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TECHNOLOGICAL PARAMETERS of DIRECT SMELTING of GOLD-CONTAINING REFRACTORY LEDGE ORES of BAKYRCHIK DEPOSIT

Abstract: Creating radically new technologies for highly efficient processing of «persistent» and «dual persistent» ores, which include Bakyrchik ore deposit, with high recovery of gold and other metals in matte, is very actual. Under the experimental conditions showed the possibility of melting persistent rich gold ore deposit Bakyrchik for getting mattes, contained up to 80.26 g/t gold and up to 56.3 g/t silver and slag, contained 0,12 - 0 18 g/t gold and 0,26 - 0,48 g/t silver. The influence of temperature on amount and composition of smelting products was studied. It was established, that the change in the temperature range 1350 – 1450 °C does not have influence on outputs products of experimental smelting, constituted 11.5 - 12.5 % for matte and 71.5 - 72.0 % for slag. Increasing temperature to 1450 °C had a marked effect on the reduction of metal contents in the slag: from 3.3 to 1.4 g/t for gold and 0.6 to 0.4 g/t for silver. In the conditions of pilot smelting held at 1450 °C, the possibility of formation of a matte without addition sulphidizer flux and produce slag with a minimum content of gold and silver was showed. Recovery of gold and silver in matte under optimal conditions of smelting was 98.7 - 99.1 % and 79.9 - 98.3 %, respectively.

Keywords: persistent gold ore, sulfide copper concentrate, flux, matte smelting, slag.

The article is published in line with the project 0855/GF4 of researches grant funding programs for 2015-2017.

Introduction. It is known that more than 50 % of the available active gold reserves are characterized as hard for benefaction and containing contaminants, i.e. arsenic, antimony and carbon. In gold metallurgy, these ores can be included into refractory ores [1-5]. A number of Kazakh large deposits of gold-bearing ores is characterized with a large number of the ore harmful impurities listed above, as well as their joint presence resulting in double refractoriness, and is the main cause of the current lack of an enterprise for extraction of gold from these raw materials. Among the fields of the East Kazakhstan region, the largest and most unique in gold reserves is the Bakyrchik deposit, which is a mineralized zone of gold-sulphide type [6]. Contractile pyrometallurgy selection method for rich gold-containing refractory ore rational technological parameters determination of Bakyrchik deposit is actual for other refractory gold-containing ores of this region. Experimental data will complement the existing two innovative patents for the CPS-process, resulting in a direct pyrometallurgical smelting of “refractory” gold ore and gold-cobalt-arsenic concentrates [7, 8].

Experimental Part and Results Discussion. The object of the study was refractory ledge ore from the Bakyrchik deposit rich in gold. As a flux were used cuprous sulphide concentrate for matte formation, calcium oxide qualified as “purified”

with mass fraction of base material not less than 97.5 % for matte formation. The composition of the starting materials and melts products were analyzed by chemical methods, gold and silver at big smelting slags were analyzed by fire assay method. The experiments were performed with the help of high temperature units, i.e. batch furnace NTS 08/16 made by Nabertherm GmbH and induction smelting unit UIP-16-10-0.005 at 1500 °C. Melting in electrical muffle was conducted with heating at a predetermined temperature for 1 hour, with the charge sample of 400 g in alundum crucibles which were covered with a graphite lid to prevent secondary oxidation of the charge. Crucibles with the sample were put into a cold furnace chamber and heated for 2 hours to achieve the given melting temperature. For smelting in induction furnace we used the alundum crucibles placed inside the graphite ones also covered with a graphite lid with a hole for removing resurgent gas. The crucibles with 500 g of charge was put into a cold graphite crucible, and the system was heated until complete charge melting followed by addition of another 500 g of charge. After complete melting of the whole volume of the charge and achievement of predetermined temperature, the crucibles with the sample to be tested were maintained at a melting temperature for 30 min, then the furnace was switched off. As there is an intensive bubbling

in the induction furnace, the crucibles with fusion cooled down in the furnace during ~ 10 min. before complete cessation of bubbling then the crucibles were taken from the furnace and cooled on air.

There were studied influence of calcium flux, sulfide copper concentrate consumption and influence of temperature on gold, silver and copper distribution at smelting products. All series of experiments were performed with a charge consisting of gold rich ore from the Bakyrchik deposit, matte- and slag-forming fluxes. The charge was calculated with the help of computing program named "Shtabel" under the condition of silicon oxide content in the slag at the rate of 50 - 56 %. The composition of starting materials is shown in Table 1.

Table 1 – Chemical composition of starting materials

Material:	Composition									
	g/t		%							
	Au	Ag	Cu	Fe	S	As	C	SiO ₂	CaO	Al ₂ O ₃
Ore from the Bakyrchik deposit	12.0	1.1	–	9.5	7.9	2.05	1.48	51.6	2.2	11.2
Copper sulphide concentrate	1.64	61.05	20.5	27.5	36.67	0.09	–	3.6	1.52	1.54
Calcium oxide	–	–	–	–	–	–	–	–	97.5	–

In the first series of experiments at a constant amount of the copper sulfide concentrate in the charge the amounts of ore and calcium oxide varied. In the second series, the amount of sulfide copper concentrate and ore changed at a constant amount of calcium oxide. Composition of charges, smelting output of products from the first and second series of experiments are specified in Table 2, and chemical compositions of slags and mattes are in Table 3.

From Table 2 it is obvious that, change of the calcium oxide content in the charge within 23 - 15 % naturally reduces the output of slag melts from 55.0 to 48.9 % at practically constant yields of gold mattes. By changing the sulfide copper concentrate flow rate gold matte output can be adjusted from charge weight within 12.7 - 23.7 %. Moreover, for this type of ore, minimum matte output (12.7 %) was obtained without use of matte forming flux. Based on these considerations, and bearing in mind that the predetermined range of the slag content of SiO₂ is

50 - 56 %, the optimum value of calcium flux additive is 15 % from the charge weight.

Table 2 – Composition of the charge, its output of smelting products

Experiment No	Charge mixture	Charge weight		Smelting output of a product from charge weight, %	
		g	%	matte	slag
First series of experiments					
1	Ore	208.0	52.0	31.7	55.0
	Concentrate	100.0	25.0		
	CaO	92.0	23.0		
	Total	400.0	100.0		
2	Ore	220.0	55.0	29.3	50.1
	Concentrate	100.0	25.0		
	CaO	80.0	20.0		
	Total	400.0	100.0		
3	Ore	240.0	60.0	29.2	48.9
	Concentrate	100.0	25.0		
	CaO	60.0	15.0		
	Total	400.0	100.0		
Second series of experiments					
4	Ore	136.0	68.0	23.7	51.3
	Concentrate	34.0	17.0		
	CaO	30.0	15.0		
	Total	200.0	100.0		
5	Ore	154.0	77.0	18.0	54.7
	Concentrate	16.0	8.0		
	CaO	30.0	15.0		
	Total	200.0	100.0		
6	Ore	170.0	85.0	12.7	63.3
	Concentrate	0.0	0.0		
	CaO	30.0	15.0		
	Total	200.0	100.0		

Table 3 – Chemical compositions of derived slags and mattes

Experiment No	Product	Composition								
		g/t		%						
		Au	Ag	Cu	Fe	S	As	SiO ₂	Al ₂ O ₃	CaO
First series of experiments										
1	Slag	1.14	3.26	0.8	2.9	1.18	0.140	45.9	13.2	24.6
	Matte	30.2	52.1	16.6	37.7	33.4	0.90	–	–	–
2	Slag	1.02	2.10	0.3	1.7	0.62	0.046	50.3	13.2	23.8
	Matte	30.7	51.2	16.8	40.6	33.1	0.86	–	–	–
3	Slag	1.12	1.70	0.6	2.2	1.10	0.040	55.6	12.9	18.3
	Matte	33.2	51.3	16.5	40.6	34.0	0.84	–	–	–
Second series of experiments										
4	Slag	1.0	0.86	0.5	2.5	–	–	56.5	11.8	17.23
	Matte	37.2	49.1	13.2	47.8	33.87	0.74	–	–	–
5	Slag	1.4	0.62	0.3	2.2	–	–	58.8	11.2	15.58
	Matte	53.8	31.8	8.2	50.7	34.95	0.70	–	–	–
6	Slag	2.0	0.24	–	3.0	–	–	57.4	10.15	14.35
	Matte	76.4	24.8	–	57.9	35.3	0.46	–	–	–

In first series of experiments, gold contents in matte was, g/t: 30.2-33.2 and silver – 51.2-52.1; in slags, g/t: Au – 1.02-1.14, Ag – 1.70-3.26. For second series: in mattes, g/t: Au – 37.2-76.4,

Ag–24.8-49.1, inslags, g/t: Au–1.0-2.0, Ag–0.24-0.86. It is obvious that in the conditions of small smelting samples (200 - 400 g) we obtained slags quite rich in gold due to insufficient conditions for separation of the melt into slag and matte.

Low residual arsenic contents in the products (in mattes 0.46 - 0.90 %, in slags 0.04 - 0.14 %) indicate a high degree of its transition into the gas phase, at the conditions of high temperature charge smelting all carbon also will transfer into the gas phase in the form of oxides.

To study the effect of temperature on compositions of smelting products at optimum flux flow we performed the experiments with 200 g charge sample with the following composition, i.e. 170 g ore (85 %), concentrate 0, flux 30 g (15 %). Weight and smelting yield of products are shown in Table 4, chemical compositions of slags and mattes – in Table 5.

Table 4 – Matte and slag outputs temperature influence

Experiment No	Temperature, °C	Outputs of a product from charge weight, %	
		matte	slag
7	1350	11.5	72.0
8	1400	12.5	71.5
9	1450	12.5	71.5

Table 5 – Chemical compositions of derived slags and mattes

Experiment No	Product	Compositions of smelting products							
		g/t		%					
		Au	Ag	Cu	Fe	S	SiO ₂	Al ₂ O ₃	CaO
7	Slag	3.3	0.6	<0.1	26.1	-	60.0	<0.1	16.5
	Matte	87.5	9.5	0.9	52.9	36.4	-	-	-
8	Slag	2.4	0.5	<0.1	18.8	-	59.5	<0.1	16.5
	Matte	90.9	4.8	0.85	52.15	37.0	-	-	-
9	Slag	1.4	0.4	<0.1	16.7	-	59.5	3.6	16.5
	Matte	83.0	3.3	0.7	53.6	37.0	-	-	-

From the data of Tables 4, 5 we can see that outputs of smelting products are: mattes – 11.5-12.5 % and slags – 71.5-72.0 %. The temperature rise from 1350 to 1450 °C has positive influence on lowering of metal content in slags within the following limits, i.e. gold 3.3-1.1 g/t and silver 0.6-0.4 g/t.

To clarify the obtained results the content of the gold and silver experimental melting products we performed coarse crucible melting's under the above-mentioned procedure with the charge weight of 1000 grams of two optimal compositions at 1450 °C. Results are listed in Table 6.

Second charge, that has not sulfide copper concentrate, because of 7.9 % sulfur and 9.5 % iron of Bakyrchik deposit ore, there is formed matte,

containing 35.97 % S and 59.4 % Fe. As described above, process does not require any supplements of matte forming flux.

As expected, the conditions of melting of charge samples with 1000 g results in low content of precious metals in slags: 0.12 - 0.18 g/t Au and 0.26 - 0.48 g/t Ag. Thus, according to the coarse melting results, the gold recovery into matte amounted to 98.7 - 99.1 %, silver - 79.9 - 98.3 %.

Table 6 – Composition, weight and outputs of the product coarse melting

Product	Weight and outputs from charge weight		Product composition							
			g/t		%					
			Au	Ag	F	S	As	SiO ₂	Al ₂ O ₃	CaO
Charge, %: ore – 60, copper sulphide concentrate – 25, Calcium oxide – 15										
Matte	278.0	27.8	27.0	56.3	47.8	17.75	0.38	-	-	-
Slag	556.0	55.6	0.18	0.48	2.6	-	-	51.0	12.97	18.16
Charge, %: ore – 85, Calcium oxide – 15										
Matte	126.0	12.6	80.26	5.93	59.4	35.97	0.33	-	-	-
Slag	723.0	72.3	0.12	0.26	1.3	-	-	55.0	13.4	14.22

Conclusions. Decreasing of calcium oxide in feed based on gold containing refractory ore of Bakyrchik ore deposit promotes decreasing of slag output and doesn't change matte output; wherein gold content in slag is 1.02 – 1.14 g/t and silver decreases from 3.26 to 1.7 g/t; in matte gold and silver content changes insignificantly: 30.2 – 33.2 g/t and 52.1 – 51.3 g/t respectively.

Change of sulfide copper concentrate content in feed from 17 % to 0 from charge's mass allows to control matte yield from 23.7 to 12.7 % and gold content from 37.2 to 76.4 g/t and silver content from 49.1 to 24.8 g/t.

After coarse laboratory melting were found that at 1450 °C feed with 85 % Bakyrchik ore and 15 % CaO there is forming matte, containing 80.26 g/t Au and 5.93 g/t Ag and slag, containing 0.12 g/t Au and 0.26 g/t Ag, with sulfide copper concentrate gold content in matte decreases to 27 g/t, and silver content increases to 56.3 g/t; recovery gold in matte when melting is 98.7-99.1 % and silver – 79.9-91.3 %.

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ТҮЙІНДЕМЕ

Ұстанымды жаңа технологияны құру «берік» және «екі есе берік» кендерді жоғары әсерлі өңдеумен қамтамасыз ететін, Бақыршық кенорны кендерінің де қатысы бар алтын және басқа да металдарды штейнге жоғары дәрежеде өткізу мәселесі өте өзекті. Қажырлы бай алтын кені жағдайында Бақыршық кенінің қоспамен сульфидті мыс концентраттары ретінде сульфидизаторға арналған тәжірибелер мүмкіндігі көрсетілді, штейнді қамтитын 80,26 г/т дейін алтын, 56,3 г/т дейін күміс және қож құрамында 0,12-0,18 г/т алтын және 0,26-0,48 г/т күміс. Балқымалар 1350-1450 °С температура интервалында шығулар мен құрамдар өнімдері әсерлі зерттелді. Тәжірибелі балқымалардың температурасының өзгеруі көрсетілген шегінде емес, күндердің өзінде елеулі әсерінен шығатын өнімдерді құрайтыны анықталған, 11,5-12,5 % штейн үшін және 71,5-72,0 % қож үшін. Алайда температураның 1450 °С дейін жоғарылауы металдардың құрамдастарына тигізілген елеулі әсерін төмендету, қождарда 3,3 тен 1,4 г/т дейін алтын және 0,6 дан 0,4 г/т дейін күміс. Тәжірибелі қаттыланған балқыту жағдайында 1450 °С температурада қождаманың құрамы тұрақты болу мүмкіндігі көрсетілді, штейн қоспасыз штейнқұрайтын қоспа алу және қождардың ең төменгі құрамында алтын мен күміс болады. Балқыту жағдайында алтын және күміс штейнін алу барысында оңтайлы қождың құрамы тиісінше 98,7-99,1 % және 79,9-98,3 % құрады.

Түйін сөздер: түпкі берік алтын кені, сульфидті мыс концентраты, қоспа, пирометаллургия, штейн, қож.

РЕЗЮМЕ

Создание принципиально новых технологий, обеспечивающих высокоэффективную переработку «упорных» и «двойной упорности» руд, к которым относятся и руды месторождения Бақырчик, с высоким извлечением золота и других металлов в штейн, весьма актуально. В условиях экспериментов показана возможность плавки упорной богатой золотом руды месторождения Бақырчик с добавкой сульфидных медных концентратов в качестве сульфидизатора на штейны, содержащие до 80,26 г/т золота, до 56,3 г/т серебра и шлаки, содержащие 0,12-0,18 г/т золота и 0,26-0,48 г/т серебра. Изучено влияние температуры в интервале 1350-1450 °С на выходы и составы продуктов плавки. Установлено, что изменение температуры в указанных пределах не оказывало заметного влияния на выходы продуктов опытных плавки, составлявшие 11,5-12,5 % для штейнов и 71,5-72,0 % для шлаков. Однако, повышение температуры до 1450 °С оказало заметное влияние на снижение содержания металлов в шлаках: от 3,3 до 1,4 г/т золота и от 0,6 до 0,4 г/т серебра. В условиях укрупненных опытных плавки шихты постоянного состава, проведенных при температуре 1450 °С, показана возможность образования штейна без добавки штейнообразующего флюса и получения шлаков с минимальным содержанием золота и серебра. Извлечение золота и

серебра в штейн при оптимальных условиях плавки и оптимальном составе шлака составило 98,7-99,1 % и 79,9-98,3 %, соответственно.

Ключевые слова: коренная упорная руда золота, сульфидный медный концентрат, флюс, плавка на штейн, шлак.

Received 07.10.2016.

UDC 669.15-198

Complex Use of Mineral Resources. № 4. 2016.

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COMPLEX FERROALLOY OBTAINING from SILICON- and ALUMINUM-CONTAINING SILICA CLAY

Abstract. For increase of technological efficiency of raw materials in manufacture of silicon-containing alloys it is necessary to raise reactivity of SiO₂ in the raw materials. The silica clay, which contains to 90 % of SiO₂ in amorphous, high active state, can be used as such the raw material. The given article contains the research results of thermodynamic modelling and electrosmelting the Darbaza deposit silica clay with obtaining a complex ferroalloy. The thermodynamic modelling has been performed by means of a software package Outokumpu, and the electrosmelting – in an arc furnace. Temperature (from 500 to 2500°C) and iron amount (from 20 to 120 % from the silica clay weight) effect on Si and Al distribution degree in a system silica clay-C-Fe has been determined. It has been found the positive influence of iron on silicon extraction in an alloy (as FeSi, Fe₂Si, Fe₃Si₃, Si) and reduction of silicon loss as SiO(g). From the thermodynamic point of view the Darbaza silica clay can be applied for obtaining a ferroalloy FS45A10 (40 % of Si, 7.5-10 % of Al) at 2048-2100°C in the presence of 20-45 % of iron and 36 % of carbon from the silica clay weight. At the experimental electrosmelting a charge contained 54 % of the silica clay, 22 % of coke and 24 % of steel shavings in an arc ore-thermal furnace the formation of a complex ferroalloy contained 46-52.8 % of ΣSi+Al has been observed. In accordance with this parameter the ferroalloy obtained corresponds to ferrosilicoaluminum of a grade of FS45A10.

Keywords: silica clay, silicon, aluminum, reduction, thermodynamic modelling, electrosmelting, ferrosilicoaluminum.

Introduction. Ferrosilicoaluminum applies to the complex ferroalloys [1], which are used for steel deoxidation and reduction of content of nonmetallic inclusions in it. The ferrosilicoaluminum requirement in the CIS countries in the beginning of XXI century made 200 ths t a year [2]. Ferrosilicoaluminum is produced from bauxites, high-ash coal, ash of thermal power stations, carbonaceous rock [1-3]. In these raw materials silicon is in a crystalline state. Increase of intensity of smelting silicon-containing alloys including ferrosilicoaluminum is possible at use of the siliceous raw materials, which have raised reactivity. Silica clay, which contains to 90 % of silicon in the amorphous, high reactionary state (in comparison with crystalline SiO₂) can be used as such the raw material. The basis of this statement is the fact that $\Delta G_{298}^{\circ}(\text{SiO}_{2\text{ amorph}}) = -849.8 \text{ kJ/mol}$, and for SiO₂(β-quartz) ΔG_{298}° is more negative: -854.7 kJ/mol [4]. Presence of Al₂O₃ in silica clay expands its possibilities as the raw material; in particular silica clay can become a potential material for

ferrosilicoaluminum manufacture. The given article contains the research results on obtaining ferrosilicoaluminum from the silica clay of the Darbaza deposit (South Kazakhstan area).

Experimental Part. The researches have been performed by means of a thermodynamic modelling method and electrosmelting the silica clay in a mixture with coke and iron shavings. The thermodynamic modelling of interaction of the silica clay with carbon and iron has been carried out with use of a software package HSC-5.1, developed by the Finnish metallurgical company Outokumpu [5]. This program allows describing in detail the processes of ferroalloy manufacture [6-8]. The modelling has been fulfilled in a temperature interval of 500-2500°C. The carbon amount has made 100 % from the amount theoretically necessary for the full reduction of silicon, aluminium and iron (36 % from the silica clay weight), and the iron amount – from 20 to 120 % from the silica clay weight. The equilibrium distribution of silicon and aluminium between the initial substances and reaction products has been determined.