Optimal parameters for obtaining ferrosilicon from a mixture of amorphous silica-containing rocks: tripoli and flask

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Abstract. Ferrosilicon smelting can be more intensive if its amorphous variety with increased reactive capacity is used instead of crystalline silicon-containing substance. The article presents the results of experimental determination of optimal process parameters for obtaining ferrosilicon from a mixture of tripoli and flask. The studies were carried out by electric smelting using the method of second-order rotary planning with subsequent geometric optimization. The influence of replacing insufficient steel cuttings with magnetite concentrate and FeSi25 ferrosilicon on the process parameters of ferrosilicon smelting was determined. The studies showed that electric smelting of a mixture of tripoli and flask (with a ratio of 1:1) results in the formation of FeSi25, FeSi45 and FeSi50 ferrosilicon. The optimal parameters for obtaining FeSi25 ferrosilicon with 90.37-92.61% Si extraction are 42.7-44% coke, 34.4-35% cuttings; FeSi45 with 75.0-78.66% Si extraction – 39.2-44% coke, 28.75-31.4% cuttings; FeSi50 with 70-73.43% Si extraction – 40.1-44% coke, 25.5-28.9% cuttings. Replacing 20% of steel cuttings with magnetite concentrate leads to the formation of FeSi50 ferrosilicon (Si content 48%) with an increase in silicon extraction into the alloy to 76.8%. Replacing 60% of steel cuttings with FeSi25 ferrosilicon allowed to obtain FeSi50 ferrosilicon and increase silicon extraction to 86.8%. At that, in comparison with obtaining a ferroalloy from quartzite, the degree of silicon extraction into the alloy and the concentration of silicon in it significantly increase.

1 Introduction

In industry, siliceous ferroalloys are obtained by electrothermal method from quartzite, coke and steel cuttings. When smelting ferrosilicon in electric furnaces, the process speed depends on several factors, but primarily on the reactive capacity of the raw materials. Recently, more than a dozen new technologies for producing siliceous ferroalloys have been proposed. All of them mainly provide for the presence of crystalline silica in the charge [1-11]. The reactive capacity of crystalline silica at the process temperature of 1600-1800°C has a certain limit. The smelting speed of siliceous alloys can be increased by selecting a more

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active type of silica, which is amorphous silica. There is positive experience in obtaining FeSi75 ferrosilicon using technogenic amorphous microsilica, a waste product of silicon production [12, 13]. From the thermodynamic point of view, amorphous SiO_2 is less durable than crystalline SiO_2 ($\Delta G^{\circ}_{298}SiO_2$ amorphous is (-749.85) kJ, and $\Delta G^{\circ}_{298}SiO_2$ crystalline is (-854.7) kJ. Using the HSC-6.0 program, it was found that the probability of forming silicon silicide ($FeSi_2$) from amorphous SiO_2 is higher than from crystalline. Thus, $\Delta G°_{1973}$ of the reaction $2SiO_{2\ cryst}+4C+Fe=FeSi_2+4CO$ is (-53.4) kJ, and the reaction $2SiO_{2\ amorph}+4C+Fe= FeSi_2+4CO$ is (-56.4) kJ.

The temperature of the beginning of $FeSi_2$ formation from $SiO_{2\ amorph}$ is lower than from $SiO_{2\ cryst}$ by 9.5 degrees. At that, the energy costs for obtaining $FeSi_2$ from $SiO_{2\ amorph}$ are also lower than from SiO_{2cryst}. For example, at 1973K $\Delta H°_{amorph}$=1202 kJ, and $\Delta H°_{cryst}$=1214.3 kJ.

The efficiency of $SiO_{2\ amorph}$ reduction increases significantly if Fe_3O_4 is used instead of iron. Thus, $\Delta G°_{1973}$ of $FeSi_2$ formation in the presence of Fe_3O_4 is (-263) kJ, and in the presence of iron (-53.0) kJ. The efficiency of using magnetite-containing material in obtaining ferrosilicon was confirmed.

The reactive capacity of $SiO_{2\ amorph}$ can also be increased if electric smelting is carried out in the presence of low-siliceous ferrosilicon, which, due to its lower (by 300 degrees) melting temperature compared to iron, accelerates the dissolution of silicon, reducing its losses with gas. Smelting ferrosilicon in the presence of FeSi25 ferrosilicon allows for a reduction in the consumption of quartzite, coke, and energy consumption.

The article presents the results of experimental determination of the optimal process parameters (amount of carbonaceous reducing agent, iron-containing material) for obtaining ferrosilicon from a mixture of amorphous silica – tripoli and flask, with partial replacement of iron from steel cuttings with iron from magnetite concentrate and FeSi25 ferrosilicon.

2 Research methods

The studies were conducted using a specially designed laboratory setup based on a single-electrode electric arc furnace lined with chrome–magnesite brick, which provides high refractoriness and chemical resistance under strongly reducing conditions. The furnace bottom was fabricated from a massive carbon–graphite block that simultaneously served as the mechanical support for the crucible and as the lower current lead, ensuring stable current distribution and minimizing contact resistance during operation. A cylindrical graphite crucible electrode with an internal diameter of 6 cm and a height of 16 cm was installed on the bottom. Such dimensions were selected to provide a sufficient melt volume while maintaining a compact, controllable arc zone. To improve heat transfer from the arc to the charge and to form a more homogeneous temperature field in the working space, the annular gap between the crucible and the refractory lining was filled with graphite chips of 0.1–0.3 cm fraction. This packing material increased the effective thermal conductivity of the side space and reduced radial temperature gradients.

The upper current lead was made from a graphite electrode with a diameter of 3 cm, which was connected to a mechanical movement system enabling controlled vertical displacement. This arrangement allowed adjustment of the arc length and stabilization of the melting regime throughout the experiment. Electrical power was supplied by a single-phase furnace transformer of the TDZhF-1002 type equipped with a thyristor power regulator, which provided smooth control of furnace power and allowed the desired combinations of current and voltage to be maintained with high precision. To reduce radiative and convective heat losses and to stabilize the furnace atmosphere, a demountable refractory cover was installed on the upper part of the lining. This cover also facilitated safe loading of the charge and inspection of the arc space when required.

For each experimental run, a batch charge weighing 0.6–0.7 kg was prepared for melting. The charge mass was selected to ensure a sufficient melt depth while preventing overflow and maintaining a stable thermal regime in the laboratory furnace. Before the start of electric smelting, the empty furnace was subjected to preliminary heating by an electric arc for 35–40 minutes at a voltage of 40–45 V and a current of 400–450 A. This stage provided uniform heating and conditioning of the lining and graphite components, removal of residual moisture, and the establishment of a quasi-stationary temperature field, thereby reducing thermal shock upon subsequent charge loading.

After the preheating stage, the first portion of the charge (200–250 g) was introduced into the heated crucible. The mass of each portion was chosen so that the solid charge could be rapidly melted under stable arc conditions without excessive temperature fluctuations. After 7–12 minutes, once the first portion had completely melted and a homogeneous molten bath had formed, the second portion of the charge was loaded, followed by the third portion under similar time intervals. The total melting time, measured from the beginning of charge loading, was 40–45 minutes. During this main melting stage, the furnace was operated at a reduced voltage of 15–20 V and an increased current of 500–550 A, which provided the necessary power input for efficient smelting while maintaining the required thermal conditions in the bath.

At the end of melting, the power was switched off and the crucible containing the melt products was subjected to controlled cooling directly inside the furnace for 3–3.5 hours. Slow cooling in the closed hot furnace volume minimized thermal gradients and reduced the risk of cracking in the solidifying alloy and slag layers. Thereafter, the crucible was removed from the furnace and further cooled in air under laboratory conditions for 4–4.5 hours, bringing the temperature of the products to near-ambient levels. Upon completion of cooling, the crucible was mechanically broken, and the solidified contents were carefully separated into metallic alloy and slag fractions. Each fraction was weighed and sampled in accordance with standard metallurgical practice to ensure representativeness of the subsequent analyses.

The elemental composition of both the initial raw materials and the obtained products was determined using a combination of instrumental and physicochemical methods. Atomic absorption spectroscopy was performed on an AAS novAA800 (Germany), which provided quantitative determination of the main metallic components in solution after appropriate dissolution and sample preparation procedures. The morphology of the phases and the distribution of elements on the micro-scale were investigated by scanning electron microscopy coupled with energy-dispersive X-ray analysis (JSM-6490LV with INSAEnergy, Japan). This technique allowed the identification of metallic and oxide phases and clarified the microstructural features of the alloy and slag. In addition, the density of selected samples was determined using the pycnometric method, which provided supplementary information on phase composition and porosity.

The degree of silicon extraction into the metallic phase, $\alpha_{Si,\,(alloy)}$, %, was used as a key technological response. It was calculated as the ratio of the mass of silicon transferred into the alloy to the initial mass of silicon in the raw materials, expressed in percentage terms. This parameter characterizes the efficiency of silicon reduction and its incorporation into the target alloy, and it was used together with the final silicon concentration in the metal as the main response variables in the optimization procedure. To determine the optimal parameters of electric smelting and to quantify the effect of operating conditions on process outcomes, the experimental studies were planned and processed using the second-order rotary design method. This approach, belonging to the class of response surface methodology (RSM), makes it possible to effectively study the influence of several factors on the response of the system—in this case, the degree of silicon extraction and its concentration in the alloy—and to construct adequate mathematical models describing these relationships within the investigated factor space.

To determine the optimal parameters of electric smelting, the studies were conducted using the second-order rotary planning method. This method allows to effectively study the influence of several factors on the system response (the degree of silicon extraction and its concentration in the alloy) and to construct mathematical models describing these dependencies. The choice of this method is due to its high accuracy and the possibility of constructing adequate models with a relatively small number of experiments. For a two-factor experiment, the number of experiments (N) is calculated using the formula:

$$N=2^k+2\times k+2k+1 \quad (1)$$

where k – the number of independent factors, 2^k – the number of experiments in the core of the plan, 2k – the number of experiments with "star shoulders". The value of the star shoulder α is calculated from the expression $\pm\alpha=2^{k/4}$. For a two-factor experiment, the value of the star shoulder is $\pm\alpha=2^{2/4}=1.414$, and the number of experiments for the planned series of experiments will be:

$$N=22+2\times 2+5=13. \quad (2)$$

To assess the adequacy of the obtained regression equations, the confidence limit was 95%. Based on the regression equations, three-dimensional and plane models were created, showing the dependence of the process parameters on the content of coke and steel cuttings in the charge. Then, using the method of superimposing plane pictures, the optimization of the process parameters was carried out by the method. This method was repeatedly used by us in research in the field of ferroalloy production.

The studies were conducted with amorphous rocks, the chemical composition of which is presented in Table 1. In electric smelting, coke was also used, containing: 85.6% C, 4.3% SiO_2, 2.9% Fe_2O_3, 3.7% CaO, 1.8% Al_2O_3, 0.1% MgO, 0.6% S, 0.4% H_2O, 0.3% - other; steel cuttings with 98% Fe, 1.3% C, 0.3% Si, 0.2% Mg, 0.2% - other; magnetite concentrate from Iron Concentrate Company LLP: 85.9% Fe_3O_4, 9.4%SiO_2, 1.2% Al_2O_3, 1.8%CaO, 0.2%ZnO, 0.1%PbO, 1.1% - other (MgO, Na_2O, K_2O, SO_3, MnO).

Table 1. Chemical composition of tripoli, flask and their mixture.

Rock	Content, %									
	SiO_2	**Al_2O_3**	**CaO**	**MgO**	**Fe_2O_3**	**K_2O**	**Na_2O**	**$CaSO_4$**	**TiO_2**	**$CaCO_3$**
Flask	81.9	7.6	1.5	1.5	1.4	2.6	0.7	2.3	0.5	-
Tripoli	70.7	9.2	7.5	1.5	4.9	2.1	0.4	-	0.2	3.5
Mixture of Tripoli-flask (1:1)	76.3	8.4	4.5	1.5	3.15	2.35	0.55	1.15	0.35	1.75

3 Results and discussion

The first stage of the research – electric melting – comprised a series of exploratory experiments aimed at identifying the influence of charge composition on the efficiency of silicon recovery into the metallic phase. At this stage, particular attention was paid to two technologically significant components of the charge: coke, which acts as the principal carbonaceous reducing agent, and steel shavings, which serve simultaneously as a source of metallic iron and as an additional heat-absorbing component that affects the melt–slag balance. The quantities of these components were varied in terms of their mass fractions in the rock mixture, expressed as coke content C (or K), % and steel shavings content St, % of the total mass of the rock mixture. Within the established experimental ranges of C and St, the response of the system was evaluated using two key indicators: the degree of silicon extraction into the alloy $\alpha_{Si(alloy)}$, %, and the silicon concentration in the metallic phase

$C_{Si(alloy)}$, %. These parameters comprehensively characterize both the efficiency of silicon reduction from the initial raw material and the quality of the obtained alloy from the standpoint of its target chemical composition. The experimental data were summarized graphically; Figure 2 illustrates the combined effect of coke and steel shavings contents on $\alpha_{Si(alloy)}$ and $C_{Si(alloy)}$, forming the basis for subsequent regression analysis and optimization. The surface plots and contour diagrams obtained from these data reveal a pronounced dependence of the process outcomes on the selected factors, confirming their relevance as key variables in the smelting regime.

At the initial exploratory stage, a separate series of experiments was performed under conditions of a fixed coke content in the charge, set at 40%. This value was chosen as technologically reasonable, providing a sufficient amount of carbon for silicon reduction while avoiding excessive carburization of the melt and deterioration of slag fluidity. Under this constraint, the mass fraction of steel shavings *St* was varied systematically, and corresponding changes in $\alpha_{Si(alloy)}$ and $C_{Si(alloy)}$ were recorded. The resulting one-factor relationships make it possible to isolate the specific influence of steel shavings on the studied responses at a constant level of the main reducing agent and to evaluate the sensitivity of the process to changes in metallic iron input.

The experimental dependencies of the degree of silicon extraction into the alloy and the silicon concentration in the metal on the content of steel shavings at a constant coke fraction of 40% were then approximated using regression analysis. In accordance with the adopted methodological approach based on second-order response surface models, the influence of steel shavings on $\alpha_{Si(alloy)}$ and $C_{Si(alloy)}$ at C=40% is described by the following equations, which reflect the non-linear nature of the factor–response relationships and provide a quantitative basis for subsequent optimization of the electric smelting parameters:

With a constant amount of coke (40%), the dependencies of $\alpha_{Si(alloy)}$ and $C_{Si(alloy)}$ on the content of steel cuttings are described by the following equations:

$$\alpha Si(alloy) = 151 - 7.4 \times St + 0.16 \times St2 \qquad (R^2 = 1) \tag{3}$$

$$C\,Si(alloy) = -53 + 8.7 \times St - 0.18 \times St2 \qquad (R^2 = 1) \tag{4}$$

It is evident from the given material that an increase in steel cuttings promotes an increase in the degree of silicon extraction, but leads to a decrease in its concentration in the alloy.

The nature of the dependence of the degree of silicon extraction and the concentration of silicon in the alloy on the amount of coke (K) at a constant content of steel cuttings (30%) (Figure 2) changes in accordance with the equations:

$$\alpha Si(alloy) = 416.2 - 18.125 \times K + 0.2375 \times K2 \ (R^2 = 1) \tag{5}$$

$$C\,Si(alloy) = -575 + 30.5 \times K - 0.375 \times K2 \qquad (R^2 = 1) \tag{6}$$

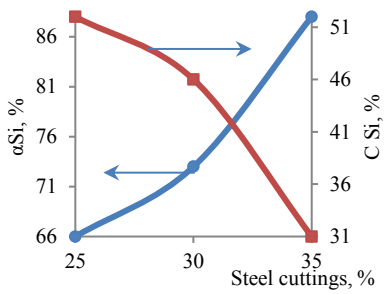


Fig. 1. Influence of steel cuttings on the degree of extraction and concentration of silicon in the alloy at 40% coke

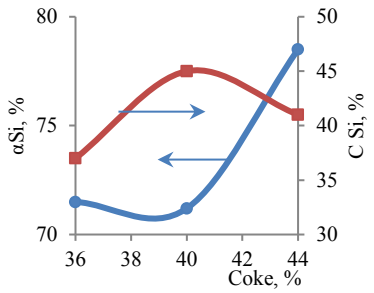


Fig. 2. Influence of coke on the degree of extraction and concentration of silicon in the alloy at 30% coke

It follows from Figure 2 that with an increase in the coke content from 36% to 44%, the extraction of silicon into the alloy increases. At 36-40% coke, a slight decrease in $\alpha Si_{(alloy)}$ is observed. With an increase in coke from 36% to 40%, an increase in $CSi_{(alloy)}$ is observed, and with an increase in coke to 44%, a decrease in $CSi_{(alloy)}$ occurs.

In order to replace expensive steel cuttings with more affordable magnetite concentrate, the influence of the degree of replacement of iron in steel cuttings with magnetite iron (γ, %) was studied. The results of this stage of the research are shown in Figure 3. The dependencies of the influence of the degree of replacement of iron in steel cuttings with magnetite iron on $\alpha Si_{(alloy)}$ and C $Si_{(alloy)}$ are described by the following equations:

$$\alpha Si(alloy)=+72.629+0.4582\gamma-0.0175\gamma 2+0.0002\gamma 3-1\times 10-6\gamma 4 \quad (R^2 = 0.95); \quad (7)$$

$$CSi(alloy)=45.706+0.2865\gamma-0.0082\gamma 2+4.5\times 10-5\gamma 3 \quad (R^2 = 0.97). \quad (8)$$

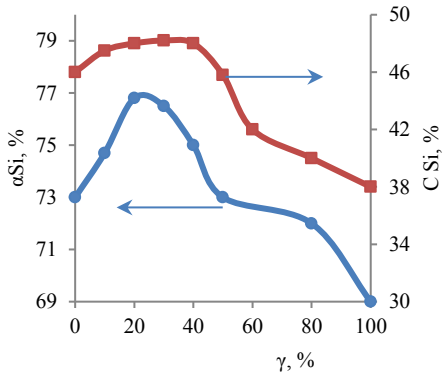


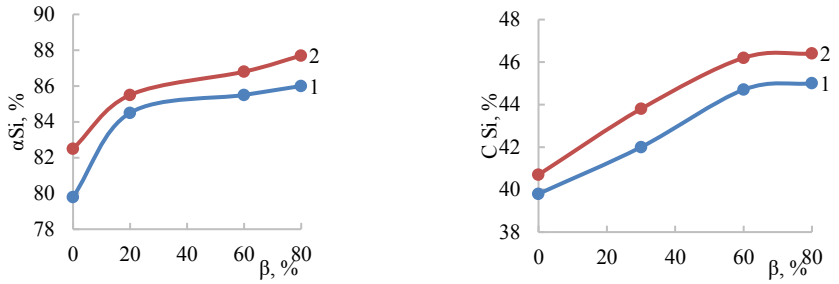
Fig. 3. Influence of the degree of replacement of iron in steel cuttings with magnetite iron (γ, %) on the degree of extraction and concentration of silicon in the alloy at 40% coke, 30% steel cuttings.

With an increase in γ to 20%, the degree of silicon extraction into the alloy increases and then decreases. The degree of silicon extraction also changes depending on the degree of iron replacement. It increases to a maximum of 48.2% (at γ = 30%), and then also decreases. From the information provided, it can be concluded that the rational degree of replacement of steel cuttings iron with magnetite iron is 20%, at which $\alpha Si_{(alloy)}$ is 76.8%, and $CSi_{(alloy)}$ is 48%.

At the next stage of the exploratory experiments, the influence of replacing steel cuttings with low-siliceous FeSi25 ferrosilicon, containing a significant amount of iron, was investigated. Figure 4 shows the influence of the degree of replacing iron in steel cutting with iron in FeSi25 ferrosilicon (β, %) and on the degree of extraction and concentration of silicon in the alloy during electric smelting of the mixture of tripoli and flask, as well as during smelting of quartzite. The obtained dependencies of the influence of β on $\alpha Si_{(alloy)}$ and C $Si_{(alloy)}$ during electric smelting of tripoli and flask are described by the following equations:

$$\alpha Si(alloy) = 82.76 + 0.1285\,\beta - 0.0009\,\beta 2 \quad (R^2 = 0.9563); \quad (9)$$

$$C\,Si(alloy) = 40.64 + 0.1347\,\beta - 0.0008\,\beta 2 \quad (R^2 = 0.9949). \quad (10)$$



The numbers at the lines: 1 – $SiO_{2(cryst)}$, 2 – $SiO_{2(amorph)}$

Fig. 4. Influence of the degree of replacement of iron in steel cuttings with iron in FeSi25 ferrosilicon (β, %) on the degree of extraction and concentration of silicon in the alloy.

It is evident from Figure 4 that the degree of extraction and concentration of silicon in the alloy during ferrosilicon production by electric smelting of tripoli and flask mixture is higher than during electric smelting of quartzite. The degree of extraction of silicon in the alloy increases with increasing β and reaches a maximum (87.7%) at β = 80%. The concentration of silicon in the alloy also increases with increasing β and is at the level of 46.2-46.4% at β = 60-80%.

Based on the conducted research, the optimal degree of replacement of iron in steel cuttings with iron in FeSi25 ferrosilicon, during electric smelting of the mixture of tripoli and flask, is 60%, at which $\alpha Si_{(alloy)}$ is 86.8%, and C $Si_{(alloy)}$ is 46.2%.

Taking into account the opposite nature of the influence of steel cuttings on $\alpha Si_{(alloy)}$ and C $Si_{(alloy)}$, as well as the extrema of the dependence of $\alpha Si_{(alloy)}$ and C $Si_{(alloy)}$ on the amount of coke, the search for optimal parameters was carried out using the second-order rotary planning method. The levels and intervals of variation of independent factors are given in Table 2. Based on the results of the experiments, a planning matrix was compiled (Table 3).

Table 2. Levels of factors and intervals of their variation in the study of the influence of coke (K) and steel cutting (St) during melting of the mixture of diatomite and flask.

Variables	**Coded notation**	**Natural view**	
		K, %	**St, %**
Main level	0	40	30
Variation interval	Δ	2.8	3.5
Upper level	+1	42.8	33.5
Lower level	-1	37.2	26.5
Upper “star” shoulder	+1.414	44	35
Lower “star” shoulder	-1.414	36	25

Table 3. Experiments’ planning matrix and their results.

№	**Variables**				**Process parameters**			
	Coded		**Natural**		$\alpha Si_{(alloy)}$ exp., %	$\alpha Si_{(alloy)}$ calc., %	C $Si_{(alloy)}$, exp., %	$CSi_{(alloy)}$, calc., %
	X_1	X_2	**K, %**	**St, %**				
1	-1	-1	37.2	26.5	64.5	65.8	45.3	46.3
2	+1	-1	42.8	26.5	67.3	69.7	50.5	50.9
3	-1	+1	37.2	33.5	83.6	82.6	31.0	30.9
4	+1	+1	42.8	33.5	85.3	85.5	35.3	34.6
5	1.414	0	44	30	79.0	77.4	42.0	42.3
6	-1.414	0	36	30	72.5	72.6	37.0	36.5
7	0	1.414	40	35	87.4	88.3	30.0	30.7
8	0	-1.414	40	25	67.6	65.3	54.0	53.1
9	0	0	40	30	72.0	72.8	44.6	44.1
10	0	0	40	30	72.1	72.8	44.5	44.1

Continuation of Table 3.

11	0	0	40	30	72.3	72.8	44.0	44.1
12	0	0	40	30	73.9	72.8	43.9	44.1
13	0	0	40	30	73.8	72.8	43.6	44.1

Based on the results of electric smelting according to the planning matrix, adequate second-order regression equations were obtained:

$$\alpha Si(alloy)=-315.1-9.792\times K-6.236\times St+0.1405\times K2+0.1652\times St2-2.8\times 10-2\times K\times St \quad (11)$$

$$CSi(alloy)=-509.439+25.57\times K+4.089\times St-0.302\times K2-9.06\times 10-2\times St.t2-$$

$$-2.296\times 10-2\times K\times St \quad (12)$$

These regression equations are adequate, since the calculated values of the Fisher criterion for equations (18) – 6.43 and (19) – 6.22 are less than the tabulated value (F_{tab}=6.59). Based on the obtained equations, volumetric response surfaces and their horizontal sections were constructed (Figure 5).

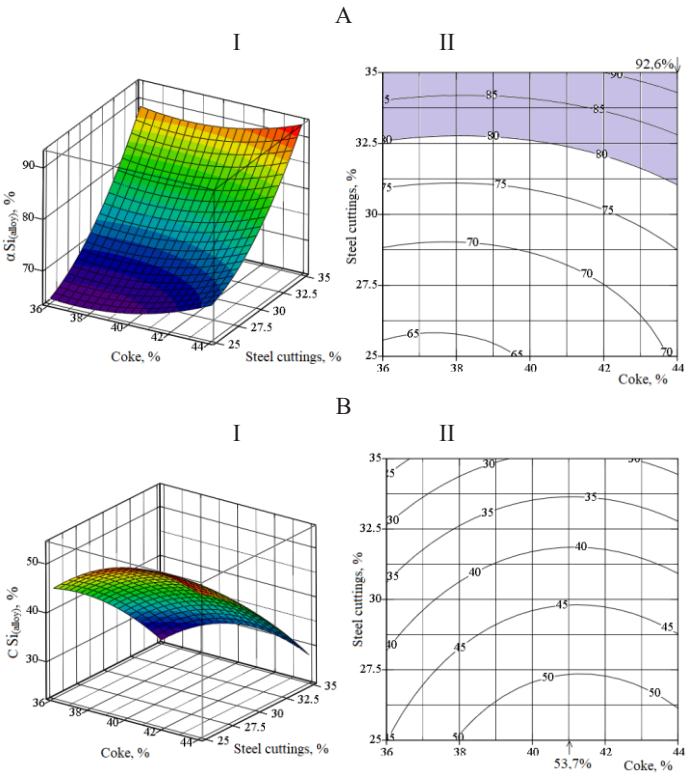


Fig. 5. Influence of the amount of coke and steel cuttings on the degree of extraction (A) and concentration (B) of silicon in the alloy during electric smelting of the mixture of tripoli and flask: I – volumetric surface, II – horizontal section.

As can be seen from Figure 5, the maximum degree of silicon extraction into the alloy is 92.61% with the coke content of 44% and steel cuttings of 35%. The highest silicon content in the alloy – 53.7% is observed with 41% coke and 25% steel cuttings.

To perform graphical optimization, a picture of the influence of the amount of coke and steel cuttings on the process parameters of electric smelting was created (Figure 6). Table 4 shows the process parameters of areas with different degrees of silicon extraction.

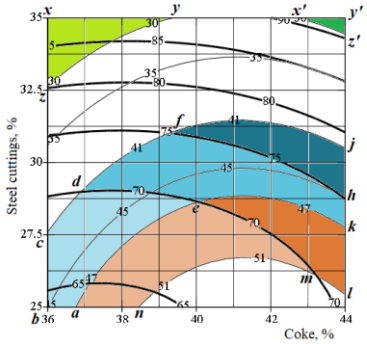


Fig. 6. Combined graphical information on the influence of the amount of coke and steel cuttings on the process parameters of electric smelting of tripoli and flask: (———) – αSi$_{(alloy)}$, %, (_____) – C Si$_{(alloy)}$, %

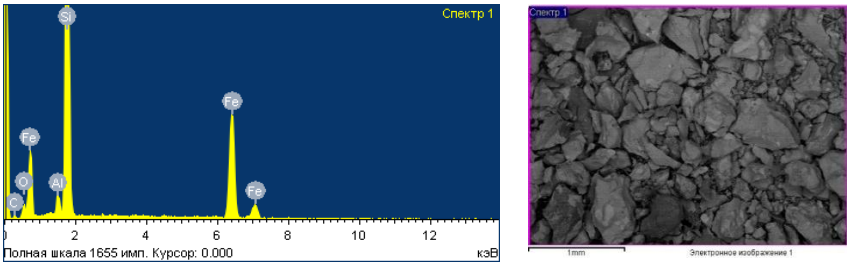
Table 4. Process parameters of the areas of Figure 6 with grades of the obtained alloy.

Area	Coke, %	Steel cuttings, %	αSi$_{(alloy)}$, %,	CSi$_{(alloy)}$, %	Alloy grade
xyz	36.0-39.4	32.6-35	80-88.25	23.2-30.0	FeSi25
x'y'z'	42.7-44	34.4-35	90.37-92.61		
abcde	36-40.1	25-29	64.3-70.0	41.0-47.0	FeSi45
dfhke	36.9-44	28.6-31	70.0-75.0		
fjh	39.2-44	28.8-31.4	75.0-78.7		
aemn	36.7-43.3	25-28.6	64.3-70	47.0-51.0	FeSi50
ekl	40.1-44	25.5-28.9	70-73.43		

As can be seen from Figure 6 and Table 4, it is possible to obtain FeSi25, FeSi45, FeSi50 ferrosilicon from the mixture of tripoli and flask. The formation of low-siliceous FeSi25 ferrosilicon with the maximum degree of silicon extraction at the level of 90.37-92.61% occurs when melting the mixture with 42.7-44% coke and 34.4-35% steel cuttings. FeSi45 ferrosilicon, with the highest degree of silicon extraction of 75.0-78.7%, is formed with 39.2-44% coke and 28.8-31.4% steel cuttings. Obtaining FeSi50 ferrosilicon is possible with 40.1-44% coke and 25.5-28.9% steel cuttings, while the maximum degree of silicon extraction is at the level of 70-73.43%.

Figure 7 shows a photo of the alloy smelted from the mixture of flask, tripoli, 39% coke, and 30% steel cuttings. According to density (5.4 g/cm^3), the Si content in the ferroalloy was 41.2%, according to SEM analysis (Figure 8), the Si content was 36.6%. According to GOST 1415-93, the resulting ferroalloy is classified as FeSi45 ferrosilicon.

Fig. 7. Photos of crucible (A) and crushed ferroalloy (B).



Element	C	O	Al	Si	Fe
Mass %	4.67	5.58	2.18	45.39	42.19

Fig. 8. SEM analysis of ferroalloy made from the mixture of tripoli and flask.

4 Conclusion

Based on the experimental results obtained during the electric smelting of a mixture of tripoli and flask in a 1:1 ratio, using iron-containing materials in combination with coke as a reducing agent, the following conclusions can be drawn:

1. During electric smelting of the mixture of amorphous rocks (tripoli and flask) with coke and steel cuttings as the iron source, the formation of ferrosilicon grades FeSi25, FeSi45 and FeSi50 is technically feasible within clearly defined compositional ranges of the charge. It has been established that the production of FeSi25 ferrosilicon occurs when the charge contains approximately 42–44% coke and 34–35% steel cuttings, under which conditions the degree of silicon extraction into the alloy reaches 90–92%. This indicates that, at relatively high contents of steel cuttings, the process is highly efficient in terms of silicon recovery, although the final silicon content in the metal corresponds to a lower ferrosilicon grade. In contrast, the formation of higher-grade ferrosilicon, FeSi45 and FeSi50, is achieved when the mixture is melted in the presence of 39–44% coke and 25–31% steel cuttings, with the degree of silicon extraction into the alloy ranging from 70 to 78%. These results show that increasing the silicon content in the alloy is associated with some reduction in the overall recovery of silicon, reflecting the changed thermodynamic and kinetic conditions of reduction and silicon distribution between metal and slag at lower iron input.

2. When 20% of the iron contained in steel cuttings is replaced by iron introduced in the form of magnetite concentrate during smelting of the tripoli–flask mixture with 40% coke, the process leads to the formation of ferrosilicon with a nominal composition corresponding to FeSi50. In this case, the silicon content in the alloy reaches 48%, which is close to the standard for FeSi50, while the degree of silicon extraction into the alloy is 76.8%. This result demonstrates that partial substitution of steel cuttings with magnetite concentrate does not impair, and may even stabilize, the production of higher-grade ferrosilicon, provided that the reducing conditions are maintained by an adequate amount of coke. The use of magnetite concentrate as an additional iron-containing component can be considered technologically justified, since it offers flexibility in raw material selection and may improve the availability and cost-effectiveness of the charge without causing a critical decline in silicon recovery. Thus, the combined use of steel cuttings and magnetite concentrate in the iron balance of the charge expands the possibilities for raw material optimization in ferrosilicon production from amorphous silica rocks.

3. Replacement of the iron contained in steel cuttings with iron supplied in the form of FeSi25 ferrosilicon during smelting of amorphous rocks (tripoli and flask) leads to a noticeable increase in the degree of silicon extraction into the metallic phase compared with traditional smelting using quartzite as the silica source. Experimental results show that when 60% of the iron from steel cuttings is substituted with iron from FeSi25 ferrosilicon in the

electric smelting of the tripoli–flask mixture, ferrosilicon of grade FeSi50 is obtained, and the degree of silicon extraction into the alloy reaches 86.8%. This indicates a significantly more efficient utilization of silicon from the charge due to the combined effect of the pre-alloyed silicon in FeSi25 and the reactive amorphous silica present in tripoli and flask. At the same time, the transition from quartzite to amorphous silica raw materials and the use of FeSi25 as an iron-bearing component make it possible to intensify the reduction process, decrease slag losses of silicon, and improve the overall material balance of the smelting process. Therefore, the proposed approach to partial replacement of steel cuttings with FeSi25 ferrosilicon can be regarded as a promising route for enhancing silicon recovery and obtaining higher-grade ferrosilicon when processing amorphous silica rocks.

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