Technological Suitability of Semi-Coke as a Carbon Reducer in Production of Manganese and Silicon Alloys

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Abstract—The paper presents results of testing semi-coke as a carbon reducing agent in the production of manganese and silicon alloys. The fundamental possibility of using semi-coke in the carbon part of the charge as a basic reducing agent to produce ferrosilicon manganese is established. It is noted that a new reducing agent in its pure form works worse than in a mixture with coal. The greatest synergistic effect in the production of ferrosilicon manganese was achieved during the interaction of semi-coke with coal, while the following indicators were obtained: maximum furnace productivity of 43 t/day, maximum extraction coefficient of 87.9\%, and minimum specific dust formation of 49 kg/t of alloy. In the production of ferrosilicon, the use of a new reducing agent did not give a significant positive effect, due to its low structural strength. It was revealed that the structure and type of the reducing agent affect the furnace performance: when using a reducing agent with a higher reactivity in the charge, it is possible to obtain higher furnace performance. In the production of ferrosilicon, a change in the specific dust generation is closely related to the level of daily production and specific energy consumption and can serve as an indicator of furnace operation. The furnace performance, ceteris paribus, is determined by the amount of useful power input. With an excess of carbon in the charge an increase in useful power leads to a slight increase in the furnace performance, but at the same time, the energy consumption and specific dust formation significantly increase. It is shown that the influence of technological factors on the technical and economic indicators of melting is determined by the degree of electrode seating in the furnace.

Keywords: semi-coke, solid carbonaceous reducing agent, ferrosilicon, ferrosilicon manganese, ferroalloy production, technological properties, reactivity, application in metallurgy

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INTRODUCTION

The production of ferroalloys is one of the most important elements of metallurgical production of Kemerovo oblast. However, at present, there is an acute shortage of the main reducing agent used in metallurgical processes, coke from scarce caking coal. In this regard, an active search is underway for new promising carbonaceous materials that can fully or partially replace coal coke in various metallurgical processes, including the production of ferroalloys [1–5].

The carbonaceous material used as a solid reducer in the smelting of silicon, as well as high-purity ferroalloys, must have a developed porous structure, high reactivity and electrical resistance, sufficient mechanical strength, and minimum ash content. The experience of industrial production of metallurgical silicon of various grades shows that charcoal, petroleum coke, some grades of low-ash coal, and wood chips have such properties. However, it should be noted that none of the above materials fully meets the requirements for a solid reducer. Only their use in various combinations makes it possible to create favorable conditions for the efficient course of reduction processes in an electric furnace [6–19].

In terms of quality indicators and the amount of mined coal reserves, the Kuznetsk basin is the most promising coal base in the country. Long-flame coals occupy a special place in the Kuznetsk basin. Their low ash content, possibility of open pit mining, thick-
ness of the layers, sulfur and phosphorus cleanness, and proximity of the basin to industrial enterprises caused the development of economically viable ways of processing them into raw materials to obtain special types of coke [20–22].

The purpose of this study was to assess the technological suitability of semi-coke as a carbon reducer in the production of manganese and silicon alloys.

Long-flame coals from Kemerovo oblast deposits were used as a feedstock. The following coal samples were investigated: (1) coal from OOO Razrez Taldinsky-Zapadny; (2) coal from OOO Razrez im. V.I. Cheremnova; and (3) coal from AO Razrez Inskoy. This paper presents the results of testing the obtained semi-coke as a carbon reducer in production of manganese and silicon alloys.

SEMI-COKE PRODUCTION

A pilot batch (about 200 tons) of semi-coke was obtained at a pilot plant in Novosibirsk. According to the technological scheme of semi-coke production, enriched coal is loaded into an electric calciner, where the raw material is preheated to 700°C with subsequent resistive heating to 900–1200°C by passing a current between the upper and lower electrodes directly through the dense coal layer. Characteristics of the obtained semi-coke: sulfur content 0.18%, moisture 7.15%, ash 4.47%, carbon 96.3% (by weight); volatiles content 2.97%; reactivity (CRI) 183.4; and electrical resistivity 4.404 mOhm m.

During the pilot campaign, the following goals were set: to determine the efficiency of using the new semi-coke as a reducer in comparison with the technology adopted for the production of ferrosilicon manganese and ferrosilicon at OOO Zapadno-Siberian Electrometallurgical Plant (OOO ZSEMZ); to determine the optimal composition of the reduction mixture; to analyze the technical and economic indicators obtained in the course of study with the use of new semi-coke for the production of ferrosilicon manganese and ferrosilicon at OOO ZSEMZ.

RESULTS OF SMELTING FERROSILICOMANGANESE USING A NEW REDUCING AGENT

A pilot campaign was carried out for smelting ferrosilicon manganese using the obtained highly reactive reducing agent. Smelting was carried out in an RKO-12 furnace. Figure 1 shows the dependences of productivity, specific dust formation, actual power and specific power consumption on the composition of the charge in different periods of melting.

Furnace operation can be divided into three periods:
—Transition period (P): reducing agent—coal.
—Period I: reducing agent—coal + received semi-coke.
—Period II: reducing agent—pure semi-coke.
During the pre-test period (3 days), the furnace was operated with an excess of carbon, the length of the electrodes was 1.3 m. The lack of the required electrode seating depth led to significant (250 kg/t alloy) dust formation (Fig. 1b), as well as to low productivity (on average 24.3 t/day).

**Transition Period**

When supplying a new reducing agent, the total quantity of carbon was corrected for a lack in charge in order to ensure a deeper electrode seating. The furnace quickly reacted to the introduction of a new reducing agent into the charge. The electrode seating increased (1.6 m), the furnace productivity grew from 24.3 to 26.8 t/day.

It should be noted that the new reducing agent has a significant effect on arcing: the arc is smoother, and the current load step is lower. This led to a significant decrease in dust formation: specific dust formation decreased from 250.0 to 80.6 kg/t of the alloy (Fig. 1b).

With a manganese recovery factor of 0.454 (the ratio of the total amount of carbon in the charge to the amount of manganese in the charge, despite the carbon deficiency, the manganese content is at a sufficiently high (71.5%) level due to a decrease in the loss of manganese with dust removal (Fig. 1b, Table 1).

**Period I**

At stage I, the amount of carbon in the charge was increased (the ratio of the amount of carbon in the charge to the amount of manganese in the charge was 0.535), mainly due to the carbon of the new reducing agent.

The electrode seating did not change, the furnace productivity was 41–43 t/day, and the specific dust formation decreased to 49 kg/t of the alloy. The recovery of manganese increased from 71.5 to 87.9% (Table 1), while the furnace also operated with a lack of carbon.

**Period II**

The operation of the furnace was tested with a pure reducing agent (without adding coal). Furnace operation in this period was represented by two intervals.

The amount of carbon per 1 ton of manganese was increased from 535 to 564 kg, as a result, the loss of manganese with slag decreased from 11.57 to 8.43%. However, a certain excess of the reducing agent worsened the furnace seating, which led to a decrease in productivity from 43.0 to 36.2 t/day, an increase in dust formation to 60 kg/t of the alloy, and a decrease in the manganese content from 87.9 to 81.9%. This period is marked as the most unstable.

After removing the reducing agent from the charge composition in interval 1, the average furnace productivity was 34.5 t/day, dust removal was 140 kg/t of alloy, and the electrode seating worsened. The furnace run should be characterized as a transitional one: apparently, the residual part of the reducing agent from the peripheral zones of the furnace gradually passed into the melting zone.

Further (interval 2), the furnace returned to its original state: the furnace productivity decreased to 27 t/day, and specific dust removal increased to 234 kg/t of the alloy.

**RESULTS OF FERROSILICON SMELTING USING A NEW REDUCING AGENT**

A pilot campaign of ferrosilicon smelting using the obtained highly reactive reducing agent was carried out. Smelting was carried out in an RKO-14 furnace. The following periods of furnace operation were chosen:

—Basic: reducing agent—coke/semi-coke.
—Experimental period.
—Experimental stage 1: reducing agent—coke + received semi-coke.
—Experimental stage 2: reducing agent—obtained semi-coke.

Tables 3—5 show the main (average daily and specific) production indicators of the furnace and the consumption of raw materials by periods.

### Table 1. Technological parameters of smelting ferrosilicon manganese by periods

| Period     | Mn, %  | C<sub>total</sub>, % | C<sub>Mn</sub> <br>coal | C<sub>Mn</sub> <br>semi-coke | α, % |
|------------|--------|---------------------|--------------------------|-----------------------------|------|
| Transition | 32.6   | 26.0                | 11.8                     | 0.454                       | 0.214 |
| I          | 33.6   | 66.4                | 35.5                     | 0.535                       | 0.081 |
| II         | 34.3   | 61.7                | 34.8                     | 0.564                       | 0     | 0.546 |

C<sub>Mn</sub> <br>coal, C<sub>Mn</sub> <br>semi-coke, are the ratios of the total amount of carbon in the charge, the amount of carbon in coal, the amount of carbon in the semi-coke to the amount of manganese in the charge, respectively; α is the calculated manganese recovery factor; C<sub>total</sub> is the total amount of carbon in the charge.
Table 2. Specific consumption of materials at different periods of smelting

| Period   | Consumption, t/t of metal |
|----------|---------------------------|
|          | ore | coal (T) | return slag | semi-coke | quartzite | anthracite |
| Pre-test | 2.064 | 0.658 | 0.223 | 0 | 0.485 | 0 |
| Transition | 2.933 | 0.284 | 0.270 | 0.251 | 0.600 | 0 |
| I        | 2.298 | 0.088 | 0.199 | 0.389 | 0.510 | 0 |
| II       | 2.375 | 0 | 0 | 0.517 | 0.497 | 0 |
| Interval I | 2.147 | 0.234 | 0.213 | 0 | 0.287 | 0.247 |
| Interval II | 2.5 | 0.214 | 0.266 | 0 | 0.315 | 0.292 |

Table 3. Key (daily average) performance indicators of an RKO-14 furnace

| Average and total values by periods | Production, fact. t | Energy consumption, MW/h | Act. power, MW | Amount of collected dust, t | Temperature under the furnace hood, °С | Temperature on gas cleaning filters, °С |
|-----------------------------------|---------------------|--------------------------|----------------|---------------------------|----------------------------------------|----------------------------------------|
|                                   | phys. t | base t |                        |                |                          |                                        |                                        |
| Average                           | 25.26   | 25.87  | 202.0                    | 8.46           | 6.86                     | 200                                    | 156                                    |
| Total                             | 277.84  | 284.6  | 2221.8                   | —              | 75.48                    | —                                      | —                                      |
| stage 1 of the experimental period|                                   |                          |                |                          |                                        |                                        |
| Average                           | 25.04   | 25.56  | 198.0                    | 8.33           | 6.33                     | 175.3                                  | 134.9                                  |
| Total                             | 425.75  | 434.57 | 3356.8                   | —              | 107.67                   | —                                      | —                                      |
| stage 2 of the experimental period|                                   |                          |                |                          |                                        |                                        |
| Average                           | 25.44   | 26.03  | 202.9                    | 8.49           | 5.49                     | 206                                    | 147                                    |
| Total                             | 101.76  | 104.1  | 811.5                    | —              | 21.97                    | —                                      | —                                      |

Figure 2 shows the dependence of the amount of ferrosilicon produced on the actual power during furnace operation in the base period and stage 1 of the experimental period.

Figure 3 shows the dependences of specific dust formation and specific power consumption in different periods of melting.

RESULTS AND DISCUSSION

Ferrosilicon Manganese Production Using a New Reducing Agent

The power of the furnace is mainly determined by the quality of the reducing agent and the resource of evacuation of gases from under the hood. Work with the new reducing agent made it possible to increase the active power from 5.23 to 7.00—7.25 MW (Fig. 1c) without visible smoke on the working platform.

An increase in the furnace power, of course, leads to an increase in its productivity, however, all other things being equal, the reaction rate of the reducing agent should be considered a more significant factor, that is, the type and composition of the reducing agents in the melting charge. Indeed, when the furnace operates in periods I and II at the same power, when a new reducing agent is used together with coal, the furnace productivity increases by 1.16 times.

The minimum specific power consumption was recorded when using the obtained semi-coke together with T grade coal. It should be noted that the use of a
new reducing agent in any combination affects the reduction in specific power consumption more significantly than when using a standard reducing agent (Fig. 1d).

The best melting indicators were obtained with the combined use of a new reducing agent and coal at $C_{\text{semi-coke}}/M_{\text{n,charge}} = 0.455$ and $C_{\text{coal}}/M_{\text{n,charge}} = 0.081$ (Table 1). Specific consumption of materials per ton of metal in this case is: 0.389 tons of new reducing agent and 0.088 tons of coal (Table 2).

Thus, we can note the characteristic features of using a new reducing agent in the charge when melting ferrosilicon manganese: promotes deeper electrode seating; stabilizes the arcing process; significantly reduces dust formation and thereby reduces the loss of manganese with dust; works worse in its pure form than in a mixture with coal; and the greatest synergistic effect was achieved when it operated together with coal, at this, the maximum furnace productivity (43 t/day), the maximum extraction (87.9%), and the minimum specific dust formation (49 kg/t of alloy) were achieved.

### Ferrosilicon Production Using a New Reducer

When a new semi-coke is introduced into the charge (stage 1 of the experimental period), the specific power consumption decreases due to an increase in the charge resistance based on a change in the structure of the carbon-containing material (Fig. 3b), while a deeper electrode seating is ensured. Electrode seating depth affects dust generation: deep electrode seating ensures minimal dust generation. During the operation of the furnace with deep electrode seating (stage 1 of the experimental period), a decrease in specific dust formation was achieved on average from 270 to 230 kg/day (Fig. 3a). The furnace productivity directly depends on the input power (Fig. 2). The productivity of a furnace operating on a charge containing the resulting semi-coke increases insignificantly in comparison with the productivity of a furnace operating on a standard reducing agent.

At stage 2 of the experimental period, unstable operation of the furnace was observed (Fig. 3).

Thus, the following conclusions can be drawn: the productivity of the furnace, other things being equal, is determined by the value of the input power; with an excess of carbon in the charge, an increase in the useful power leads to a slight increase in the furnace productivity, but at the same time, power consumption and specific dust formation increase significantly; a change in the value of specific dust formation is closely related to the level of daily production and specific energy consumption and can serve as an indicator of the operation of the furnace; the influence of technological factors on the technical and economic indicators of melting is determined by the degree of electrode seating.
seating in the furnace; the structure and type of the reducing agent affects the furnace productivity: when using a reducing agent with a higher reactivity in the charge (P-2 semi-coke and the resulting special coke), it is possible to obtain higher production indicators of the furnace.

It was not possible to achieve high furnace productivity and minimum dust formation. When working with the new semi-coke, the production parameters of the furnace correspond to those of the furnace with P-2 semi-coke. The use of a new reduction agent can slightly reduce dust formation. Due to the low structural strength in the process of transportation and dosing of the new semi-coke, its significant crushing was noted.

CONCLUSIONS

The principal possibility of using the obtained semi-coke in the composition of the carbon part of the charge as a basic reducing agent to produce ferrosilicon manganese has been established. The greatest synergistic effect in the production of ferrosilicon manganese was achieved when the obtained semi-coke was operated together with coal, while the maximum furnace productivity was 43 t/day, the maximum extraction was 87.9%, and the minimum specific dust formation was 49 kg/t of the alloy.

It was found that in the production of ferrosilicon, the use of a new reducing agent did not give a significant positive effect (due to its low structural strength). In the production of ferrosilicon, the change in the value of specific dust formation is closely related to the level of daily production and specific energy consumption and can serve as an indicator of furnace operation.

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