

THERMODYNAMIC ANALYSIS OF OBTAINING FERROALLOY  
FROM SILICON-ALUMINUM-CONTAINING SILICA CLAY*Danijel' Amanov<sup>1, \*</sup>, Viktor Shevko<sup>1</sup>, Gul'nara Karatayeva<sup>1</sup>,  
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**Abstract.** The article presents results of thermodynamic modeling of Fe-Si-Al complex containing alloy of the silica clay (77.8 %  $\text{Al}_2\text{O}_3$ , 11.6 %  $\text{Al}_2\text{O}_3$ ). The modeling is based on the principle of minimum Gibbs energy and fulfilled by means of software complex HSC-5.1. It was found that the joint reduction of silicon and aluminum from an amorphous  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  is characterized by higher thermodynamic probability than from a mixture of a crystalline  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$ . At the silicon reduction there is the undesirable formation of a gaseous  $\text{SiO}$ ; the transition degree of silicon in  $\text{SiO}$  can be reduced by means of decrease in temperature and increase in carbon content.

**Keywords:** Si-Al containing silica clay, thermodynamic modeling, carbothermic reduction, complex ferroalloy.

## 1. Introduction

In the production of siliceous ferro alloys, the initial components are quartzite, iron shavings and coke [1]. For the improvement of engineering and economical performance of complex ferroalloys production the researches on the coke replacement by various carbonaceous reducers [2-8] have been carried out. Also investigations connected with substitution of quartzite by cheap and effective siliceous material have been fulfilled [9, 10]. It is found that silica clay can be used as a raw component. Its distinctive feature is the presence of 90 % of silicon oxide not in a crystalline state, but in an amorphous one [11]. In accordance with [12] heat formation and Gibbs free energy of amorphous silica are less than those for quartz (for amorphous silica  $\Delta H_{298}^0 = -901.56832$  kJ;  $\Delta G_{298}^0 = -848.64072$  kJ and for  $\text{SiO}_2(\beta\text{-quartz})$   $\Delta H_{298}^0 = -911.066$  kJ;  $\Delta G_{298}^0 = -853.536$  kJ). In this connection high reactivity of amorphous  $\text{SiO}_2$  in comparison with crystalline  $\text{SiO}_2$  can be expected.

A purpose of the given work is a research of a possibility of a complex silicon-aluminum-containing

ferroalloy production from a silica clay of the Darbaza deposit located in the South Kazakhstan area.

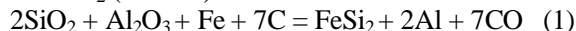
## 2. Experimental

The silica clay chemical composition was (%):  $\text{SiO}_2$  77.8;  $\text{Al}_2\text{O}_3$  11.6;  $\text{Fe}_2\text{O}_3$  3.4;  $\text{CaO}$  1.6;  $\text{MgO}$  1.5;  $\text{TiO}_2$  0.5 and  $\text{CaSO}_4$  1.5. The research has been performed by means of a modeling technique on the basis of a complex HSC 5.1 program [13] in accordance with two subprograms. Equilibrium Compositions subprogram has been used for the Gibbs energy calculation, and the equilibrium element distribution has been determined by means of Reaction Equations subprogram using a principle of the Gibbs energy minimization.

Earlier this software package has been used by us at the research of equilibrium element distribution in iron-silicon-carbon-containing systems and for chloride sublimation processes [16].

## 3. Results and Discussion

At the first stage it has been found, that joint reduction of silicon and aluminum according to Eq. (1) from an amorphous  $\text{SiO}_2$  is more preferable, than from a crystalline  $\text{SiO}_2$  (Table 1).



At the modeling of ferroalloy from the silica clay an amount of carbon has been calculated proceeding from a full reduction of silicon, aluminum and iron; and an iron amount – based on iron content in the ferroalloy – 55 %.

The curve of the temperature and carbon content influence on the equilibrium distribution of  $\alpha$  silicon and aluminum is represented in Fig.1. It follows from Fig. 1 that basic siliceous substances in the system “silica clay-carbon-iron” are  $\text{SiO}_2$ ,  $\text{FeSiO}_3$ ,  $\text{Al}_2\text{SiO}_5$ ,  $\text{CaSiO}_3$ ,  $\text{MgSiO}_3$ ,  $\text{Fe}_3\text{Si}$ ,  $\text{FeSi}$ ,  $\text{Si}$ ,  $\text{SiO}_{(\text{g})}$ , and aluminum-containing compounds are  $\text{Al}_2\text{SiO}_5$ ,  $\text{Al}$  and  $\text{Al}_2\text{O}_3$ . Besides the silicon in small amounts also passes into  $\text{FeSi}_2$ ,  $\text{Fe}_3\text{Si}$ ,  $\text{CaSi}$ . The silicon reduces at lower temperature in comparison with aluminum. It is connected with the fact that the temperature of silicon reduction beginning is 1941 K, and for aluminium – 2307 K.

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Table 1

Influence of temperature and SiO<sub>2</sub> form on  $\Delta G$  (J) of silicon and aluminum reduction

SiO <sub>2</sub> form	1573 K	1673 K	1773 K	1873 K	1973 K	2073 K	2173 K	$T_r$ , K
Crystalline	629.2	505	381.5	258.9	136.9	16.1	-104.0	2086.4
Amorphous	625.5	501.8	378.7	256.9	135.1	14.1	-106.3	2084.7

Note:  $T_r$  – temperature of the reduction beginning ( $\Delta G = 0$ )

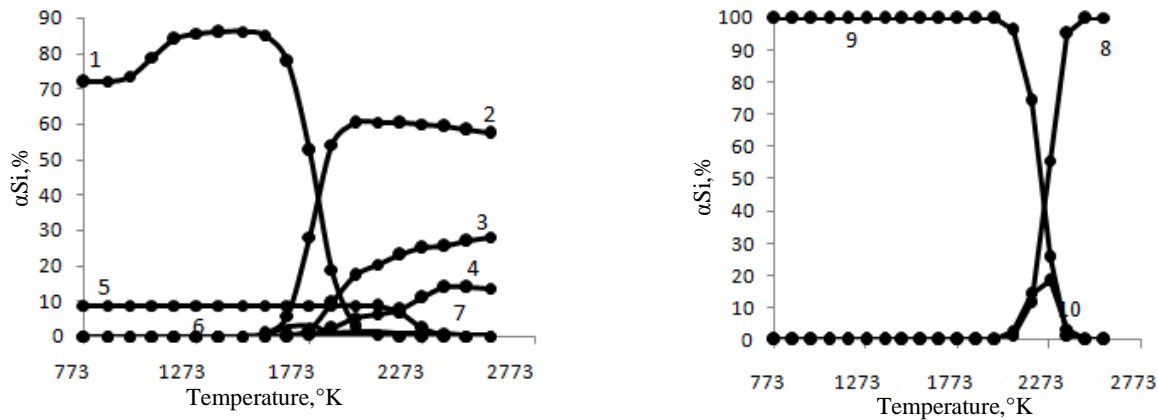


Fig. 1. Temperature effect on the  $\alpha$ -Si and  $\alpha$ -Al distribution in the system “silica clay-carbon-iron”: SiO<sub>2</sub> (1), FeSi (2), Al<sub>2</sub>SiO<sub>5</sub> (3), Si (4), SiO<sub>2(g)</sub> (5), Fe<sub>3</sub>Si (6), FeSi (7), Al (8), Al<sub>2</sub>SiO<sub>5</sub> (9) and Al<sub>2</sub>O<sub>3</sub> (10)

Table 2

Influence of temperature and carbon content on the element silicon formation degree (%)

$T$ , K	Carbon content, %			
	30	36	42	48
1473	$3.3 \cdot 10^{-4}$	$4.24 \cdot 10^{-4}$	$5.18 \cdot 10^{-4}$	$6.14 \cdot 10^{-4}$
1573	$9.42 \cdot 10^{-3}$	$12.1 \cdot 10^{-3}$	$14.91 \cdot 10^{-3}$	$17.168 \cdot 10^{-3}$
1673	0.13	0.17	0.21	0.25

Fig. 2 contains the information about the influence of temperature and carbon content on the equilibrium distribution degree of  $\alpha$ -silicon in iron silicides. It follows from this figure that the silicon starts to turn into FeSi at  $T \geq 1523$  K. The maximum  $\alpha\text{Si}(\text{FeSi})$  is observed at 1973–2273 K (60 %) and carbon content of 36–48 % relative to the silica clay weight. The silicon in an appreciable degree ( $>0.1$  %) begins to reduce at  $T \geq 1673$  K (Table 2).

Increase in the carbon amount from 30 to 48 % relative to the silica clay weight promotes the growth of silicon transition degree in element silicon;  $\alpha\text{Si}(\text{Si})$  increases from 12.92 to 33 %. In the process the dependence  $\alpha\text{Si}(\text{Si})_{\text{max}} = f(C)$  can be represented as follows:

$$\alpha\text{Si}(\text{Si})_{\text{max}} = -131.01 + 44.289 \ln C \quad (2)$$

The dependence of silicon transition degree in Fe<sub>3</sub>Si and FeSi<sub>2</sub> on carbon content ( $C$ ) has an extremal character (for Fe<sub>3</sub>Si – at 1973 K, and for FeSi<sub>2</sub> – at 1773 K). The increase in carbon content from 30 to 42 %  $\alpha\text{Si}(\text{Fe}_3\text{Si})$  raises from 2.1 to 3.5 % and  $\alpha\text{Si}(\text{FeSi}_2)$  changes from 1.15 to 1.37 %. Thus the carbon content

influence on the values of  $\alpha\text{Si}(\text{FeSi})$  and  $\alpha\text{Si}(\text{FeSi}_2)$  is described by Eqs. (3) and (4):

$$\alpha\text{Si}(\text{Fe}_3\text{Si}) = 33.309 - 1.4421C + 1.75 \cdot 10^{-2} \cdot C^2 \quad (3)$$

$$\alpha\text{Si}(\text{FeSi}_2) = -157.9 + 13.164C - 0.36C^2 + 3.3 \cdot 10^{-3} \cdot C^3 \quad (4)$$

The temperature and carbon content effect on the total silicon transition ( $\alpha\text{Si} \Sigma$ ) in an alloy as FeSi, Fe<sub>3</sub>Si, FeSi<sub>2</sub>, CaSi, CaSi<sub>2</sub> and Si is represented in Fig. 2. It is obvious from the figure that the appreciable ( $\geq 0.1$  %) silicon transition in the ferroalloy is observed at 1473 K.

The increase in carbon amount leads to the increase of  $\alpha\text{Si} \Sigma$ . So, if carbon content is 30 % the maximum value of  $\alpha\text{Si} \Sigma$  is 73 % at 2073–2273 K, and in the presence of 48 % of carbon  $\alpha\text{Si} \Sigma$  increases to 91 % at 2373–2473 K. The dependence of  $\alpha\text{Si} \Sigma_{\text{max}} = f(C)$  can be expressed by the equation:

$$\alpha\text{Si} \Sigma = -23.064 + 4.713C - 5.4 \cdot 10^{-2} \cdot C^2 \quad (5)$$

Because of the complex dependence of temperature and carbon amount influence on the extraction of silicon into the alloy, in further studies we used the method of the second order experimental design [16]. We found the

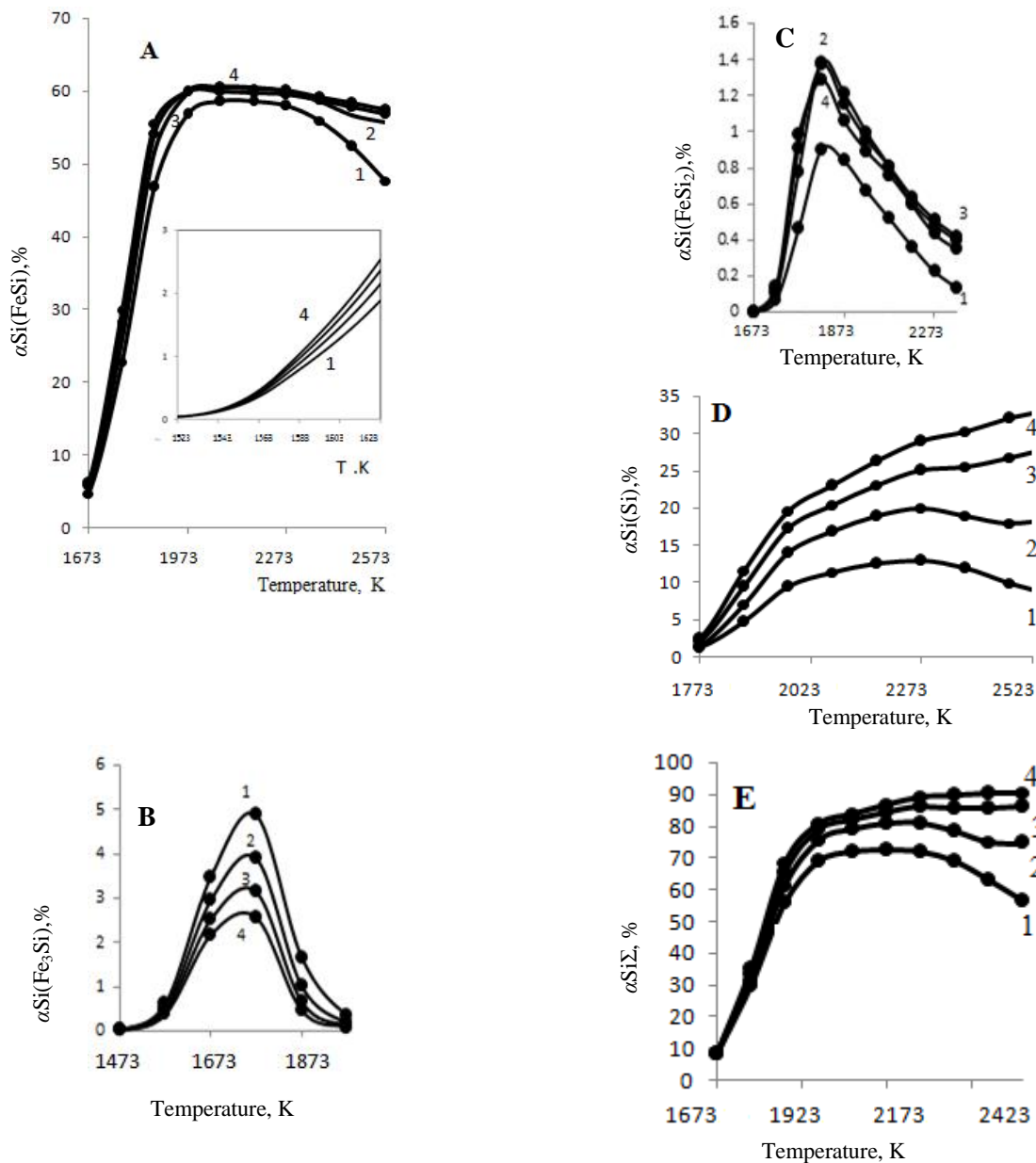
following adequate regression equation: the effect of temperature ( $T$ , K) and the amount of carbon ( $C$ , % relative to the weight of the silica clay) on  $\alpha\text{Si}\Sigma$ .

$$\alpha\text{Si}\Sigma = 1.63 \cdot 10^{-10} \cdot T \cdot C - 9.51 \cdot 10^{-5} \cdot T^2 + 0.36T - 0.04C^2 + 0.93C - 378.42 \quad (6)$$

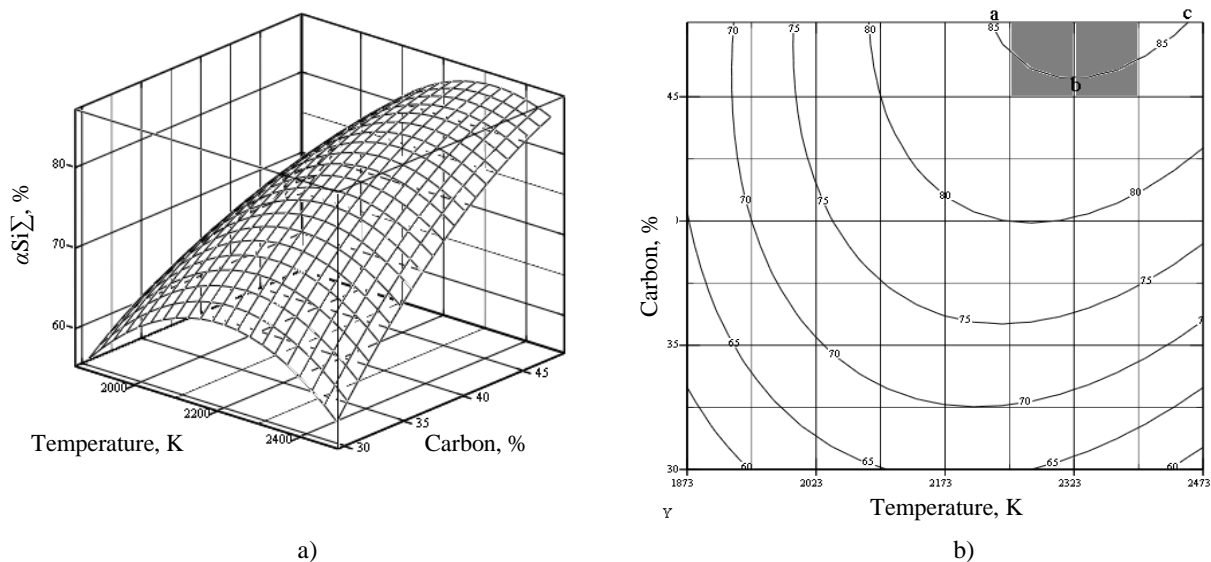
Using Eq. (6) and the methodology published in [17] we received three-dimensional image surface and its horizontal cuts as a dependence on temperatures and

carbon amount (Fig. 3). Fig. 3 shows that high  $\alpha\text{Si}\Sigma$  (85–87%) can be obtained in the technological field abc, that is takes place when the temperature is 2200–2470 K and 46–48 % carbon relative to the weight of the silica clay.

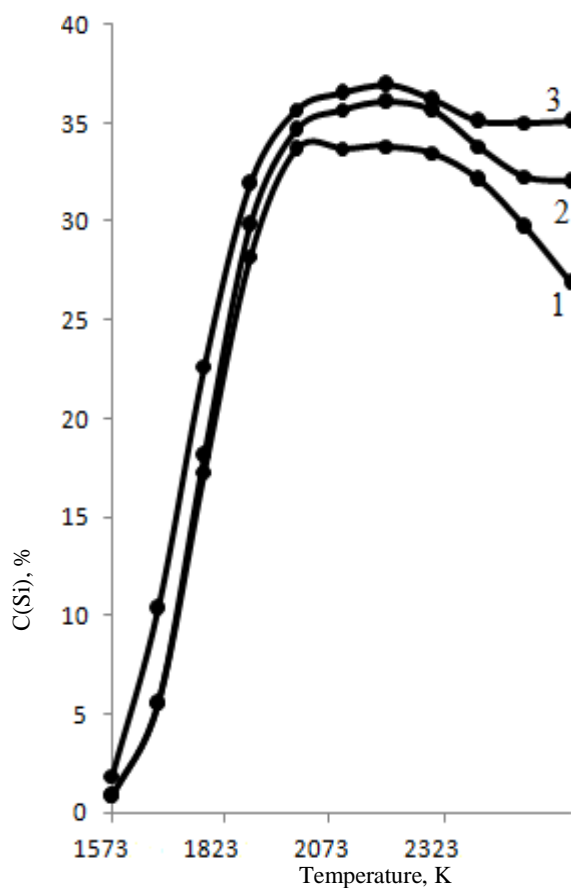
The temperature and carbon amount effect on aluminum content in the ferroalloy produced is represented in Table 3, and on silicon content and Al and Si sum in the ferroalloy – in Figs. 4 and 5.



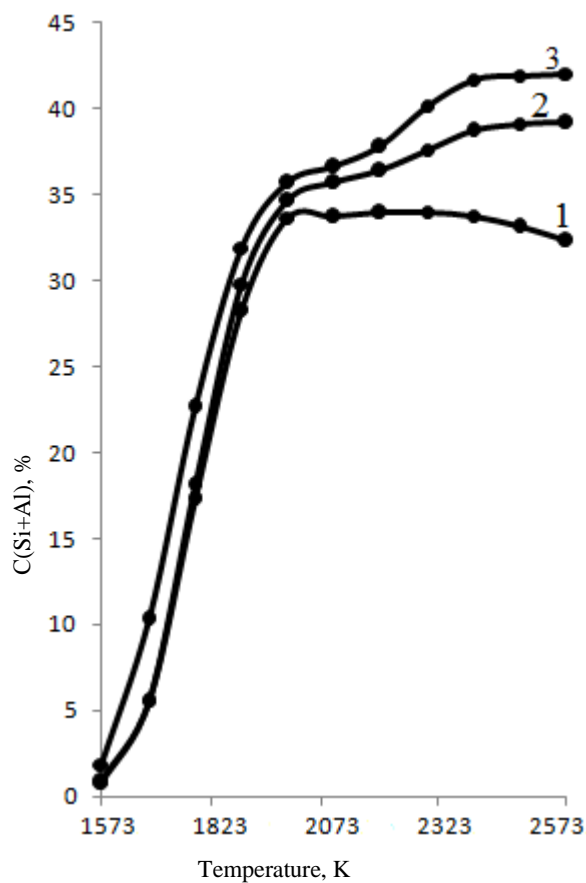
**Fig. 2.** Influence of temperature and carbon content on the silicon transition degree into iron silicides and element silicon in the system “silica clay-carbon-iron”. Silicon transition degree into FeSi (A),  $\text{Fe}_3\text{Si}$  (B),  $\text{FeSi}_2$  (C), Si (D) and  $\text{Si}\Sigma$  (E).  $C$ , %: 30 (1); 36 (2); 42 (3) and 48 (4)



**Fig. 3.** Influence of temperature and carbon on the degree of transition silicon in ferroalloy in the system “silica clay-carbon-iron”: three-dimensional image of the response surface (a) and horizontal sections of the response surface (b).  
 Digitals on the lines are  $\alpha\text{Si}\Sigma$



**Fig. 4.** Temperature and carbon amount effect on Si content in the ferroalloy with C, %: 30 (1); 36 (2) and 42 (3)



**Fig. 5.** Temperature and carbon amount effect on Si+Al content in the ferroalloy with C, %: 30 (1); 36 (2) and 42 (3)

Table 3

## Temperature and carbon amount effect on aluminum content in the obtained ferroalloy

B, %	Temperature, K						
	1973	2073	2173	2273	2373	2473	2573
30	$6 \cdot 10^{-4}$	$6.5 \cdot 10^{-3}$	$6.9 \cdot 10^{-3}$	0.47	1.64	3.41	5.45
36	$2 \cdot 10^{-3}$	$3.1 \cdot 10^{-3}$	0.36	2.01	4.91	6.83	7.21
42	$4 \cdot 10^{-3}$	$7.9 \cdot 10^{-2}$	0.87	3.97	6.63	6.91	6.93

Note: B – carbon content relative to the silica clay weight

It follows from the data submitted in Table 2 that at 2373–2573 K the ferroalloy contains 6–7 % of aluminum.

The produced ferroalloy is a complex alloy; it represents ferrosilicoaluminum [14]. The content of the sum of silicon and aluminum in the alloy increases with increasing temperature and the amount of carbon (Fig. 5). Maximum Si+Al content in the alloy is 41 %. In accordance with Al/Si ratio in the obtained alloy (0.189–0.197) the given ferroalloy complex corresponds to ferrosilicoaluminum of FS45A10 grade [15].

## 4. Conclusions

On the basis of the results of thermodynamic modeling the interaction of silica clay with carbon and iron it is possible to draw the following conclusions:

- the joint reduction of silicon and aluminum from an amorphous  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  is characterized by higher thermodynamic probability than from a mixture of the crystalline  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$ ;
- at the chemical interaction of an amorphous  $\text{SiO}_2$ -based silica clay with carbon in the presence of iron there is the reduction of silicon and aluminum and formation of  $\text{Fe}_3\text{Si}$ ,  $\text{FeSi}$ ,  $\text{FeSi}_2$ , Si, Al; in the process the silicon mainly converts into  $\text{FeSi}$ ;
- at the silicon reduction there is the undesirable formation of the gaseous  $\text{SiO}$ ; the transition degree of silicon in  $\text{SiO}$  can be reduced by means of decrease in temperature and increase in carbon content;
- a high (>85 %) degree of the silicon transition from the silica clay in the ferroalloy is observed at 2200–2470°K and 46 % of carbon (relative to the silica clay weight); the complex ferroalloy obtained – ferrosilicoaluminum – has the total silicon-aluminum content up to 42 %.

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## ТЕРМОДИНАМІЧНИЙ АНАЛІЗ ОДЕРЖАННЯ ФЕРОСПЛАВУ З КРЕМНІЙ-АЛЮМІНІЙ-ВМІСНОЇ ОПОКИ

**Анотація.** Приведено результати термодинамічного моделювання процесу одержання комплексного Fe-Si-Al сплаву з опоки (77.8 %  $\text{Al}_2\text{O}_3$ , 11.6 %  $\text{Al}_2\text{O}_3$ ). Термодинамічне моделювання проведено за допомогою програмного комплексу HSC-5.1. Визначено, що сумісне відновлення кремнію та алюмінію з аморфного  $\text{SiO}_2$  та  $\text{Al}_2\text{O}_3$  характеризується вищою реакційною здатністю, ніж із суміші кристалічного  $\text{SiO}_2$  та  $\text{Al}_2\text{O}_3$ . Показано, що при відновленні кремнію відбувається небажане утворення газоподібного  $\text{SiO}$ ; ступінь перетворення кремнію в  $\text{SiO}$  може бути зменшений за рахунок пониження температури і збільшення вмісту вуглецю.

**Ключові слова:** Si-Al-вмісна опока, термодинамічне моделювання, карботермічне відновлення, комплексний феросплав.