Crossref
DOI: 10.31643/2023/6445.07
Metallurgy

Electrothermal production of ferroalloy from tripoli

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Received: *May 29, 2022*
Peer-reviewed: *June 5, 2022*
Accepted: *July 25, 2022*

ABSTRACT
The article presents the research results on the electrothermal production of a ferroalloy from an amorphous sedimentary rock tripoli. The studies were carried out by electric melting in a single-electrode arc furnace using the second-order rotatable experiment planning (Box-Hunter plan). The influence of the amount of coke and steel chips on the degree of extraction of silicon into the alloy and the content of silicon in it is determined. It was found that silicon from tripoli to ferroalloy passes by 49-90.6%, and the silicon content in the alloy is 28-48%. Ferrosilicon grade FS25 (23.0-29% Si) is formed in the presence of 30-33.6% coke and 40.6-45.0% steel chips, grade FS45 (41-46.6% Si) with 32.1-40.9% coke and 26.2-37.0% steel chips. The maximum degree of silicon extraction (90.0-90.3%) in FS45 grade ferrosilicon (42.6-43.5% Si) is observed in a small coke range (36.0-37.3%) and steel chips (33.0-35.2%). Using tripoli instead of quartzite in the charge makes it possible to reduce the duration of the process by 1.2 times.
Keywords: tripoli, electric melting, thermodynamics, ferroalloys, ferrosilicon

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Introduction

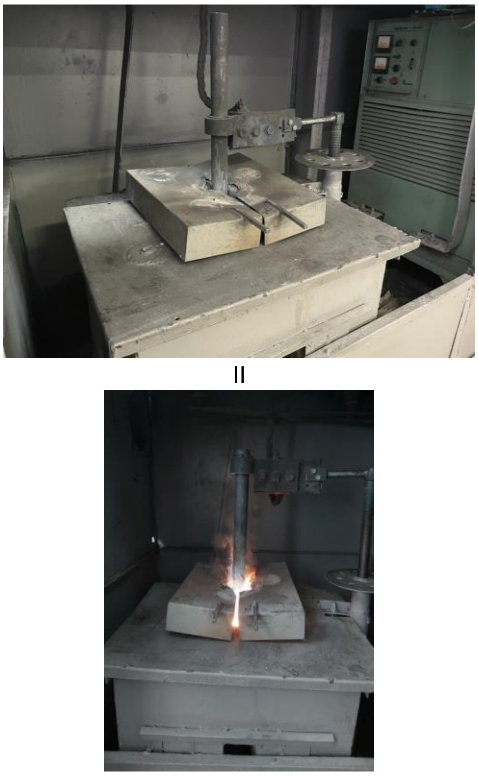
According to [1], the world reserves of tripoli, a sedimentary rock containing up to 86% SiO_2, are > 1.1 billion tons. The main part of tripoli consists of opal-like silica and a small number of shells of diatomaceous algae [[2], [3]]. Therefore, silica in tripoli is mainly in an amorphous state, a characteristic feature of which is an increased reactivity in comparison with the crystal form [4]. Using this property of amorphous silica, in contrast to the known methods of its application [[5], [6], [7], [8], [9], [10]], it was proposed to use tripol as a silicon-containing raw material to produce a siliceous ferroalloy [11] for the smelting of which quartzite is used [[12], [13], [14], [15]]. The article presents the results of studies to determine the optimal parameters for the electrothermal production of silicon ferroalloy from tripoli.

Experimental part

The studies were carried out on the setup shown in Figure 1.

The main components of the installation include an arc single-electrode electric furnace, transformer, and short circuit. An electric furnace is a unit lined with chrome-magnesite bricks. The hearth of the furnace is made of a carbon-graphite block, which served as the lower conductor. A graphite electrode with an internal diameter of 9 cm and a height of 20 cm was installed on the hearth. The space between the crucible and the lining was filled with graphite chips with a particle size of 0.1–0.3 cm. The upper current conductor was made of a graphite electrode with a diameter of 5 cm.

I



II

I - General view, II - Electric melting

Figure 1- Installation for electric melting of tripoli

The furnace was equipped with a mechanical device for moving the electrode. The installation used a single-phase furnace transformer brand TDZhF-1002. The transformer was equipped with a thyristor power regulator. Maximum power 56kV·A. The short net was made of aluminum tires. An aluminum bus was connected to a graphite hearth using three copper studs. The upper electrode is connected to the aluminum bus by a flexible copper cable 2 cm in diameter. In the upper part, a detachable refractory cover 7 cm thick was installed on the lining.

Before melting, tripoli was ground in a ball mill to fractions <0.1 m and pelletized in the presence of bentonite clay on a bowl granulator. Dried granules 1-1.5 cm in size were mixed with coke and steel shavings. The charge was melted in portions (300-500 g each) in an arc furnace at a voltage of 20-50 V and a current of 400-500 A. The melting time of the last charge was 30 minutes. After melting, the crucible with the charge was removed from the furnace and cooled for 4-5 hours. Then the crucible was broken. Alloy and slag were weighed. The content of metals in the alloy was determined using Scanning electron microscopy. In addition, the density of the alloys was determined by the pycnometric method (P, g/cm^3), using which the silicon content in the alloy was determined from the expression [16]:

$$CSi=690.679-545.783 \cdot P+166.151 \cdot P^2-17.467 \cdot P^3 \quad (1)$$

The degree of extraction of silicon into the alloy (αSi, %) was determined from the ratio of the mass and metal in the alloy to the mass of metal in the charge.

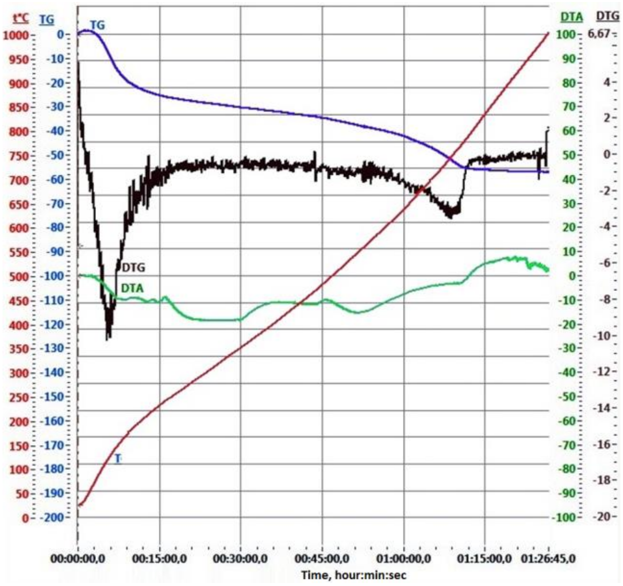
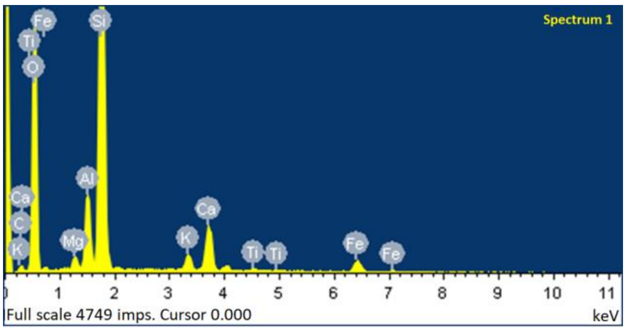


Figure 2- DTA analysis

Figure 2 shows a tripoli derivatogram, which shows that the heating of tripoli was accompanied by two endothermic effects. The first at 50-220 °C and the second at 600-830 °C. The first effect is associated with the decomposition of magnesium and calcium carbonates. The weight loss of tripoli was 13.52%. Figure 3 shows the SEM analysis of tripoli dried at 200-230 °C for 30 minutes.

I



II

Element	C	O	Mg	Al	Si	K	Ca
Weight, %	2.63	53.93	0.85	4.41	28.3	1.6	4.9

I- electronic image, II- elemental composition

Figure 3-SEM analysis of tripoli

It can be seen that in the original tripoli the Si concentration is -28.3%, Al-4.4%, O-53.93%. After burning at 800 °C the tripoli contained mass %: 71.6% SiO_2, 9.2% Al_2O_3, 7.5%CaO, 1.5% MgO, 2.1% K_2O, 4.9% Fe_2O_3, 0.2% TiO_2, 2.8% CO_2, and coke, mass %: 5.1% SiO_2, 2.0% Fe_2O_3, 1.8% Al_2O_3, 1.5% CaO, 0.4% MgO, 0.8% S, 1.2% H_2O, 85.8% C, 1.4% others. In steel chips, Fe was -96.9%, C -1.5%, Si-0.2%, Mn 0.3%, others (Ni, Cr, Cu) – 1.1%.

The studies were carried out by the method of planning experiments using a rotatable plan of the second order (the Box-Hunter plan) [17]. Regression equations for the influence of technological parameters on the degree of silicon extraction into the alloy and the silicon content in it, as well as a graphical representation of the parameters for optimizing the determination, respectively, according to the methods [[18], [19]]. As independent variables using the amount of coke (C) and steel chips (St), % of the mass of tripoli. The intervals of variation of independent variables are shown in Table 1, and the matrix of experiment planning and their results are shown in Table 2.

Table 1-Variable intervals

Level	Coded look		Natural look	
	Coke	***Steel shavings***	***Coke***	***Steel shavings***
	X1	***X2***	***C, %***	***St., %***
Zero level	0	0	38	35
Lower level	-1	-1	32.4	28
Upper level	+1	+1	43.6	42
Upper star shoulder	+1.414	+1.414	46	45
Lower Star Shoulder	-1.414	-1.414	30	25

Using the method described in [18,] and the data in Table 2, the following regression equations were obtained:

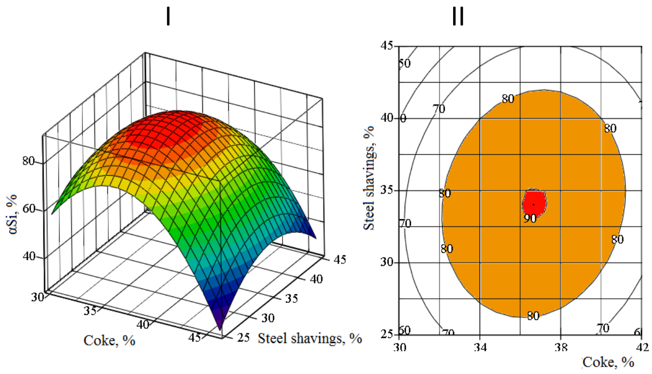
$$\alpha Si=-696.16+34.52\cdot C+9.012\cdot St-0.503\cdot C^2-0.166\cdot St^2+0.063\cdot C\cdot St; \quad (2)$$

$$CSi=-179.25+11.92\cdot C+0.96St-0.173\cdot C^2-0.036\cdot St^2+0.021\cdot C\cdot St. \quad (3)$$

Table 2-Experiment design matrix and results

№ of experiment	Variables				Technological optimization parameters			
	Coded		Natural					
	X_1	X_2	C, %	St., %	α_{Si} (exp), %	α_{Si} (distr), %	C_{Si} (exp), %	C_{Si} (distr), %
1	-1	-1	32.4	28	73.6	76.7	42.2	43.8
2	+1	-1	43.6	28	53.8	57.3	35.5	36.8
3	-1	+1	32.4	42	69.2	68.7	32.4	32.0
4	+1	+1	43.6	42	59.3	59.2	29.1	28.4
5	+ 1.414	0	46.0	35	49.5	47.7	28.0	27.8
6	- 1.414	0	30.0	35	69.3	68.1	36.0	35.3
7	0	+ 1.414	38	45	69.8	70.8	30.8	31.8
8	0	- 1.414	38	25	79.2	75.2	47.9	46.0
9	0	0	38	35	88.8	89.3	42.0	42.4
10	0	0	38	35	89.9	89.3	41.5	42.4
11	0	0	38	35	89.0	89.3	42.8	42.4
12	0	0	38	35	88.0	89.3	42.6	42.4
13	0	0	38	35	89.3	89.3	43.2	42.4

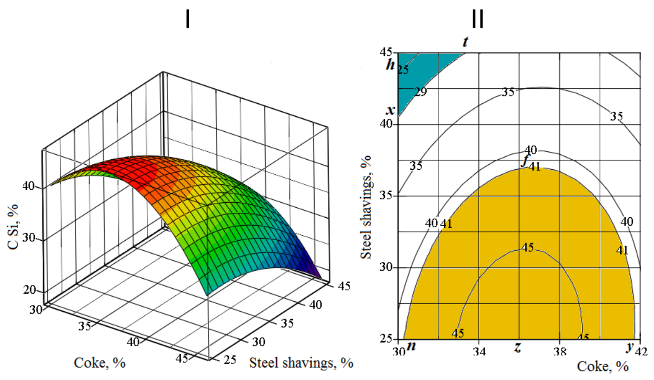
Figures 4 and 5 show volumetric and planar images constructed in accordance with [19] of the effect of coke and steel chips on the degree of silicon extraction into the alloy and the concentration of silicon in it.



I- volumetric image, II- planar image

Figure 4-Influence of coke and steel chips on the extraction of silicon into an alloy

Figure 4 shows that the degree of extraction of silicon into the alloy from 80 to 90% is observed at 32.1-41.2% of coke and 25.9-41.8% of steel chips (shaded area in the figure), and from 90.0 up to 90.6% at 36.0-37.3% coke and 33.2-35.0% steel chips (shaded area of Figure 4).



I - volumetric image, II - planar image

Figure 5- Effect of coke and steel chips on the silicon content of the alloy

A ferroalloy containing from 41 to 47% silicon (ferrosilicon grade FS45 [20]) is formed in the ***nfyz*** region (Figure 5), in which the amount of coke is from 30.3 to 41.6%, steel chips - from 25 to 37%. Low-silicon ferrosilicon (FS25) is formed in the ***xht*** region in the presence of 30.0-33.3% coke and 40.6-45% steel chips. Figure 6 shows combined information on the effect of coke, and steel chips on αSi and CSi.

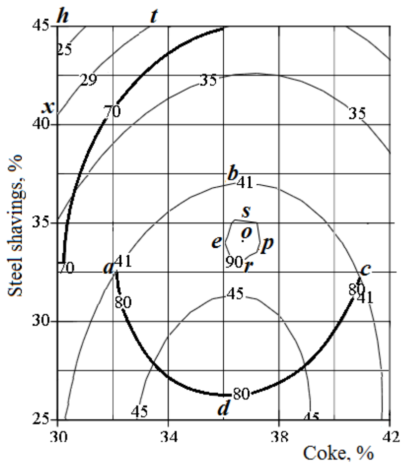


Figure 6 - Combined information on the effect of coke and steel chips on the extraction of silicon into the alloy and the content of silicon in it

The choice of optimal conditions for obtaining a ferroalloy from tripoli was determined based on the accepted conditions: αSi ≥80% and CSi>41%. The region ***abcd*** meets these conditions. Table 3 shows the boundary parameters of the three regions in Figure 6.

Table 3 - Boundary values of technological parameters in the production of ferroalloys from Tripoli

Point in the figure	Technological parameters			
	Coke, %	Steel chips, %	C Si, %	αSi, %
a	32.1	32.5	41.0	80.0
b	37.0	37.0	41.0	88.9
c	40.9	32.2	41.0	80.0
d	36.3	26.2	46.6	80.0
x	30.0	40.6	29.0	58.3
h	30.0	45.0	23.0	47.7
t	33.3	45.0	29.0	62.5
o	36.6	34.0	43.5	90.3
e	36.0	34.5	43.0	90.0
s	37.0	35.2	42.6	90.0
p	37.3	34.5	43.0	90.0
r	37.0	33.0	44.0	90.0

Table 6 shows that ferrosilicon grade FS45 is formed from tripoli in the presence of 32.1-40.9% coke and 26.2-37.0% steel chips. The degree of extraction of silicon into the alloy is 80-90.6%. Ferrosilicon grade FS25 is formed with a large number of steel chips - 40.6-45.0% and less coke - 30.0-33.3%. However, the extraction of silicon into the alloy, in this case, is only 47.7–62.5%. It is necessary to dwell on the region ***espr***, in which αSi is 90.0-90.3%, and the concentration of Si in the alloy is 42.6-43.5%. Such indicators are achieved with 36-37.3% coke and 33.0-35.2% steel chips.

Figure 7 shows photographs of ferroalloys obtained with various amounts of coke and steel chips.

I №3 II №11

The numbers in the photographs correspond to the melting numbers according to table 3
I- ferrosilicon FS25 (Si=29-32%), II- ferrosilicon FS45 (Si=41.5-43.2%)
Figure 7-Photos of some ferroalloys obtained from tripoli

It should be noted that in comparison with the conventional charge, which uses quartzite, the smelting of ferrosilicon from tripoli is more intensive. So, for experiment No.14, the duration of melting of the last portion of the charge decreases from 30 to 25 minutes, i.e. 1.2 times.

Conclusions

Based on the studies carried out on the production of ferroalloys by electric melting of tripoli, the following conclusions can be drawn:

- silicon from tripoli into ferroalloy is extracted by 49-90.6%, and the silicon content in the alloy was 28-48%;
- ferrosilicon grade FS25 (23.0-29% Si) is formed in the presence of 30-33.3% coke and 40.6-45.0% steel chips, grade FS45 (41-46.6% Si) with 32.1-40.9% coke and 26.2-37 % steel chips;
- the maximum degree of extraction of silicon (90.0-90.3%) in ferrosilicon FS45 (42.6-43.5% Si) is observed in a small range of coke (36.0-37.3%) and steel chips (33.0-35.2%);
- in comparison with the standard charge, the duration of the smelting of ferrosilicon from tripoli is reduced by 1.2 times.

Cite this article as: Shevko VM, Mirkayev NM, Aitkulov DK. Electrothermal production of ferroalloy from tripoli. Kompleksnoe Ispolzovanie Mineralnogo Syra = Complex Use of Mineral Resources. 2023;324(1):50-56. https://doi.org/10.31643/2023/6445.07

Трепелден ферроқорытпаны электротермиялық тәсілмен алу

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Мақала келді: 29 мамыр 2022
Сараптамадан өтті: 05 маусым 2022
Қабылданды: 25 шілде 2022

ТҮЙІНДЕМЕ
Мақалада аморфты шөгінді тау жыныстарынан - трепелден ферроқорытпаны электротермиялық өндіруді зерттеу нәтижелері келтірілген. Зерттеулер екінші ретті экспериментті ротатабельді жоспарлау әдісін (Бокс-Хантер жоспары) қолдана отырып, бір электродты доғалы пеште электрмен балқыту арқылы жүргізілді. Кокс пен болат жоңқаларының мөлшері кремнийдің қорытпаға шығарылу дәрежесіне және ондағы кремнийдің құрамына әсері анықталды. Трепелден ферросплавқа кремний 49-90.6% - ға ауысады, ал қорытпадағы кремний мөлшері 28-48% - ды құрайды. Кокс 30-36.3% және болат жоңқалар 40.6-45.0% қатысуымен ферросилиций маркалы ФС25 (23-29% Si) құрылады, Кокс 32.1-40.9% және болат жоңқалар 26.2-37% кезінде ферросилиций маркалы ФС45 (41-46.6% Si) түзіледі. Фс45 (42.6-43.5% Si) маркалы ферросилицийде кремнийді алудың ең жоғары дәрежесі (90.0-90.3%) шағын Кокс интервалында (36.0-37.3%) және болат жоңқасында (33.0-35.2%) байқалады. Кварциттің орнына трепелді қолдану процестің жалғасуын 1,2 есе азайтады.
***Түйін сөздер*:** Трепел, электрлік балқыту, термодинамика, ферроқорытпа, ферросилиций

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Электротермическое получение ферросплава из трепела

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Поступила: *29 мая 2022*
Рецензирование: *05 июня 2022*
Принята в печать: *25 июля 2022*

АННОТАЦИЯ

В статье приводятся результаты исследований электротермического получения ферросплава из аморфной осадочной породы-трепела. Исследования приводились электроплавкой в дуговой одноэлектродной печи с использованием метода рототабельного планирования эксперимента второго порядка (план Бокса-Хантера). Определено влияние количество кокса и стальной стружки на степень извлечения кремния в сплав и содержание в нем кремния. Найдено, что кремний из трепела в ферросплав извлекается на 49-90.6%, а содержание кремния в сплаве составило 28-48%; ферросилиций марки ФС25 (23-29% Si) образуется в присутствии 30-33.3% кокса и 40,6-45.0% стальной стружки, марки ФС45 (41-46.6% Si) при 32.1-40.9% кокса и 26.2-37% стальной стружки; максимальная степень извлечения кремния (90.0-90.3%) в ферросилиций ФС45 (42.6-43..5% Si) отмечается в небольшом интервале кокса (36.0-37.3%) и стальной стружки (33.0-35.2%). В сравнении со стандартной шихтой продолжительность выплавки ферросилиция из трепела сокращается в 1,2раза.

Ключевые слова: трепел, электроплавка, термодинамика, ферросплавы, ферросилиций

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