage served as a baseline for comparison with the subsequent stages.

The second stage involved the continuation of the traditional charge and further collection of pilot data. This allowed for a more comprehensive understanding of the melting process and helped identify areas for improvement [32–35].

In the third and fourth stages, pre-reduced products with different chromium metallization degrees were used as the charge material. This allowed for a comparison of the melting performance and quality of the final product using different degrees of pre-reduction.

Finally, in the fifth stage, the charge material with an average chromium metallization degree was used. This provided insight into the optimal degree of pre-reduction for achieving efficient melting and high-quality ferrochromium.

Overall, these pilot tests provided valuable data and insights into the melting of high-carbon ferrochromium using pre-reduced products. The results obtained will help inform the development of more efficient and sustainable melting processes in the future.

During the remelting process, the charge is divided into portions based on material charges. Each material charge requires 20 kg of chromium-containing product. The pre-reduced product from two crucibles with the lowest and highest chromium metallization degree in the current batch was fed into the furnace proportionally to their weight. This process continues until the output of the product from the first two crucibles is complete. Then, the next pair with the maximum difference in metallization degree in the remaining batch is used [36–39].

In the first stage of melting, the melting modes for high-carbon ferrochromium are worked out. This includes determining the transformer stage, melting duration, and volume of the single loading of charge materials, among other factors. However, during this stage, there were issues with metal freezing on the hearth above the tap-hole level and the melt crucible narrowing in the furnace.

During the furnace's hot run, it was challenging to separate the energy consumption for melting the skull on the hearth and expanding the melt crucible from the consumption of melting the high-carbon ferrochromium from a single charge batch. As a result, reliable values for the specific energy consumption for melting the high-carbon ferrochromium were not obtained during the first stage.

The increased disruptions during the stages of remelting the pre-reduced product are mainly attributed to the composition of the ore dust used in the gas cleaning process. This ore dust was found to be significantly different from other chromium raw materials used in the production of the pre-reduced product.

Pilot tests of pre-reduction showed that the mixture of drying dust and reducing agent, which had a particle size less than 0.2 mm, could segregate materials based on crucible height and remove carbonaceous particles from outside the crucible. This resulted in an uncontrolled lack of carbon in the pre-reduced product, which is essential for chromium reduction during remelting. It also made it challenging to determine the appropriate amount of reducing agent to add for each melting [40].

Furthermore, the change in the content of slag-forming components in the charge containing the pre-reduced product from the ore drying dust necessitated an additional supply of quartzite and reducing agent compared to other mixtures. Overall, the specific composition of the ore dust used in the pre-reduced product was causing disruptions in the remelting process, requiring adjustments in the carbon content and the supply of quartzite and reducing agent.

The analysis was conducted in three stages, specifically at stages 2, 3, and 4. During these stages, a continuous series of 10–15 stable melts were separated for further analysis.

Various factors such as changes in the skull level on the hearth, the size of the melting crucible in the furnace, and problems with the release of the melt were not observed during these stages.

The specific energy consumption was determined based on average data from these series, considering the metallization degree of the pre-reduced product. The obtained results allowed for the calculation of the specific energy consumption required for melting high-carbon ferrochromium in the DC furnace at melting shop No. 4 of the Aktobe ferroalloy plant, depending on the product's metallization degree.

Throughout the entire remelting period, a total of 291 melts were produced, resulting in the production of 7056.6 kg of high-carbon ferrochromium, which met the requirements specified in GOST 4757-91.

The graph in Figure 5 shows the results of melts of ore and pre-reduced chromium raw materials and the calculated data on the specific energy consumption in the DC furnace at Aktobe ferroalloy plant. The calculations were performed for an average furnace capacity of 60 MW [36,37].

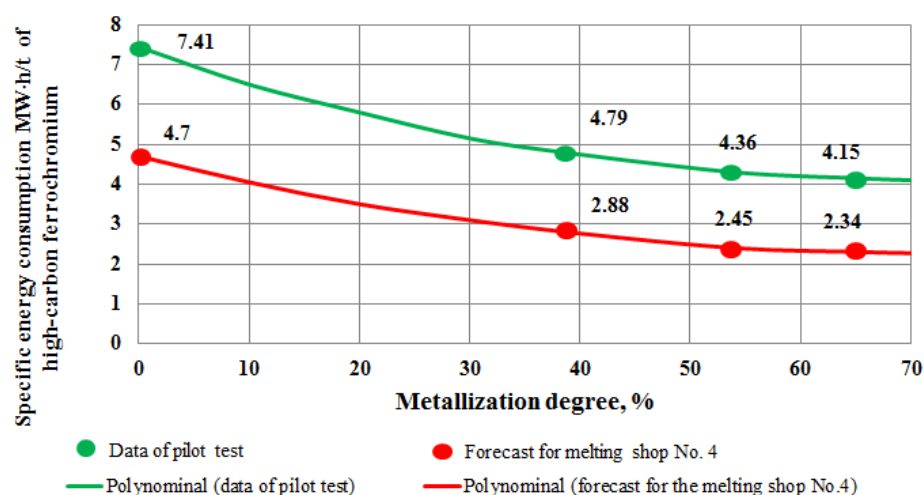


Figure 5. Dependence of specific energy consumption on the metallization degree of pre-reduced product during melting of high-carbon ferrochromium.

The graph reveals a clear correlation between the chromium metallization degree in the chromium raw material and the specific energy consumption for melting of the high-carbon ferrochromium. This means that as the chromium metallization degree increases, the specific energy consumption for melting the high-carbon ferrochromium decreases.

This correlation is important because it indicates that improving the chromium metallization degree in the chromium raw material can lead to a reduction in energy consumption during the melting process. This can have significant benefits for the efficiency and cost-effectiveness of the ferroalloy production at Aktobe ferroalloy plant.

The specific energy consumption of the pilot 0.2 MVA furnace decreased by a factor of 1.79 during the melting of high-carbon ferrochromium compared to the power consumption during the remelting of chromite ore. This means that the furnace is more efficient and requires less energy to melt the high-carbon ferrochromium [41].

Based on this improvement, the forecasting specific energy consumption in the DC furnace at the Aktobe ferroalloy plant was reduced by half. This indicates that the energy consumption for melting high-carbon ferrochromium in the larger DC furnace at the plant will be significantly lower compared to the energy consumption for remelting chromite ore (the basic stage).

Overall, these improvements in specific energy consumption for the pilot furnace and the forecast for the DC furnace at the plant indicate that the Aktobe ferroalloy plant will see significant energy savings and increased efficiency in their ferrochromium melting process.

Results of pilot tests and their calculations were more optimistic than predicted. The lower power consumption obtained in the actual result could be due to several factors. Firstly, the use of actual rates of the DC furnace during the remelting charge may have resulted in more efficient energy usage compared to the calculated rates. Additionally, the presence of moisture in the charge may have contributed to a more efficient melting process, as the heat generated during the melting can potentially be used to evaporate the moisture, thus reducing the overall energy consumption.

Furthermore, the addition of quartzite and bauxite as a flux may have contributed to a reduction in the energy required for melting. Quartzite is known to have a high thermal conductivity, which can enhance heat transfer and reduce the energy needed for melting. Bauxite, on the other hand, has a high alumina content that can form a protective layer on the lining of the furnace, reducing wear and potential heat losses.

Lastly, the use of air-dry materials instead of materials with a high moisture content and the omission of bauxite in pilot tests may have resulted in a more efficient melting process. Moisture in the charge can potentially absorb heat, leading to higher energy consumption, while the presence of bauxite as a flux may have contributed to improved heat transfer and reduced energy losses [30].

Overall, the combination of using actual rates, the presence of moisture, and the addition of fluxes in the actual process may have contributed to the lower power consumption observed in the obtained result compared to the calculated value.

The great difference has been also observed in comparison with the data described in [7]. Referring to this study, the specific energy consumption during the remelting of pre-reduced product of 65% in DC furnace was 2.67 MW·h/t of high-carbon ferrochromium. The pre-reduced product was supposed to be produced from Kazakhstan chromites with a chromium oxide content of 58.97%. For calculation, it had a temperature of 800 °C before the supply in the DC furnace. In this case, two reasons could be for the apparent discrepancy as follows:

- The product pre-reduced by 65% has a lower metallic chromium content compared to the product with a pre-reduction degree of 65%. The assessment of the product pre-reduction degree is based on the ratio of metallic chromium content to the total chromium content in the charge. According to the research paper referenced, the pre-reduction degree is estimated as a fraction of the total reduction, which is the mass loss associated with the reduction in chromium and iron oxides to metal. It can also be assessed as a fraction of the oxygen removed from the ore related to chromium and iron;
- The studies mentioned in the passage compare the specific energy consumption for melting high-carbon ferrochromium using different methods. The first method described is the melting of high-carbon ferrochromium in skull furnaces using Kazakhstan chromite. This method resulted in a specific energy consumption of 4.47 MW·h/t with a chromium oxide content of 59.2%.

The second method discussed is the melting of chromite with a chromium oxide content of 59.2% in a DC skull-free furnace at the Aktobe ferroalloy plant. This method had a specific energy consumption of 4.22 MW·h/t of high-carbon ferrochromium. However, it should be noted that the raw materials supplied for this method had a chromium oxide content that did not exceed 52%. The specific energy consumption in this case was 4.76 MW·h/t of high-carbon ferrochromium.

The studies conclude that using pre-reduced raw materials with a low metallization degree (below 50%) is less effective than using the pelletizing processes with annealing and heating of the charge [25].

In general, the pilot tests have determined the dependence of specific energy consumption for melting of the high-carbon ferrochromium on the chromium metallization degree in the pre-reduced product. The application of the pre-reduced chromium raw materials with a chromium metallization degree of 65% has decreased the power consumption for melting of the high-carbon ferrochromium to 44% for the pilot furnace. The calculated power

consumption for industrial DC furnaces in the melting shop No. 4 at Aktobe ferroalloy plant at the same metallization degree of raw materials can be reduced to 50%.

3. Conclusions

1. The scheme with pre-reduction has been proven to be more effective in reducing the total power consumption for melting high-carbon ferrochromium when compared to the schemes of heating and sintering the charge. This conclusion is based on the use of South African chromites with a chromium reduction degree of over 50% and Kazakhstan chromites with a chromium reduction degree of more than 60%. By implementing pre-reduction, the total power consumption for the melting process is reduced. Pre-reduction involves the reduction of chromite ore before it is charged into the furnace. This process helps to remove the excess oxygen from the ore, resulting in a more efficient melting process. The use of South African chromites with a chromium reduction degree of over 50% and Kazakhstan chromites with a chromium reduction degree of more than 60% further enhances the effectiveness of pre-reduction. These chromite ores have already undergone a significant reduction in chromium content, making them more suitable for the pre-reduction process. Overall, the scheme with pre-reduction offers a more energy-efficient solution for melting high-carbon ferrochromium compared to the alternative schemes of heating and sintering the charge. The combination of pre-reduction and the use of chromite ores with high chromium reduction degrees results in a reduction in total power consumption during the melting process;
2. Results of the pilot tests have demonstrated the possibility of achieving a chromium reduction degree more than 60%. Thus, it provides the expediency of pre-reduction during the ferrochromium melting in the DC furnace;
3. It is necessary to assess the real value of reduction in power consumption during remelting of the pre-melting product for the melting of the high-carbon ferrochromium in the ore-smelting furnace and DC furnace;
4. The proposed pre-reduction technology can provide a high uniformity in the chromium reduction degree. Thus, it will have a good effect on the subsequent remelting process;
5. It is necessary to refine upon solutions that will exclude the material sticking to the crucible walls and segregation of charge materials during the pre-reduction.

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