Physicochem. Probl. Miner. Process., 59(1), 2023, 161853

http://www.journalssystem.com/ppmp

Physicochemical Problems of Mineral Processing

ISSN 1643-1049

Theoretical and experimental substantiation of obtaining an alloy from flotation tailings of lead-zinc sulfide ore

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Abstract: The article presents the results of thermodynamic and experimental research on the processing of cinders from the firing of Shalkiya deposit lead-zinc ore tailings with the production of siliceous ferroalloys. Thermodynamic modeling carried out using the HSC-6.0 complex based on the Gibbs energy minimization principle showed that the interaction occur with the formation of $CaSiO_3$, $FeSiO_3$, $MgSiO_3$, $K2O{\cdot}SiO_2$, FeSi, Fe_5Si_3, SiC, Fe_3Si, Si, SiO_g, $FeSi_{2.33}$, $FeSi_2$, CaSi, Zn, Zn_g, Pb, Pb_g; an increase in the iron amount in the system allows increasing the silicon extraction degree into the alloy at 1800°C to 76%, to reduce the silicon concentration in the alloy from 41 to 24%; FS25 grade ferrosilicon formed at 1752-1867°C in the presence of 88-100% iron, and FS45 grade ferrosilicon – at 1863-1900°C and 20-22.4% iron. Electric melting of a charge containing 63.83% calcined cinder of tailings, 19.15% coke, and 17.02% steel chips allows to obtain FS45 grade ferrosilicon (44.1-43.9% Si) with the extraction of 69.7% silicon and sublimates with the content of 32-38% zinc and lead. The results obtained allow complex processing of lead-zinc sulfide ore tailings with the extraction of not only non-ferrous metals, but also silicon in the ferroalloy.

Keywords: lead-zinc ore, cinder, enrichment tailings, thermodynamic modeling, electric melting, ferrosilicon, lead-zinc sublimates

1. Introduction

Zinc is obtained by pyro- or hydrometallurgical methods, involving preliminary enrichment (Sousa et al., 2017; Mütevellioğlu and Yekeler, 2019; Jian et al., 2019; Onukwuli and Nnanwube, 2022; Omarova et al., 2022). When enriching lead-zinc sulfide ores, only up to one tenth of the ore passes into a concentrate (Turkebaev and Sadykov, 1988; Shevko et al., 2021a). The rest (most) is stored in dumps, is used to fill the worked-out area (Feigl et al., 2010; Behera et al., 2020; Akkaya et al., 2021) or, at best, is used in the construction industry (for example, as an aggregate in concrete (Evdokimov et al., 2016; Peng et al., 2021; Onukwuli and Nnanwube, 2022; Ibrahim and Atmaca, 2022), the production of silicate and ceramic wall materials (Liu et al., 2019; Zhou et al., 2021; Zou et al., 2022), cement and concrete (Liang et al., 2017; Saedi et al., 2022)). The vast majority of enrichment tailings contains a significant amount of non-ferrous metals. As a rule, the processing of such tailings is reduced to the base metal flotation (Snurrnikov, 1986; Pacholewska et al., 2007; Semushkina et al., 2017; Feng et al., 2019; Hussaini et al., 2021). For example, during the flotation of tailings containing zinc, it is possible to obtain a standard pyrite and barite concentrate, sulfide middlings containing 6.2-7.7% Zn, 0.9-1.1% Pb and 0.7-0.9 % Cu. The extraction of non-ferrous metals from the ore in this case increases by 4.5% (Snurrnikov, 1986). And, with the combined use of a combined collector and a water-air microemulsion generator, the extraction of zinc increases by 14.13% (Semushkina et al., 2017). The work (Bekturganov et al., 2017) shows that using a flotation agent from a mixture of modified dithiophosphate, TC-1000 thionocarbamate and modified xanthate during tailings flotation allows increasing the degree of zinc extraction from the ore to 8.64%. To extract metals from tailings, heap leaching is used, which involves the conversion of the oxidation of sulfides in an oxygen environment

DOI: 10.37190/ppmp/161853

with the formation of water-soluble sulfates (Kametenko et al., 2017). The results of studies of the lead-zinc ore flotation process using regrinding and a modified reagent showed that in the zinc cycle, the zinc content increases from 41.9 to 57.9% (Mukhanova et al., 2015).

An attempt was made to comprehensively process the Bayaldyr deposit tailings of Achipollimetal plant with the production of cement clinker and sublimates containing Zn-Pb (Turkebaev and Sadykov, 1988). However, the technology was not implemented due to the tailings' impoverishment, the presence of 1-2% chlorine in the clinker and the insufficiently high extraction of non-ferrous metals into sublimates.

In the south of Kazakhstan in 1963, the Shalkiya lead-zinc deposit was discovered with reserves of 129.35 million balance ores (4.28% Zn, 1.18% Pb) and 119.56 million off-balance ores (2.73% Zn, 0, 61% Pb). Until 2008, the flotation enrichment of Shalkiya ore was carried out at Kentau concentrating mill (Shalkiya Zinc LTD JSC. Annual report for 2016-KASE). However, the technological parameters were low. This was due to several reasons: in the process of ore breaking and reduction, it was not possible to obtain relatively homogeneous particles of ore minerals that differed in their properties from waste rock minerals; enrichment did not provide a sufficiently complete extraction of zinc and lead into the concentrate due to the presence of minerals in the ore that form hard-to-open aggregates with waste rock minerals; mechanical ore breaking and reduction, in this case, did not provide high flotation rates (Polkin and Adamov, 1983; Abramov and Leonov, 1991).

Nevertheless, the project for the expansion of Shalkiya mine was completed, which also provided for low extraction rates of metals into concentrates: zinc – 70%, lead – 49% with tailings – 91.2% (O'Beirne et al., 2015). Recently, several new options for the enrichment of Shalkiya ore were developed (Telkov et al., 2019; Seksenova et al., 2021), which allowed to increase the extraction of Zn from 41.9 to 57.9%, Pb to 51.3% (Mukhanova et al., 2015; Semushkina et al., 2015). Nevertheless, losses with metal tailings were significant (Zn up to 16-25%, Pb up to 46%). Therefore, the problem of tailings processing is currently not completely resolved.

From the above material it follows that the main method of extracting zinc from enrichment tailings is flotation in different options. This technology is not rational, since they do not provide for the production of products from the non-metallic component of the tailings. Therefore, we are developing a new technology for processing tailings with the extraction of not only zinc, but also the silicon and iron contained in them.

The article presents the results of the study on the complex processing of Shalkiya ore enrichment tailings, as a result, zinc, lead and semi-siliceous ferroalloy were obtained from the tailings from one furnace unit.

2. Materials and methods

2.1. Methods

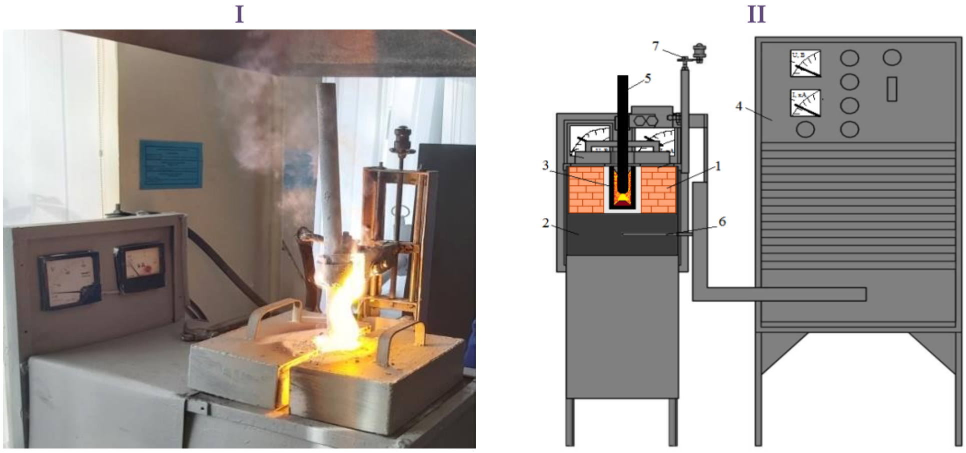
The research was carried out by the method of computer thermodynamic modeling and electric melting in an arc furnace.

Thermodynamic research was carried out using the HSC-6.0 software package (Roine, 2021). This complex was developed by Outokumpu Research Oy, Finnish metallurgical company, was intended for the analysis of chemical reactions and the calculation of equilibria. The developers of the complex were based on the ideology of the SGTE consortium, which allowed using it to illustrate one of the options for implementing the SGTE principles. The developers of the HSC Chemistry are constantly developing the complex in terms of expanding the database and increasing the options. The consortium includes specialized research centers in Germany, Canada, France, Sweden, Great Britain and the USA (Scientific Group Thermodata Europe). In computer thermodynamic modeling, one of the 14 options of the HSC-6.0-Equilibrium Compositions complex was used.

All calculations were carried out on a computer automatically using a database that contains information about the enthalpy, entropy, and heat capacity of more than 17 000 chemical compounds. The HSC-6 program is based on the principle of minimizing the Gibbs energy of a thermodynamic system. The equilibrium parameters of a thermodynamic system are determined by solving the mathematical problem of finding the extremum, taking into account the Lagrange function. For the calculation, the Newton's method of successive approximations or another rational method are used.

To determine the equilibrium degree of element distribution in the systems under study, we developed an algorithm published in (Shevko et al., 2019).

The electric melting of the charge was carried out in a single-electrode arc furnace (with a power of up to 15 kVA) lined with chromium-magnesite bricks (Fig. 2). The bottom electrode was made of a graphite block. A graphite crucible (d=6cm, h=12cm) was placed on the hearth. The furnace in the upper part was closed with a removable lid with holes for a graphite electrode with a diameter of 3 cm and a gas outlet. The crucible was preliminarily heated by an arc for 20-25 min. After that, the first portion of the charge (200-250 g) was loaded into the crucible. It was melted for 3-6 minutes, then every 4-6 minutes the charge of 200-250 g was loaded. For 1 experiment, 1500-2000 g of the charge was melted. During the melting period, the current strength was 350-400A, the voltage was 30-35V. Electricity was supplied to the furnace from a transformer TDZhF-1002. The required power was supported by a thyristor regulator. After the electric melting, the furnace was cooled for 6-7 hours. The graphite crucible was removed from the furnace and broken. The ferroalloy was weighed and analyzed on a SEM (Scanning Electron Microscopy) instrument.



I – overall view, II – sketch

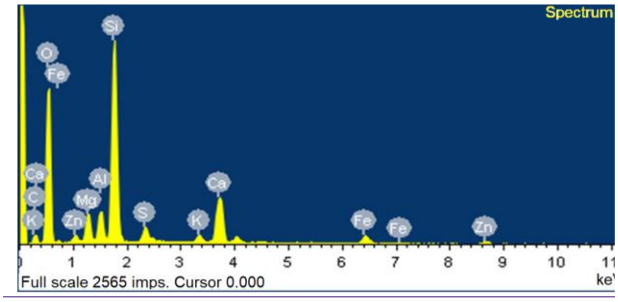
Fig. 1. Single-electrode electric arc furnace: 1 – chromium-magnesite lining, 2 – carbon-graphite hearth, 3 – graphite crucible, 4 – transformer TDZhF-1002, 5 – graphite electrode, 6 – lower current lead, 7 – electrode movement mechanism

2.1. Materials

In the work, Shalkiya deposit tailings were used. Scanning electron microscopy of the tailings is shown in Fig. 3, and DTA in Fig. 4. It can be seen that the tailings contain 23.58% Si, 7.07% Ca, 2.67% Al, 3.07% Mg, 2.72% Fe, 2.14% Zn, 6.57% C, 49.97% O, 1.28% S, 0.94% K.

It should be noted that the analysis performed at National Center for Complex Processing of Mineral Raw Materials of the Republic of Kazakhstan showed that the content of SiO_2 in the tailings reaches 57.54%, and the content of lead – up to 0.6%.

It follows from Fig. 3 that when heated to 1000°C, the tailings' weight loss is 23.5%. Endothermic effects with minima at 770°C and 880°C are attributed to the decomposition of $MgCO_3$ and $CaCO_3$.



Element	Weight, %	Element	Weight, %
C	6.57	S	1.28
O	49.97	K	0.94
Mg	3.07	Ca	7.07
Al	2.67	Fe	2.72
Si	23.58	Zn	2.14

Fig. 2. Analysis of Shalkiya ore tailings (Energy-dispersion spectra and sublimate composition made by the scanning electron microscopy)

Fig. 3. Derivatogram of Shalkiya ore tailings

A slight exothermic background at 420-660°C refers to the oxidation of zinc, lead and iron sulfides. Before the melting, the tailings were pelletized with 3% bentonite clay. Then the granules were fired at 950°C for 1 hour. The firing was carried out to decompose calcium and magnesium carbonates. Preliminary, before the melting, decarbonization of the tailings reduced the consumption of carbon and electricity, since the reaction of carbon gasification did not occur in the furnace after decarbonization: $CO_2+C=2CO$. For the electric melting, coke was used containing 87.2% C, 1.0% volatile substances, 0.85% S, 10.0% ash content (SiO_2, 2.5% Al_2O_3, 1.4%Fe_2O_3, 0.4% CaO+ 0.1% MgO), 0.95% moisture and steel chips – carbon steel in which the concentration of iron was 97.41%, carbon – 1.8%, Si – 0.41%, Mn – 0.3%, ΣS and P – 0.1%.

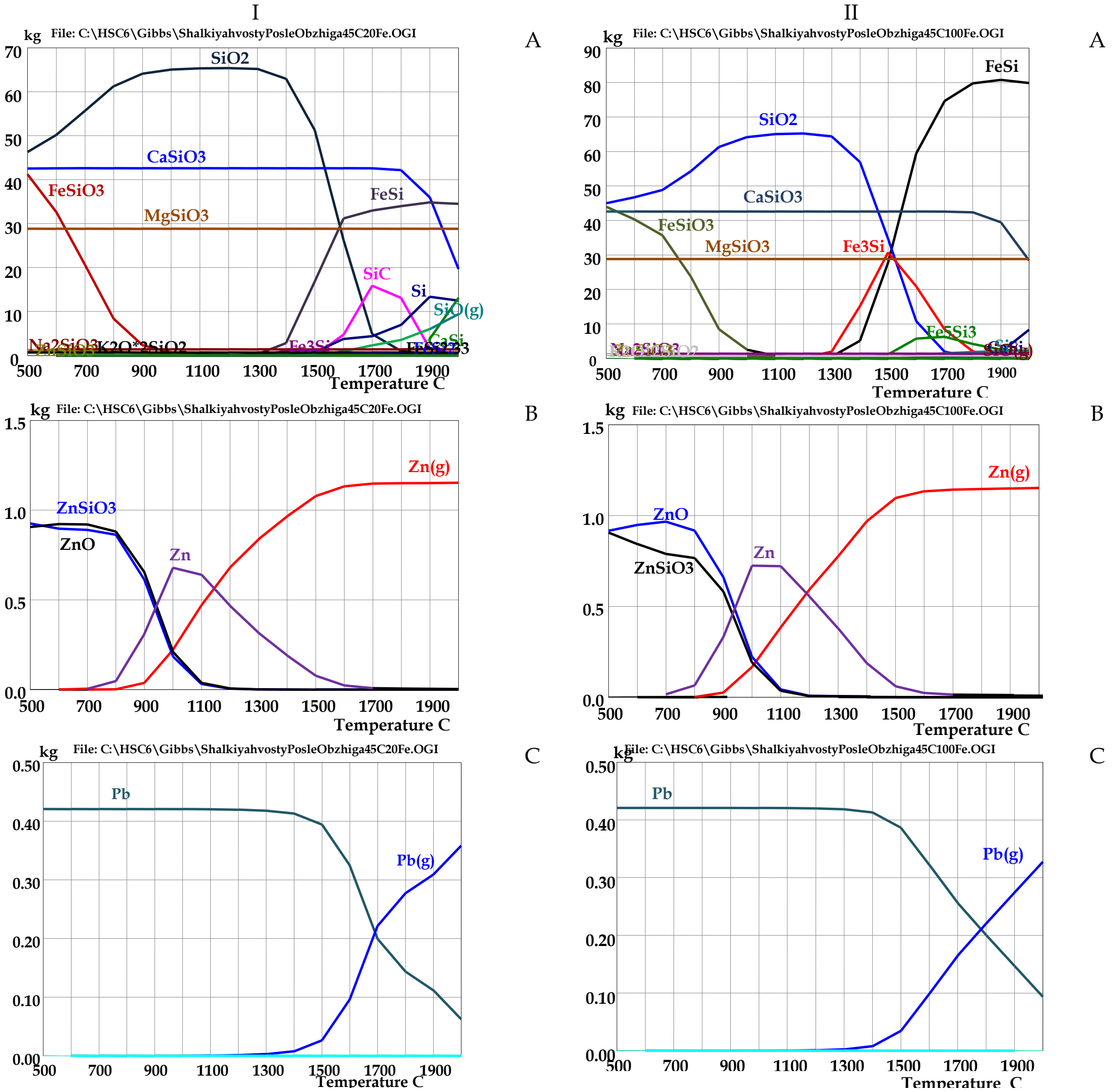
3. Results

Fig. 4 shows the influence of temperature and iron on the equilibrium quantitative (kg) distribution of Si, Zn and Pb. In the system: cinder – C – Fe, the carbon amounted to 12.6% of the cinder weight from the tailings. It can be seen from Fig.4 that, depending on the temperature in the system under consideration, the main formed substances were $CaSiO_3$, $FeSiO_3$, $MgSiO_3$, $K2O{\cdot}SiO_2$, FeSi, Fe_5Si_3, SiC, Fe_3Si, Si, SiO_g, $FeSi_{2.33}$, $FeSi_2$, CaSi, Zn, Zn_g, Pb and Pb_g. Moreover, silicides were formed at T>1200°C, Zn_g – atT>800°C, and Pb_g– atT>1200°C. In the presence of 100% iron, no SiC was formed in the system. This was due to the fact that iron could destroy silicon carbide (Ershov, 1980). Figures 5 and 6 and Table 2 show the influence of iron temperature on the equilibrium degree of distribution (α) of silicon and zinc, and the onset temperature T_{onset} of silicon-containing substances is shown in Table 1.

It can be seen from Table 1 that as T_{onset} increases, silicon-containing substances are arranged in a row: FeSi (1200°C), Fe_3Si (1200-1300°C), Si (1300-1400°C) Fe_5Si_3 (1400-1500°C) SiO_g (1400-1500°C), SiC (1500°C), $FeSi_2$ (1500°C), $FeSi_{2.33}$ (1500-1600°C), $FeSi_{2.43}$ (1600°C), CaSi (1700-1800°C). Moreover, an increase in iron increases T_{onset} of $FeSi_{2.33}$, CaSi, SiO_g, Si and reduces T_{onset} of Fe_3Si, Fe_5Si_3.

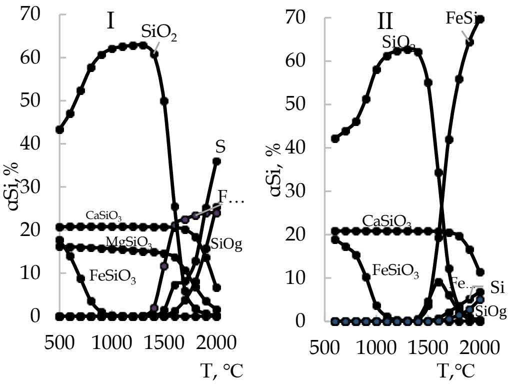
Table 1. The onset temperature (T_{onset},°C) of silicon-containing substances

Iron amount, %	FeSi	$FeSi_2$	$FeSi_{2.33}$	Fe_3Si	Fe_5Si_3	$FeSi_{2.43}$	CaSi	SiC	SiO_g	Si
20	1200	1500	1500	1300	1500	1600	1700	1500	1400	1300
100	1200	1500	1600	1200	1400	1600	1800	-	1500	1400



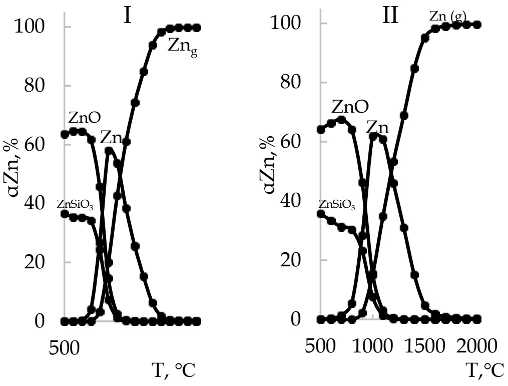
Iron amount, % by weight of the cinder: I – 20, II – 100

Fig. 4. Influence of temperature and iron on the equilibrium quantitative distribution of substances containing silicon (A), zinc (B), lead (C)



I – 20% iron, II – 100% iron

Fig. 5. Influence of temperature and iron on the main equilibrium degree of distribution of silicon-containing substances



I – 20% iron, II – 100% iron

Fig. 6. Influence of temperature and iron on the equilibrium degree of distribution of zinc-containing substances

It can be seen from Fig.5 that in the technological range of 1700-1800°C, an increase in the iron charge allows (for example, at 1800°C) to increase the silicon extraction degree in FeSi from 23.4 to 64.43%, to reduce in SiOg from 8.14 to 2.75%, and in SiC at 1700°C from 27.5 to <0.01%. In this case, the silicon extraction degree into the elemental state decreases from 12.87 to 5.13%.

Table 2. Influence of temperature and iron on the low equilibrium degree of silicon distribution in Fe_3Si, Fe_5Si_3, $FeSi_2$, $FeSi_{2,33}$, $FeSi_{2,43}$andCaSi

Substance, %	Temperature, °C							
	1300	1400	1500	1600	1700	1800	1900	2000
Fe_3Si	0.03	0.28	0.37	0.07	0.03	0	0	0
Fe_5Si_3	0.00	0.00	0.01	0.01	0.03	0.02	0.00	0.00
	0.00	0.01	0.60	3.14	4.2	3.72	2.86	2.10
$FeSi_2$	0.00	0.00	0.04	0.30	0.40	0.51	0.63	0.58
	0.00	0.00	0.02	0.14	0.23	0.28	0.30	0.29
$FeSi_{2,33}$	0.00	0.00	0.01	0.16	0.29	0.48	0.74	0.79
	0.00	0.00	0.01	0.16	0.29	0.48	0.74	0.79
$FeSi_{2,43}$	0.00	0.00	0.00	0.02	0.04	0.05	0.06	0.07
	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
CaSi	0.00	0.00	0.00	0.00	0.01	0.07	0.73	3.32
	0.00	0.00	0.00	0.00	0.00	0.03	0.15	0.41

*- Numerator – 20% iron, denominator–100% iron

As seen from Table 2, in the remaining silicides in iron, the silicon transition degree is insignificant and does not exceed 4.25% in Fe_5Si_3 at 100% iron. The iron content in the charge has practically no influence on the zinc transition degree into a gas (Fig. 6). So, at 1700-1800°C, this indicator for 20% iron is 99.5-99.7%, and for 100% iron – 99.1-99.4%. The picture of the change in the iron influence on the lead extraction degree into gas is shown in Table 3.

Table 3. Influence of the iron amount on the lead extraction into gas, %

Iron amount, %	Temperature, °C						
	1400	1500	1600	1700	1800	1900	2000
20	1.98	6.75	25.16	58.89	75.44	82.48	87.86
100	1.84	8.12	23.41	39.08	52.30	65.08	77.80

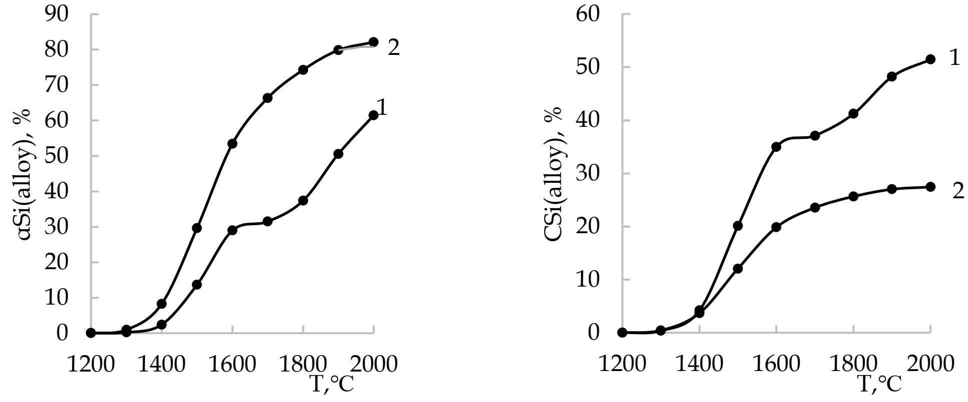
It can be seen from Table 3 that an increase in the iron amount in the charge significantly reduces the lead extraction into the gas, at 1800°C this indicator decreases from 75.44 to 52.30%.

As shown from Fig. 7(I) it follows that in the temperature range of 1400-2000°C, an increase in the temperature and the iron amount increases the silicon extraction into the alloy in the form of Σ iron silicides and elemental silicon. In this case, the silicon concentration in the alloy naturally decreases.

To obtain FS50 grade ferrosilicon, the process must be carried out in the presence of 20% iron in the temperature range of 1880-2000°C, and FS45 – at 1790-1880°C.

It is possible to obtain FS25 grade ferrosilicon at 20% iron. This requires the temperature of 1500-1550°C, and at 100% iron – 1640-1780°C. However, the silicon extraction degree into the alloy is not high. For example, at 20% iron, it is 13-19.4%, and at 100% iron, it is 59-72%.

Bearing in mind the opposite nature of the iron influence on the silicon transition degree into the alloy and the concentration of this element in it, further research to determine the process parameters that provide the conditions for obtaining grade ferrosilicon (at αSi→max.) was carried out by the second-order rotatable planning method (Akhnazarova and Kafarov, 1985) followed by geometric optimization, which we described in the production of ferroalloys from various natural and technogenic raw materials (Shevko et al., 2018; Shevko et al., 2020; Shevko et al., 2021b). In this case, the independent variables were temperature (T, °C) and iron amount (Fe, % of the cinder mass). The research matrix and results are shown in Table 4.



1 – 20% iron, 2 – 100% iron

Fig. 7. Influence of temperature on the silicon extraction degree in the alloy (A) and the silicon concentration in the alloy (B)

Table 4. Planning matrix and research results

№	Variables				$\alpha_{Si(alloy)}$,%		$C_{Si(alloy)}$, %	
	Coded view		Natural view		By research	By equation	By research	By equation
	X1	X2	T, °C	Fe, %				
1	-1	-1	1644	32.0	43.5	42.11	33.0	32.06
2	+1	-1	1856	32.0	57.7	58.12	41.3	40.64
3	-1	+1	1644	88.0	58.0	58.27	24.3	23.80
4	+1	+1	1856	88.0	74.6	76.68	29.0	28.83
5	+1.414	0	1900	60.0	74.2	72.57	35.3	35.64
6	-1.414	0	1600	60.0	47.3	48.23	25.2	26.00
7	0	+1.414	1750	100.0	71.0	69.48	24.5	24.73
8	0	-1.414	1750	20.0	44.1	44.92	38.0	38.91
9	0	0	1750	60	65.6	65.0	31.6	31.64
10	0	0	1750	60	65.0	65.0	31.8	31.64
11	0	0	1750	60	64.3	65.0	31.5	31.64
12	0	0	1750	60	66.0	65.0	31.0	31.64
13	0	0	1750	60	64.1	65.0	32.2	31.64

From Table 4 it follows that the maximum error for $\alpha_{Si(alloy)}$is 3.18% (position 1 in Table 4), and for $C_{Si(alloy)}$ – 3.18% (position 6 in Table 4).

Using the data given in Table 5 according to the method (Akhnazarova and Kafarov, 1985), the following regression equations $\alpha_{Si(alloy)}$=f (T, Fe) and $C_{Si(alloy)}$ = f (T, Fe) were obtained:

$$\alpha_{Si(alloy)}=-7.19.24+0.785\cdot T+0.533\cdot Fe-2.04\cdot 10^{-4}\cdot T^2-4.97\cdot 10^{-3}\cdot Fe^2+2.02\cdot 10^{-4}\cdot T\cdot Fe; \quad (1)$$

$$C_{Si(alloy)}=-92.601+0.141\cdot T-0.723\cdot Fe-3.62\cdot 10^{-4}\cdot T^2+1.14\cdot 10^{-4}\cdot Fe^2+3\cdot 10^{-4}\cdot T\cdot Fe. \quad (2)$$

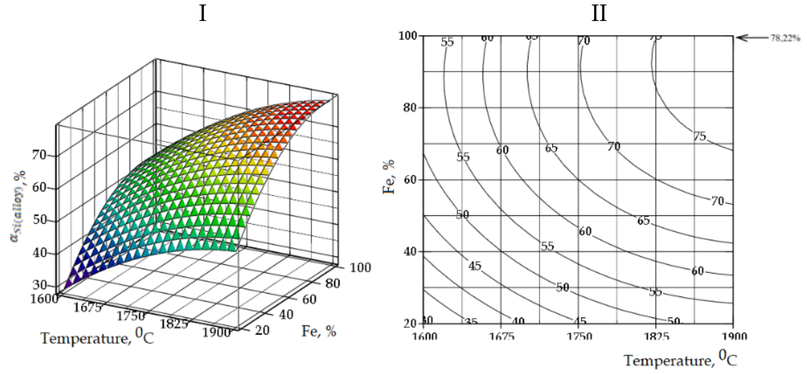
The equation coefficients' significance was determined by the Student's criterion (Akhnazarova and Kafarov, 1985). In both equations, the equation coefficients turned out to be significant. The equations' adequacy was determined using the Fisher criterion (F) (Akhnazarova and Kafarov, 1985). In the case of Eq. 1, $F_{calculation}$=4.94 and Eq. 2, $F_{calculation}$=6.54. In our research, the tabular F criterion is 6.59. The inequalities $F_{calculation}<F_{tabular}$ indicate that both regression equations are adequate in our case.

Based on the Eqs. 1 and 2, according to the method (Inkov et al.,2003; Ochkov, 2009), volumetric and planar images of the influence of temperature and iron on $\alpha_{Si(alloy)}$ and $C_{Si(alloy)}$ were constructed (Figs. 8 and 9).

Fig. 7 shows that in the temperature range of 1600-1900°CαSi in the alloy can vary from 30% (1600°C and 20% Fe) to 75.7% (1900°C and 100% Fe). The silicon concentration in the alloy varies from 17.4% (1600°C and 100% Fe) to 41.6% (1900°C and 20% Fe). Fig. 9 shows the regions in which the formation of FS20, FS25, FS45 grade ferrosilicon is possible (State standard 1415-93, 2011).

4. Discussion

The Combined information on the influence of temperature and iron on $\alpha_{Si(alloy)}$ and $C_{Si(alloy)}$ is shown in Fig. 10. Table 5 shows the technological parameters at the boundary points in Fig. 10.



I – volumetric image, II – planar image

Fig. 8. Influence of temperature and iron amount on the silicon extraction degree into the alloy

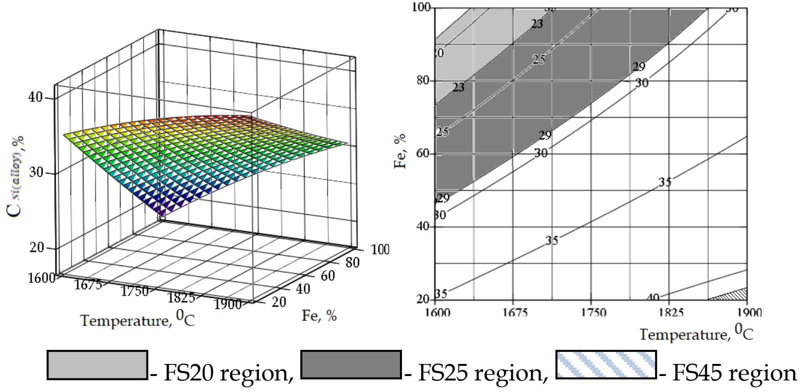
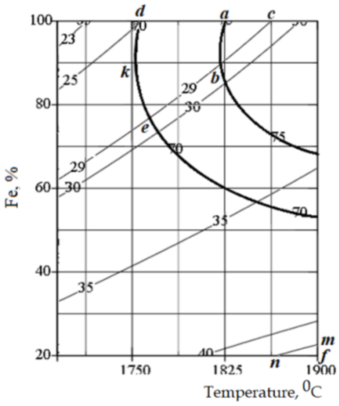


Fig. 9. Influence of temperature and iron amount on the silicon concentration in the alloy

Table 5. Values of technological parameters at the boundary points in Fig. 10

Points in Fig. 10	Technological parameter			
	T, °C	Fe, %	$\alpha_{Si(alloy)}$, %	$C_{Si(alloy)}$, %
a	1825	100	75.0	27.7
b	1820	88.3	75.0	29.0
c	1867	100	77.4	29.0
d	1753	100	70	25.0
k	1752	90.0	70	29.0
e	1764	76.4	70	29.0
n	1863	20	50.3	41.0
m	1900	22.4	54.0	41.0
f	1900	20.	51.2	41.6



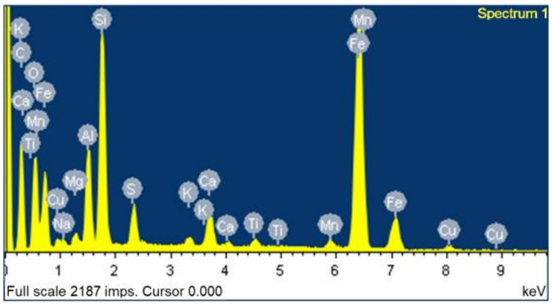
(——)-$C_{Si(alloy)}$, %; (▬▬)-$\alpha_{Si(alloy)}$, %

Fig. 10. Combined information on the influence of temperature and iron on the silicon extraction into the alloy and the content of Si in it

Under the condition $\alpha Si_{(alloy)}$>75% (75-75.7%) the alloy formed in the abc region belongs to FS25 grade. This requires a temperature of 1820-1867°C and 88.3-100% Fe. At $\alpha_{Si(alloy)}$ from 70 to 75% the formed alloy containing 25-29% Si also belongs to FS25 grade (the abekd region). In this region, the process occurs at a temperature of 1752-1825°C and 76.4-100% Fe. To obtain FS45 grade ferrosilicon containing 41.0-41.6% Si, conditions are necessary that limit the nmf region (1863-1900°C, 20-22.4% Fe). However, at that $\alpha_{Si(alloy)}$ will be 50.5-54.0%.

If necessary, FS20 grade ferrosilicon (19-23% Si) can be obtained from the cinder. This, based on Fig.5, is possible in the temperature range of 1600-1725°C and 71-90.8% Fe. In this case $\alpha_{Si(alloy)}$ is 51-66%. Fig. 11 and 12 show photographs of a ferroalloy melted from a charge containing 63.83% tailing cinder, 19.15% coke, and 17.02% steel chips.

Fig. 11. Photographs of the ferroalloy



Element	Weight, %	Element	Weight, %
C	0.21	K	0.10
O	9.05	Ca	1.12
Na	0.35	Ti	0.54
Mg	0.24	Mn	0.84
Al	1.95	Fe	41.20
Si	44.1	Cu	0.25
S	0.05	K	0.10

Fig. 12. Analysis of the ferroalloy (Energy-dispersion spectra and sublimate composition made by the scanning electron microscopy)

The ferroalloy density (P, g/cm^3), determined by the pycnometer method, was 5.27 g/cm^3. The silicon content in the alloy was determined based on the Eq. (3) (Shevko et al., 2016):

$$C_{Si(alloy)}=252{,}405-101{,}849 \cdot P +18{,}209 \cdot P^{2}-1{,}213 \cdot P^{3} \tag{3}$$

In our case, the silicon content in the alloy was:

$$C_{Si(alloy)} =252.405-101.849 \cdot (5.27) +18.209 \cdot (5.27)^{2}-1.243 \cdot (5.27)^{3}=43.9\% \tag{4}$$

According to this indicator, the ferroalloy corresponds to FS45 grade ferrosilicon (State standard 1415-93, 2011). During the melting, the silicon extraction degree in the alloy was 69.7%. It should be noted that during the electric melting, almost all zinc and lead (98-99%) passed into sublimates. Analysis of sublimates collected from under the furnace lid and electric holders showed that they contain ∑ Zn and Pb 32-38%, which is 11.6-12.7 times higher than in the source cinder.

5. Conclusions

Based on the research carried out on the processing of cinders from the firing of Shalkiya deposit lead-zinc ore tailings, the following conclusions can be drawn:

1. In equilibrium conditions

- interaction occurs with the formation of $CaSiO_3$, $FeSiO_3$, $MgSiO_3$, $K_2O·SiO_2$, FeSi, Fe_5Si_3, SiC, Fe_3Si, Si, SiO_g, $FeSi_{2.33}$, $FeSi_2$, CaSi, Zn, Zn_g, Pb and $Pb_{g,}$

- an increase in the iron amount allows to extract of silicon into the alloy at 1800°C to 76% and reduce the silicon concentration in the alloy from 41 to 24%

- FS25 grade ferrosilicon is formed at 1752-1867°C in the presence of 88-100% iron, FS45 grade ferrosilicon – at1863-1900°C and 20-22.4% iron

2. The electric melting of the charge containing 63.83% tailing cinder, 19.15% coke, and 17.02% steel chips allows obtaining FS45 grade ferrosilicon (44.1-43.9% Si) with the extraction of 69,7% silicon and sublimates containing 32-38% zinc and lead.

3. The results obtained allow complex processing of lead-zinc sulfide ore enrichment tailings with the extraction of not only non-ferrous metals, but also silicon in the ferroalloy.

4. Further study of the complex processing of sulfide raw materials will be associated with direct electric melting bypassing enrichment with the production of siliceous ferroalloys and Zn-Pb sublimates (oxide Zn and Pb concentrate).

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