Smelting of high-carbon ferrochromium from pre-reduced chromite raw materials

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The article presents the results of smelting of high-carbon ferrochromium (HCFeCr) from pre-reduced chromite raw materials. Experimental melts of three batches of pre-reduced chromite raw material with varying degrees of chromium metallization were conducted using a 0.2 MVA furnace at the Zh. Abishev Chemical-Metallurgical Institute in Karaganda. To assess the technical-economic indicators of remelting of pre-reduced chromite raw materials in industrial DC furnaces, a batch of basic charge for HCFeCr smelting, containing chromite ore, coke breeze and quartz flux, was separately smelted. The study determined the relationship between specific energy consumption for HCFeCr production and content of metallized chromium in the experimental furnace, ranging from 15.37 % to 22.28 %. The assessment results indicate possibility of halving the specific energy consumption to 3.4 MW·h per ton of chromium, when content of metallized chromium in pre-reduced product is 22.28 %.
Key words: smelting, metallization, ferroalloy, chromite ore, coke breeze, high-carbon ferrochromium, ore smelting furnace.
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Introduction

High-carbon ferrochromium (HCFeCr) is mainly used in production of stainless steel and other special steel grades. Its conventional production technology includes smelting of chromite ore with coke and quartz (or other silicon-containing materials) in an electric arc furnace [1]. However, this process is characterized by consumption of essential energy and is connected with enormous emissions of CO_2 (up to 1.8–5.5 t per 1 t of high-carbon ferrochromium) and other greenhouse gases [1–3]. Development of the technologies based on preliminary heating and/or preliminary reduction of chromite raw materials is observed in the ferroalloys industry during last decade, as a response on growing ecological problems and increasing electric energy expenses. This technology allows to decrease specific consumption of electric energy, to cut smelting time and thereby to rise productivity of a smelting furnace [4–10].

Preliminary reduction includes partial reduction of chromite ore using more cheap carbon sources before smelting. This process can take place in rotary furnaces, in tubular furnaces or multi-stage fluidized-bed furnaces, where ore is subjected to the effect of reducing gases at the temperature from 800 to 1,500 °C [3, 11–13]. Preliminary reduction transforms chromite ore at first in ferrum oxide and chromium oxides, and their complete reduction will require significantly smaller amount of energy during consequent smelting.

Similar technology developed by "Outokumpu" (Finland) exists, it is based on roasting of pellets from chromite raw material. This or similar technologies are used in Finland, Greece, Turkey and South Africa [6–16]; according to their experience, preliminary ferrum reduction up to 90 % and chromium up to 50 % decreases electric energy consumption by 40 % [17], while consequent decrease to 50 % is possible due to the combination of pre-reduction and preliminary heating [18].

Possibilities of pre-reduction use applying to the South Africa ores are widely examined (South Africa is one of the three largest ferrochromium producers in the world, together with China and Kazakhstan). At the same time, taking into account rich Kazakh ores, it seems necessary to provide research of efficiency of pre-reduction process for HCFeCr smelting from these ores, in order to optimize smelting process and to decrease ecological load during ore smelting.

The aim of this research is development and testing of HCFeCr smelting technology from pre-reduced chromite raw material in an ore smelting furnace. This investigation will allow not only to check technical possibility of such approach, but also to evaluate its industrial and ecological advantages. It is especially important to provide sustainable development of the ferroalloys industry in the conditions of permanently increasing requirements for energy efficiency and ecological safety.

Materials and methods

Technological researches of HCFeCr manufacturing technology using pre-reduced charge were conducted at the large-scale laboratorial single-phase electric furnace with graphite conducting hearth and having capacity 200 kVA. Power supply was provided by OMU-200 transformer. Temperature in arc discharge reaches 4,500 °C and os provided by graphite electrode with diameter 150 mm [16–20].

Graphical construction of the furnace bath and its sight are presented in the **Fig. 1**. Heating of the electric furnace was carried out on a coke bed, which is also electric current conductor. After heating, the electric furnace was completely cleaned with removal of parts of the coke bed. Electric procedure of heating was implemented under conditions with secondary voltage 24.6 V and electric current at the high side 150–200 A [21–25].

Three compositions of experimental charge with pre-reduced material having different metallization degree and one basic composition from charge with non-pre-reduced ore (for comparison) were tested. Chemical and technical compositions of initial materials, which were used in this research, are presented in the **Table 1** and **Table 2**.

Pre-reduction was carried out using the mix of high-ash coal and anthracite, with natural gas supply, at the temperature above 1300 °C, varying the holding time within 35–45 h. Energy consumption for pre-reduction made 2.23; 4.16; 5.18–6.37 MV h/t for low, average and high metallization degree, respectively [26].

Discussion

Pilot-industrial testing on application of pre-reduced charge during HCFeCr smelting were conducted in the conditions of Zh. Abishev Chemical and Metallurgical Institute. Duration of the pilot campaign was 23.49 days (without accounting furnace downtime). Totally 291 melts were carried out.

Furnace heating was started with the basic charge. Then transition to a balanced melting using basic charge was realized during 3 melts. In general, the tests were divided by 5 consequent periods:

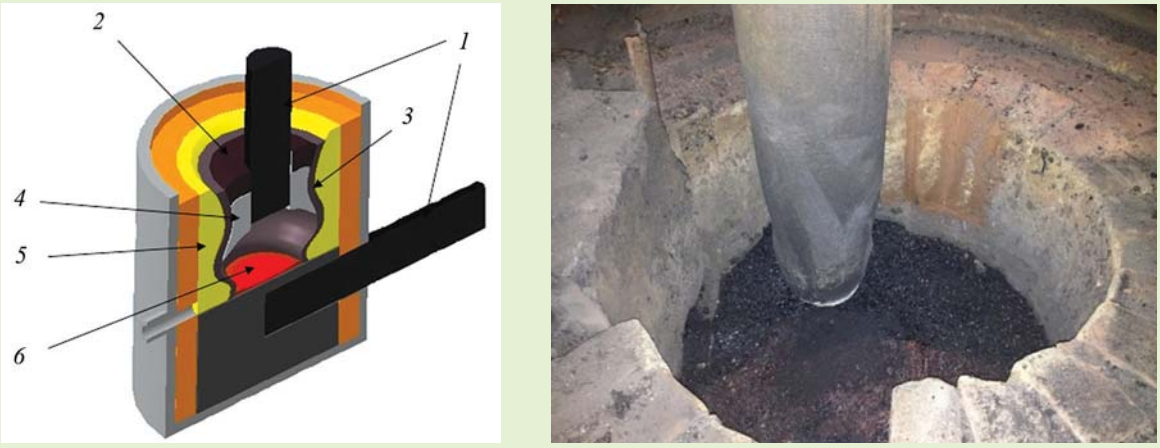

Fig. 1. Construction of ore smelting furnace bath with transformer capacity 200 kVA:
1 – electrodes; *2* – initial charge; *3* – area of softened charge; *4* – transition area; *5* – wall lining; *6* – melt and metal-carbide skull

Table 1. **Chemical compositions of average samples for pre-reduced materials with different metallization degree, % (mass.)**

Material	Cr_2O_3	SiO_2	CaO	MgO	Al_2O_3	FeO	C	C_{rmet}	P	S
Chromite ore, fraction 0–10 mm	51.5	6.63	0.78	18.0	7.70	12.4	—	—	0.00	0.02
Quartzite, fraction 0–10 mm	—	96.4	0.33	0.40	2.17	0.94	—	—	—	0.01
Pre-reduced chromite material with low metallization degree	29.02	8.20	0.19	20.31	8.50	12.48	10.38	15.37	—	—
Pre-reduced chromite material with average metallization degree	26.32	8.22	0.19	19.98	8.20	12.48	8.64	17.22	—	—
Pre-reduced chromite material with high metallization degree	18.92	8.25	0.13	20.82	7.90	12.32	10.05	22.28	—	—

Table 2. **Technical coke composition % (mass.)**

C_{sol}	W_t^r	A^r	V^r	S	P_{tot}
69.45	14.19	15.18	1.1	0.032	0.04

No. 1 — basic charge (36 V);

No. 2 — pre-reduced charge with low metallization degree;

No. 3 — pre-reduced charge with high metallization degree;

No. 4 — basic charge (49 V);

No. 5 — pre-reduced charge with average metallization degree.

Basic charge No. 1. The tests were started with the basic charge, which is used at present time in the smelting shop No. 4 at Aktyubinsk Ferroalloys Plant for HCFeCr smelting. In order to examine technological smelting conditions, the first stage was carried out with voltage 36 V. Charge composition contained: 76.05 % of chromite ore, 16.35 % of coke and 7.6 % of quartzite.

45 melts were produced during 4.57 days according to this variant. Average chemical analysis of molten products during this period displayed the following contents: 70.06 % Cr, 2.36 % Si, 7.04 % C, 0.028 % S, 0.036 % P (for metal) and 5.01 % Cr_2O_3, 34.57 % SiO2; 40.91 % MgO, 15.39 % Al_2O_3, 1.14 % FeO (for slag). No apparent violations of furnace practice were observed, melt pouring was rather intensive, metal and slag yield was stable. The furnace productivity made 201.97 kg of HCFeCr per day, chromium extraction was 94.13 %.

Pre-reduced charge No. 2 with low metallization degree. After mastering the technological conditions for HCFeCr with the basic charge, with voltage 36 V, transition to pre-reduced chromium material with low metallization degree was implemented. In order to find the optimal slag composition, quartzite was added; the charge included the following materials: 90.5 % of pre-reduced charge with low metallization degree, 3.2 % of coke, 6.24 % of quartzite.

77 melts were produced during 6.66 days according to this variant. Furnace practice was characterized by stability, good hearth heating and rather complete metal yield. However, otherwise to the conventional technology, when refractory crust in top throat remained until the end of smelting process, complete bath fusion penetration occurred. In such way, production process in the conditions of DC furnaces in the smelting shop No. 4 at Aktyubinsk Ferroalloys Plant was simulated. The furnace productivity made 284.8 kg of HCFeCr per day, chromium extraction was 87.76 %.

Average chemical analysis of molten products during this period displayed the following contents: 65.49 % Cr, 2.58 % Si, 7.43 % C, 0.014 % S, 0.0081 % P (for metal) and 4.68 % Cr_2O_3, 29.85 % SiO_2; 38.47 % MgO, 17.61 % Al_2O_3, 0.76 % FeO (for slag).

Pre-reduced charge No. 3 with low metallization degree. Pre-reduced chromium material with high metallization degree was used during this testing period as a charge, which included the following materials: 91.12 % of pre-reduced charge with high metallization degree, 0.75 % of coke, 7.8 % of quartzite.

62 melts were produced during 4.76 days according to this variant. Average chemical analysis of molten products during this period displayed the following contents: 67.68 % Cr, 1.62 % Si, 7.71 % C, 0.018 % S, 0.049 % P (for metal) and 2.85 % Cr_2O_3, 29.85 % SiO_2, CaO (traces), 44.91 % MgO, 19.43 % Al_2O_3, 0.73 % FeO (for slag).

The furnace productivity increased by 29.3 % (in comparison with the previous variant, stage No. 2) and reached 368.23 kg of HCFeCr per day, chromium extraction was 89.41 %.

Basic charge No. 4. After complete processing of pre-reduced chromium material with high metallization degree, transition to the basic charge was executed in order to examine and improve technological HCFeCr smelting conditions with voltage 36 V. Charge composition contained: 76.57 % of chromite ore, 16.73 % of coke and 6.7 % of quartzite.

16 melts were produced during 1.17 days according to this variant. Average chemical analysis of molten products during this period displayed the following contents: 65.4 % Cr, 1.88 % Si, 7.73 % C, 0.018 % S, 0.056 % P (for metal) and 1.96 % Cr_2O_3, 34.95 % SiO_2; CaO (traces), 42.21 % MgO, 18.78 % Al_2O_3, 1.01 % FeO (for slag).

The furnace productivity increased by 22.51 % in comparison with the first basic period (stage No. 1) and made 247.44 kg of HCFeCr per day.

Comparison between HCFeCr smelting with pre-reduced charge with high metallization degree (stage No. 3) and with basic charge with voltage 49 V (stage No. 4), furnace productivity rose by 1.5 times.

Pre-reduced charge No. 5 with low metallization degree. 4,900 kg of pre-reduced chromium material with average metallization degree was smelted during this period of pilot-industrial tests. The charge included the following materials: 91.95 % of pre-reduced charge with high metallization degree, 1.56 % of coke, 7.05 % of quartzite.

84 melts were produced during 6.33 days according to this variant. Average chemical analysis of molten products during this period displayed the following contents: 69.73 % Cr, 1.71 % Si, 8.33 % C, 0.028 % S, 0.048 % P (for metal) and 3.39 % Cr_2O_3, 28.56 % SiO_2, CaO (traces), 41.96 % MgO, 19.08 % Al_2O_3, 1.08 % FeO (for slag).

The furnace productivity was 346.64 kg of HCFeCr per day, chromium extraction was 83.73 %.

The results on specific consumption of electric energy for HCFeCr smelting, which were obtained during the tests, are presented in the **Table 3**.

4,800 kWt of electric energy is consumed for smelting of 1 t of HCFeCr in the conditions of the smelting shop No. 4 at Aktyubinsk Ferroalloys Plant. Taking into account large heat losses and construction features of the experimental furnace, it is impossible to reach this parameter. Electric energy consumption for smelting of 1 t of HCFeCr in the conditions of an ore smelting furnace with transformer capacity 200 kVA is larger by 48.37 % and makes 7,121.8 kWt, according to the data presented in the Table 3 (stage No.4). Based on information about difference between specific consumption values for different furnaces, we can calculate approximate specific consumption of electric energy for HCFeCr smelting with use of pre-reduced chromite material in the conditions of the smelting shop No. 4 at Aktyubinsk Ferroalloys Plant.

Technical and economical parameters of HCFeCr smelting with use of basic and pre-reduced charge with different metallization degree are presented in the **Table 4**.

Comparing the values of specific consumption of electric energy in the conditions of the ore smelting furnace with

Table 3. **Specific consumption of electric energy for HCFeCr smelting, which were obtained during the tests**

Stage No.	Actual electric energy consumption, kWt	Amount of smelted alloy, kg	Specific consumption of electric energy during campaign, kW·h/t
1	7551.88	922.9	8182.8
2	11012.21	1896.1	58078
3	8304.92	1754.20	4734.3
4	2068.18	290.40	7121.8
5	10977.42	2193.00	5005.7

Table 4. **Comparative values of specific consumption of electric energy for HCFeCr smelting**

Title of stage	Specific values of electric energy consumption, kWt·h/t	
	Experimental data in the conditions of the furnace with transformer capacity 200 kVA	Calculated data for industrial furnaces in the smelting shop No. 4
Basic charge	7121.8	4800*
Pre-reduced chromium material with low metallization degree	5807.8	3914.38
Pre-reduced chromium material with average metallization degree	5005.7	3373.74
Pre-reduced chromium material with high metallization degree	4734.3	3190.84

* Production data in the smelting shop No. 4

transformer capacity 200 kVA (see the Table 4), we can see that specific consumption of electric energy with use of pre-reduced chromium material with low, average and high metallization degree is lower that specific consumption of electric energy with use of basic charge by 18.4 %, 29.7 % and 33.5 % respectively.

Indeed, it is difficult to speak about general economical efficiency of this method during accounting of expenses for pre-reduction operation at the examined stage of development, despite saving of specific consumption of electric energy and increase of productivity of the ore smelting furnace. However, further use of furnace waste gases for heating during pre-reduction can provide essential economical efficiency. Additionally, this approach opens possibility of using more poor raw material in charge, which is hardly valid or completely invalid in initial form for HCFeCr smelting in the ore smelting furnace.

Evaluation of specific consumption of electrodes for HCFeCr smelting. As soon as electrode slipping and build-up was carried out not in each shift and number of manufactured smelted metal varied in a wide range, specific consumption of electrodes was determined by averaged data during whole testing period. It was determined by difference of electrode weight before and after testing, taking into account electrode build-up. Thus, electrode consumption during smelting made 425 kg, i.e. 60.23 kg/t of produced HCFeCr, taking into account heating effect.

Evaluation of productivity of the ore smelting furnace with transformer capacity 200 kVA during HCFeCr smelting with use of pre-reduced materials. It was noted during the testing campaign that furnace productivity increased dramatically with use of pre-reduced charge. Processing of large amount of charge materials and provision of long-term furnace operation in stable procedure allowed to reach optimal smelting technical and economical parameters. Metal output increases steadily and specific consumption of electric energy and chromium-containing material decreases as well with rise of metallization degree of pre-reduced materials.

As a result of smelting stages, content of chromium oxide in slag does not exceed standardized limits and varies from 1.96 to 5.01 % in average.

In general, 7,056.6 kg of HCFeCr was obtained in accordance to the requirements of GOST 4757-91 during conduction of the pilot-industrial testing.

To determine through chromium extraction, corresponding calculations were carried out; their results are presented in the **Table 5**.

The value of material imbalance was within the range from 0.81 to 12.89 %, what is considered as a rather essential value. Material was charged in the furnace using shovels during testing. This method does not exclude mechanical losses of fine charge materials (< 10 mm) during their charging; it was principally observed during testing. The authors concluded that 0.81—12.89 % of losses can be classified as mechanical losses during charging and blowing-off of fine ore particles in the gas cleaning system.

Conclusions

Due to preliminary roasting, total energy consumption of smelting process decreases. Pre-reduction includes reduction of chromite ore before its charging in the furnace. This process allows to remove excessive oxygen from ore, what leads to more efficient smelting.

Conducted pilot-industrial testing displayed possibility of HCFeCr production via smelting in the ore-smelting furnace, using pre-reduced chromium raw material with different metallization degree as initial material; it allows to decrease specific consumption of electric energy by 18.4—33.5 %.

Advantages of use of pre-reduced chromium raw material in comparison with conventional charge are mainly expressed when comparing the stages 3 and 4. It led to productivity rise almost by 2.5 times, as well as to saving electric energy by 33.5 %.

Table 5. **Chromium balance**, *kg*

Stage No.	Chromium input, kg		Chromium consumption, kg			Imbalance, kg	Imbalance, %	Chromium extraction in metal and slag, %
			Output with metal	Output with slag	Total			
1	Input from ore	676.5	646.58	24.48	671.1	5.49	0.81	99.19
2	Input from pre-reduced material with low metallization degree	1490.8	1241.76	56.85	1298.61	192.19	12.89	87.11
3	Input from pre-reduced material with high metallization degree	1353.8	1187.24	32.88	1220.13	133.67	9.87	90.13
4	Input from ore	211.42	189.92	3.53	193.45	17.97	8.50	91.50
5	Input from pre-reduced material with average metallization degree	1807.12	1529.18	51.71	1580.88	226.24	12.52	87.48

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