Laboratory-scale production of ferrosilicon using amorphous siliceous sedimentary rocks

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Abstract. Amorphous silica-rich sedimentary rocks, including diatomite, opoka, and tripoli, demonstrate significant potential as alternative raw materials for ferrosilicon production due to their enhanced reactivity compared to conventional quartzite. This study presents comprehensive laboratory-scale smelting trials utilizing these materials for ferrosilicon synthesis. Experimental procedures involved arc furnace melting of a charge mixture containing 77.2% SiO_2, 7.1% Al_2O_3, 3.8% CaO, 4.3% $\Sigma(Na_2O+K_2O)$, 1.3% MgO, and 3.3% other oxides, with a total charge mass of 35-37 kg comprising sedimentary rocks, steel shavings, and coke. The smelting process yielded either FeSi50 ferrosilicon (47.2% Si) or a Fe-Si-Al alloy (46.5% Si, 4.6% Al), depending on furnace power settings and charge composition. Silicon recovery rates reached 90.7% for FeSi50 production, while the Fe-Si-Al alloy process achieved 89.7% silicon recovery and 78.8% aluminum recovery. These results indicate the technical feasibility of substituting traditional quartzite with more reactive amorphous silica sources in industrial ferrosilicon production. The findings suggest broader applications for amorphous silica-containing rocks in manufacturing other silicon alloys, including ferrosilicomanganese, ferrosilicochromium, and ferrosilicocalcium, potentially improving process efficiency and reducing energy consumption in metallurgical operations.

1 Introduction

Steel production is a dynamically developing industrial sector. Thus, in 2000, the volume of the steel produced in the world amounted to 0.85 billion tons, and in 2022 it increased by 2.15 times, amounting to 1.89 billion tons [1]. The growth of steel production leads to a corresponding rise in ferroalloy output, including ferrosilicon. Thus, if in 2000, 2.654 million tons of silicon were extracted into ferrosilicon in the world, which, in terms of FeSi45, is 5.89 million tons, then in 2022 its production increased to 8 million tons [2]. The main silicon-containing raw material for manufacturing ferrosilicon is quartzite [3-6]. Its amount necessary for producing 1 ton of ferrosilicon depends on a grade of ferrosilicon, amounting, for example, according to [6, 7], from 552 kg (for FeSi25) to 1930 kg (for FeSi75). Silica in quartzite is in a crystalline form; therefore the rate of carbothermic reduction of SiO_2 has a

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certain limit due to the limitation of its reactivity. The reactivity of silica can be increased by using its amorphous form, which, like all amorphous substances, has increased reactivity [8]. Amorphous silica-containing raw materials include sedimentary rocks such as diatomite, tripoli, and opoka, containing up to 70-90% of SiO_2, mainly in the amorphous form.

Deposits of amorphous rocks are found on all continents [9-12]. Thus, diatomite reserves in Kazakhstan amount to 2 billion tons, Russia – 0.35 billion tons, the USA – 0.25 billion tons, China – 0.1 billion tons [13]. Opoka also has a wide geographical distribution. Deposits of this mineral in the form of Cretaceous and Paleogene strata up to 700 m thick are located in France, Poland, Belarus, Russia, and Central Asian countries [14-16]. According to [17], the largest deposits of tripoli are located in South Africa, the USA, Russia, and Belarus. It follows from the above material that the raw material potential of active silica-containing raw materials is quite high. Taking this into account, theoretical and practical studies were conducted on ferrosilicon smelting in arc furnaces using amorphous rocks [7, 18], which allowed for determining the optimal parameters for producing silicon ferroalloys from such raw materials.

The article presents the results of large-scale laboratory experiments on the production of silicon-containing ferroalloys using a 1:1:1 mixture of diatomite, tripoli, and opoka.

2 Research methods

The experiments were conducted using a setup centered around a single-phase, single-electrode electric arc furnace. The furnace had a bath with a volume of 9600 cm3 (20x20x24 cm). A diameter of a graphitized electrode was 7 cm. The bath was lined with chromium magnesite bricks. The furnace bottom was a graphite block (70x70x25 cm). In the upper part, the furnace had an opening lid with a hole with a diameter of 9 cm to place the electrode. The space between the lining and the furnace casing was filled with asbestos sheets 2.5 cm thick. The furnace featured a device designed to support and move the electrode. Energy was supplied to the furnace from a TDZhF-1002 furnace transformer, which was equipped with a thyristor regulator with power from 0 to 56 kVA. The short network was made in the form of aluminium busbars (1.5x4.5 cm) and a flexible part (from the bus to the electrode). Three copper pins were inserted into the graphite hearth, to which the aluminium bus was connected from the low side of the transformer. Current and voltage were monitored using ammeters and voltmeters installed on the transformer panel and the electric furnace panel (ammeter – TENGEN 42L6 GB/T7676-1998, voltmeter – CHNT 4226-China). Temperature under the furnace dome was measured with an infrared thermometer GM2200-EN-01 (China).

A photograph of the enlarged laboratory setup and fragments of the melting process are shown in Fig. 1. Before the electric melting, the furnace was heated with an arc for 5 hours. Following the heating stage, the initial portion of the charge (6–7 kg) was introduced into the furnace bath. After draining the melt, the second portion of the charge was loaded. The loading and draining cycle was repeated twice more until the charge was completely processed. After the charge was melted, the melt (slag and ferroalloy) was poured through a taphole into stainless steel molds measuring 28x8x9 cm. Before pouring the melt, the taphole was cleared with a crowbar and then processed with a burning device. After the pouring, the mold with the melt was transported from the niche along the overpass for preliminary cooling (up to 1.5 hours), and then the mold was moved to the cooling platform. After its cooling, the contents of the mold were sorted into alloy and slag.

I- furnace ignition, II – melting, III – draining the melt

Fig. 1. Large-scale laboratory setup

The melting of the charges was carried out for 4 hours. To increase the degree of aluminium extraction in the alloy, the melting of the second charge was performed with increased power.

The silicon and aluminium content in the resulting ferroalloy was determined by the methods established in State Standards 13230.1-93 and 13230.7-93. In addition, the silicon and aluminium content in the alloy and in the slag was determined by scanning electron microscopy (scanning electron microscope JSM-6490LV (Japan)).

The amorphous rocks with a fraction of 5-15 mm, coke – 5-10 mm and steel shavings with a coil length of 5-8 mm were used in the experiments. The composition of the amorphous rocks and their mixtures used for carrying out the experiments is shown in Table 1. The coke contained 85.65% of C, 4.6% of SiO_2, 1.4% of CaO, 0.3% of MgO, 2.0% of Al_2O_3, 2.3% of Fe_2O_3, 1.2% of H_2O, 1.9% of others; the composition of steel shavings was 97.8% of C, 1.8% of Si, 0.4% of others. Table 2 shows the composition of the charges used in the melting processes.

Table 1. Comparative chemical composition of amorphous rocks and their combinations (mixtures)

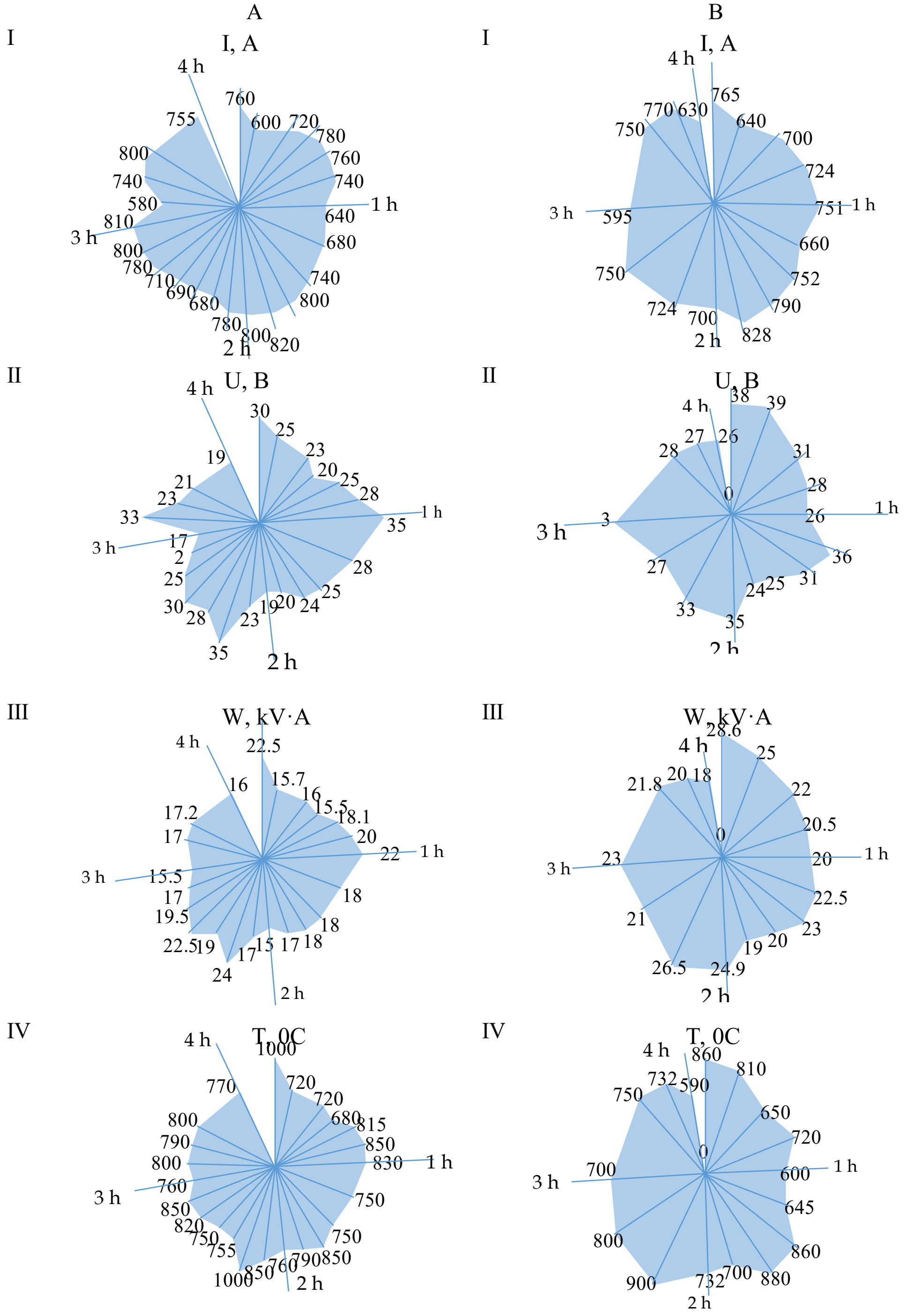
Rock	Content, %						
	SiO_2	CaO	MgO	Al_2O_3	Fe_2O_3	ΣNa_2O and K_2O	Others
Tripoli	79,0	3,5	1,2	7,3	3,3	2,6	3,1
Diatomite	80,3	2,6	1,3	6,8	2,8	4,2	2,0
Opoka	72,4	4,3	1,4	7,2	5,0	4,8	4,8
Mixture	77,2	3,8	1,3	7,1	3,7	4,3	3,3

Table 2. Chemical composition of the charges

# of charge (material mixture)	**Mixture**		**Coke**		**Steel shavings**		**Total**	
	kg	**%**	**kg**	**%**	**kg**	**%**	**kg**	**%**
1	20	51,7	8	22,8	7	20,1	35	100
2	21	56,7	9	24,3	7	19,0	37	100

3 Results and discussion

The first charge was melted at a current of 580-820 A, voltage of 17-35 V and power of 16-24 kVA, and the second charge was processed at 595-828 A, 24-39 V and 18-28 kVA. The temperature at the furnace throat varied within the range of 590–1000 °C. The electrical and temperature modes of the melting processes are shown in Fig. 2. Tables 3 and 4 show the material balances of the melting processes.



A – charge # 1, B – charge # 2
I – current, A; II – voltage, V; III – power, kVA; IV – temperature of the furnace throat, ^{0}C

Fig. 2. Electrical and temperature modes of melting the amorphous rocks' mixture

Table 3. Material balance of electric melting of charge No. 1

Input	kg	%	Amount						Distribution, %		
			Silicon		Iron		Aluminium		Silicon	Iron	Aluminium
			kg	%	kg	%	kg	%			
Rocks' mixture	20	57.1	7.3	36.5	0.5	2.5	0.74	3.7	96.7	0.66	90.25
Coke	8	22.8	0.22	2.8	0.18	2.2	0.08	1.0	2.91	2.38	9.75
Steel shavings	7	20.1	0.03	0.4	6.86	98	-	-	0.39	96.96	-
Total	35.0	100	7.55	21.8	7.54	21.5	0.82	2.3	100	100	100
Output											
Ferroalloy	14.5	41.4	6.85	47.2	7.2	49.6	0.14	0.96	90.7	95.5	17.0
Slag	3.7	10.6	0.26	7.1	0.16	4.3	0.66	17.8	3.4	2.1	81.2
Gases and discrepancy	16.8	48.0	0.44		0.18		0.02		5.9	2.4	1.8
Total	35	100	7.55		7.54		0.82		100	100	100

Table 4. Material balance of electric melting of charge No. 2

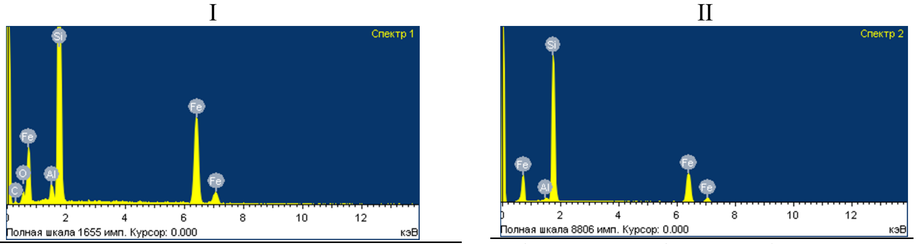
Input	kg	%	Amount						Distribution, %		
			Silicon		Iron		Aluminium		Silicon	Iron	Aluminium
			kg	%	kg	%	kg	%			
Rocks' mixture	21	56.7	7.66	36.5	0.52	2.5	0.78	3.7	96.4	6.86	89.65
Coke	9	24.3	0.25	2.8	0.20	2.2	0.09	1.0	3.23	2.63	10.35
Steel shavings	7	19.0	0.03	0.40	6.86	98.0	-	-	0.37	90.51	-
Total	37	100	7.94	21.4	7.58	20.5	0.87	2.35	100	100	100
Output											
Ferroalloy	14.8	40.0	7.12	46.5	7.3	47.7	0.68	4.6	89.7	96.4	78.8
Slag	2.8	7.6	0.26	9.3	0.15	5.5	0.15	5.5	3.2	1.9	17.3
Gases and discrepancy	19.4	52.4	0.56		0.13		0.04		7.1	1.7	3.9
Total	37.0	100	7.94		7.58		0.87		100	100	100

Photographs of the resulting alloys are presented in Fig. 3. Fig. 4 shows the result of the SEM analysis (general and local spectra), which confirmed that the produced ferroalloy belongs to the FeSi50 grade of ferrosilicon.


I II

I – alloy produced from charge #1, II – alloy produced from charge #2

Fig. 3. Photos of alloys



Element	C	O	Al	Si	Fe
Weight, %	4.67	5.58	2.19	45.38	42.18

Element	Al	Si	Fe
Weight, %	1.15	54.25	44.6

I – general spectrum, II – local spectrum

Fig.4. SEM analysis of the alloy produced from charge #1 (Energy-dispersion spectra and alloy composition made by the scanning electron microscopy)

When melting charge #1, the degree of silicon extraction into the alloy was 90.7%. The concentration of this element in the alloy was 47.2%. During the melting, the better part of aluminium (81.2%) was extracted in slag. For this reason, aluminium content in the alloy was 0.96%. In accordance with State standard 1415-93 (Kazakhstan), in terms of silicon and aluminium content, the resulting ferroalloy can be classified as FeSi50 ferrosilicon. The weight of the ferroalloy produced from 20 kg of the rocks' mixture was 14.5 kg (in terms of 1 t of the mixture, 0.725 t of ferroalloy is formed). The energy consumption per 1 t of the alloy was 4990 kW·h.

When melting the charge of the second composition, 89.7% of silicon and 78.8% of aluminium were extracted into the alloy. The concentrations of these elements in the alloy were 46.5% and 4.6%, respectively. In terms of 1 t of the mixture, the weight of the resulting alloy was 0.71 t. The energy consumption per 1 t of the alloy was 5300 kW·h. The resulting ferroalloy can be classified as FeSi50 ferrosilicon enriched with aluminium, i.e., as a Fe-Si-Al alloy.

In the future, these amorphous rocks may be the object of research into replacing quartzite for producing ferrosilicochromium and ferrosilicomanganese (for manufacturing of 1 t of these ferroalloys 298-1464 kg and 285-333 kg of quartzite, respectively, are used as well as other silicon-containing alloys, such as ferrosilicocalcium [19].

4 Conclusion

Widespread sedimentary rocks – diatomite, tripoli, opoka – are the potential reserve silica-containing raw materials for the production of ferrosilicon. They contain silica predominantly in its amorphous form, which has increased reactivity; this allows improving the speed characteristics of smelting ferrosilicon. The results of the large-scale laboratory tests on the electric smelting of mixtures of the amorphous rocks in continuous mode showed the possibility of producing FeSi50 ferrosilicon, containing 47.2% of silicon, with the degree of silicon extraction in the ferroalloy of 90.7%, as well as a Fe-Si-Al alloy, containing 46.5% of Si and 4.6% of Al, with the extraction of 89.7% of silicon and 78.8% of aluminium in the alloy.

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