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Research article
Научная статья

Processing of copper anode slimes by aeration leaching (decopperization) and flotation

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Abstract: With the declining quality of feedstock in the copper industry, maintaining metal recovery rates and controlling production costs for non-ferrous and precious metals has become increasingly critical. A key research priority is therefore the development of processing strategies that not only concentrate target metals into flotation products but also recover valuable minor elements previously lost with slags and flue dust. One approach involves designing process flowsheets that integrate hydrometallurgical and beneficiation operations. Previous studies have demonstrated the effectiveness of combining autoclave leaching and flotation for decopperization of copper anode slimes and their concentration in gold, silver, and selenium. However, autoclave leaching requires significant capital and operating expenditures. For this reason, a series of tests was carried out on aeration leaching (decopperization) of copper anode slimes followed by flotation, yielding promising results. This study examined the influence of aeration leaching conditions (temperature, agitation, and specific oxidant consumption—air and oxygen), disintegration of the leached product, and flotation parameters on the selective separation of oxide and chalcogenide phases and the quality of the resulting concentrates. Based on the experimental results, process operations were developed that make it possible to concentrate precious metals in copper anode slimes two- to threefold without the use of autoclave leaching. Optimal conditions and equipment configurations were determined for deep decopperization of slimes (to less than 0.5–0.8 % residual copper). An acceptable degree of separation of precious-metal chalcogenides from lead and antimony oxides was achieved, enabling downstream recovery of marketable products from the respective concentrates. Analytical characterization of the products was performed using scanning electron microscopy (SEM) and energy-dispersive *X*-ray spectroscopy (EDS). The findings contribute to the development of an integrated hydrometallurgical technology for processing copper anode slimes..

Key words: copper anode slimes, aeration leaching (decopperization), flotation processing, bulk concentrate, final tails, precious metals, silver, selenium, tellurium, lead.

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Обогащение медеэлектролитных шламов по технологии «аэрационное обезмеживание – флотация»

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Аннотация: В условиях ухудшения качества сырья в медной подотрасли проблема сохранения параметров извлечения и себестоимости цветных и благородных металлов становится еще более важной. Поэтому приоритетной задачей для исследователей является разработка технологических приемов, позволяющих не только концентрировать целевые металлы в обогащенные продукты, но и извлекать ранее теряемые со шлаками и пылями ценные элементы-примеси. Одним из способов ее решения является создание технологических схем, сочетающих гидрометаллургические и обогатительные операции. Ранее проведенными исследованиями была показана эффективность применения автоклавных процессов и флотации для обезмеживания медеэлектролитного шлама и его обогащения по золоту, серебру и селену. Однако применение автоклавных процессов требует больших капитальных и текущих затрат. Поэтому был проведен цикл экспериментов по аэрационному обезмеживанию шлама с последующей флотацией и получены соответствующие результаты опытов. В настоящей работе было изучено влияние условий аэрационного выщелачивания (температуры, условий перемешивания, удельного расхода окислителя – воздуха и кислорода), дезинтеграции полученного продукта, а также параметров флотации на селективность разделения оксидной и халькогенидной фаз и качество получаемых при этом концентратов. По результатам экспериментов разработаны технологические операции, позволяющие обогащать медеэлектролитные шламы в 2–3 раза по содержанию драгоценных металлов без использования автоклавных процессов. Определены условия и аппаратурное оформление для глубокого обезмеживания шлама (менее 0,5–0,8 % остаточного содержания меди). Достигнут приемлемый уровень разделения халькогенидов драгоценных металлов и оксидных соединений свинца и сурьмы, что позволит в дальнейшем извлекать при переработке соответствующих концентратов товарные продукты. Приведены результаты анализа получаемых продуктов с использованием методов РЭМ и РСМА. Полученные данные являются вкладом в создание комплексной гидрометаллургической технологии переработки анодных шламов медного производства.

Ключевые слова: медеэлектролитный шлам, аэрационное обезмеживание, флотационное обогащение, концентрат, хвосты флотации, драгоценные металлы, серебро, селен, теллур, свинец.

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Introduction

Copper anode slimes represent a unique feedstock for recovering not only precious metals but also chalcogens, which worldwide are predominantly extracted from primary copper-bearing raw materials [1—4]. The conventional global practice of slime processing, yielding Doré (silver—gold alloy), enables the separation of precious and base metals as well as selenium and tellurium. During oxidative roasting, selenium transitions into the gas phase as dioxide and is subsequently recovered from wet gas-cleaning solutions. In the smelting of the calcine, tellurium is transferred into soda slags, which are further processed to obtain commercial tellurium, while heavy minor metals such as lead and antimony are distributed into silicate or other slags [1; 5—7].

These processes are characterized by significant fuel and energy consumption and relatively low efficiency due to:

— limited recovery of precious metals, selenium, and tellurium, caused by the large quantities of waste generated—slags, dust, furnace refractories, and off-gases from roasting and smelting units;

— the environmental impact of these wastes (containing substances of hazard classes I—II) and the associated costs of multistage gas cleaning, which can reach up to 10 % of production costs;

— additional losses of lead, antimony, and tin to slags and other by-products.

Therefore, the development of new, as well as the improvement of existing, slime treatment operations and the creation of advanced, high-efficiency technologies for the comprehensive processing of copper anode slimes with maximum recovery of valuable components remain pressing objectives.

Among the most notable international developments, pilot tests, and in some cases industrial implementations, hydrometallurgical technologies for anode slime processing are considered highly promising. They have been applied at enterprises such as Kennecott Utah Copper Magna (USA) [8], Naoshima Smelter and Refinery (Japan) [9], Outokumpu Technology Oy (Finland) [10], and Yunnan Smelter (China) [11]. Recent studies include work on leaching metal chalcogenides from slimes in alkaline solutions [12; 13], sintering slimes to convert minor elements into soluble forms [14], as well as analyses of combined pyro- and hydrometallurgical approaches [15].

Based on the analysis of advantages and limitations of the proposed flowsheets and individual operations [9], as well as our own research and laboratory trials, we developed a technology for slime processing involving autoclave oxidative leaching followed by flotation [16]. Pilot-scale testing produced a flotation concentrate containing more than 80—85 % of Au + Ag + Se. The recovery of gold and silver into the high-grade concentrate reached 96—98 %. The secondary concentrate, with 40 % Pb and 20 % Sb, essentially represents a rich lead—antimony concentrate. Despite the advantages of this technology, decopperization and preparation of slimes for flotation under autoclave conditions requires high capital and operating expenditures.

The aim of this study was to evaluate the feasibility of replacing autoclave leaching of slimes with a less costly alternative based on aeration leaching (decopperization) followed by flotation of the decopperized slime, and to analyze this approach in the context of its use as a preliminary stage in an integrated technology for processing copper anode slimes.

Aeration leaching (decopperization): procedure and results

Aeration treatment of the slime slurry was carried out in a 50-dm^3 "Bourbon" type reactor equipped with gas dispersers[1]. As dispersion (air or oxygen) ensured maximum contact area between the gas phase and the slime pulp by generating bubbles 0.05—0.30 mm in size. In one of the experiments, a mechanochemical activator was tested. The experimental conditions are summarized in Table 1.

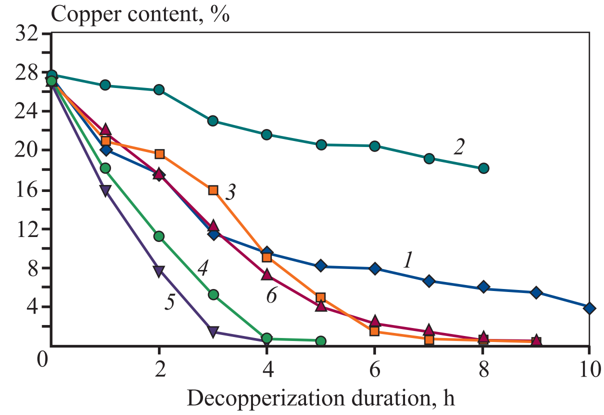

Fig. 1. Change in copper content in slimes over time under different test conditions

The numbering of the curves corresponds to the test number (see Table 1)

Рис. 1. Изменение содержания меди в шламе по времени в зависимости от условий опытов

Нумерация кривых соответствует № опыта (см. табл. 1)

Figure 1 shows the results of the experiments:

— in Test *2*, a mechanochemical activator was used, which blocked the leaching process: the elemental copper present in the slime apparently sealed the reactive surface of the material;

— in Tests *1* and *2*, the required copper content (<3 %) in the solid phase of decopperization was not achieved, indicating that the use of air as an oxidant is ineffective for deep decopperization of copper anode slimes, regardless of flow rate;

— the use of oxygen as an oxidant (Tests *3*—*6*) made it possible to achieve the target copper content in the decopperized residue;

— the duration of decopperization with oxygen depended on its flow rate and the solid—liquid ratio in the slurry.

Based on pilot-scale laboratory trials, the optimal oxygen consumption was determined to be 715 m^3 (31.9 kg) per 1 t of processed slime. Changing the solid—liquid ratio from 1 : 10 to 1 : 5 (Test *6*) increased the decopperization time from 5 to 9 h

[1] Experiments were conducted on equipment and with technical support provided by BFK-Engineering (Moscow).

Table 1. **Experimental conditions for aeration leaching (decopperization)**

Таблица 1. Условия проведенных экспериментов по аэрационному обезмеживанию

Parameter	Test No.					
	1	*2**	*3*	*4*	*5*	*6*
Moisture content of slime, %	25.8	25.8	31	31	26	26
Copper content in slime, %	27.7	27.7	27.1	27.1	27.0	27.0
Slime mass (dry basis), kg	3.9	3.4	4.2	4.2	3.9	9.4
Initial H_2SO_4 concentration, g/dm^3	198.7	204	210	188	196.7	170
Agitation speed, rpm	262	262	315	315	315	315
Solid–liquid ratio (S : L)	1 : 10	1 : 10	1 : 10	1 : 10	1 : 10	1 : 5
Process temperature, °C	94–95	94–95	94–95	94–95	94–95	94–95
Air flow rate, L/min	20	18–19	–	–	–	–
Oxygen flow rate, L/min	–	–	8	10	20	32
Gas consumption, m^3/t of slime	3073.6	2542.6	801.3	715.4	1229.5	1838.5
Duration of leaching, h	10	8	7	5	4	9

* Test involving mechanochemical activation.

and significantly increased oxygen consumption (1839 m^3/t).

Visual inspection and monitoring of the ceramic gas dispersers during decopperization indicated that fluoropolymer-based materials such as PTFE should be used for gas dispersion.

It is known that in unprocessed anode slime, copper is mainly present in elemental form, with a smaller fraction occurring as chalcogenides—primarily copper—silver selenides and tellurides. Previous studies established that during leaching, elemental copper dissolves first, whereas chalcogenides, which require a higher oxidation potential, leach at a later stage. Thus, copper can be oxidized with air down to a residual copper content in the slime of 3—6 %, while deeper decopperization (to 0.5—1.0 %) requires oxygen under elevated pressure, higher initial solution acidity, and efficient gas—slurry contact. It was also established that using a solution containing 200 g/dm^3 sulfuric acid during decopperization reduces tellurium dissolution to 5—8 %, whereas in autoclave treatment tellurium dissolution may reach 25—40 %.

Deep decopperization of slime while maximizing selenium and tellurium retention is important for the effective separation of the chalcogenide and oxide components of decopperized copper anode slimes during flotation processing.

Flotation processing: methodology and results

Phase analysis of copper anode slimes [1; 17] established that in the decopperized slime, gold is mainly present in elemental form, silver occurs as silver selenide, while lead and antimony are present as oxides (sulfates, antimonates, arsenates, etc.). In global practice of sulfide ore processing, flotation methods are widely used to separate oxide minerals from chalcogenides (sulfides, selenides, tellurides). These methods are based on differences in the wettability of minerals in aqueous media, with flotation reagents used to regulate this process.

For the flotation experiments on decopperized slime, samples of the residues obtained after Tests *3—6* were taken. The analysis of these samples for precious metals, lead, and antimony is presented in Table 2.

Bulk flotation of the decopperized slime was carried out at pH = 1.5 and a solid—liquid ratio of 1 : 10. The total consumption of flotation reagents was 450—470 g/t of Aeroflot and 50—65 g/t of MIBK (methyl isobutyl carbinol). The duration of the bulk flotation cycle was 51—62 min. The bulk concentrate was then subjected to regrinding in a bead mill, followed by cleaner flotation stages. Initially, comparative experiments were performed on flotation

Table 2. **Chemical composition of decopperized slime residues (Tests *3–6*)**

Таблица 2. Химический состав проб исходного шлама после опытов *3–6*

Residue (Test No.)	Metal content, %			
	Au	Ag	Pb	Sb
3	0.57	13.44	4.59	14.50
4	0.66	13.78	5.70	15.00
5	0.66	16.13	7.00	15.02
6	0.77	16.36	7.48	14.21

processing of copper anode slime from Test *6* (without regrinding and with regrinding). For concentrate regrinding, a 2.0 L bead mill manufactured by Knelson—Deswik, operating in a circulating mode, was used.

Bead milling of the slime to a particle size of 4—6 μm was previously justified by the need to break down silver selenide spheroids (average size 8—10 μm) that encapsulate oxide compounds of lead, antimony, and arsenic [18—19]. Achieving this particle size increased the transfer of these compounds into the secondary flotation product, thereby improving the quality of the flotation concentrate. As an example, Fig. 2 presents the particle size distribution of the concentrate from decopperization Test *6* after bead milling, measured with a HELOS Particle Size Analyzer (Sympatec).

Comparative flotation results for decopperized copper anode slime processed according to the flowsheet “aeration leaching (decopperization) — flotation — concentrate regrinding”, with and without regrinding of the bulk concentrate, are presented in Table 3. Analysis of these data shows that without regrinding, the gold content in the second cleaner concentrate is lower by 22.0 % and the silver content by 10—16 % compared with the second cleaner concentrate obtained after regrinding of the bulk concentrate. Therefore, regrinding of the bulk concentrate prior to cleaner flotation is justified.

The flowsheet for open-circuit flotation tests with concentrate regrinding and 4—5 cleaner stages of the bulk flotation concentrate is shown in Fig. 3. In the first cleaner stage of the reground concentrate, Aeroflot and MIBK were added, except for the slime sample from Test *6*. The highest reagent consumption was 230 g/t of Aeroflot and 60 g/t of MIBK, with a cleaner flotation time of 38 min for the slime sample from Test *5*. Water glass at a dosage of 300 g/t was added in the second, third, fourth, and fifth cleaner stages.

The flotation reagent regimes for copper anode slime samples from Tests *3—6* (see Table 1), along with the duration of the flotation stages, are presented in Table 4.

Technological performance indicators of flotation processing of decopperized copper anode slime according to the flowsheet “flotation — cleaner flotation of the concentrate” are presented in Table 5.

The summarized results of slime flotation are presented in Table 6.

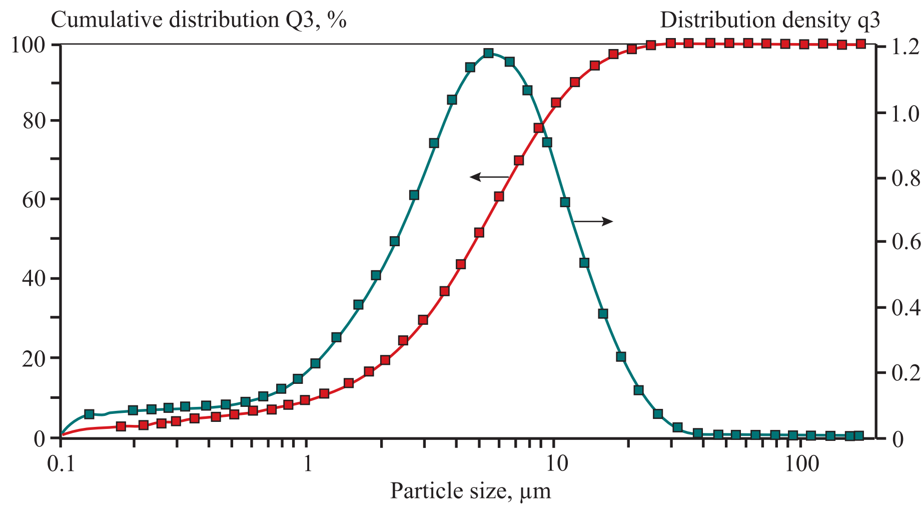

Fig. 2. Particle size distribution of the bulk flotation concentrate of decopperized slime obtained in Test *6* (see Table 2)

Рис. 2. Результаты гранулометрического анализа коллективного концентрата флотации обезмеженного шлама, полученного в опыте *6* (см. табл. 2)

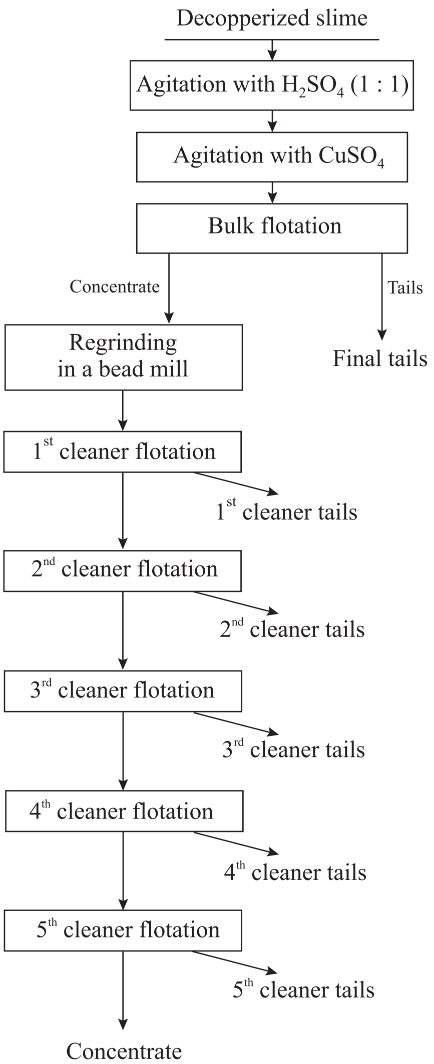

Fig. 3. Flowsheet of open-circuit flotation tests

Рис. 3. Схема проведения флотационных опытов в открытом цикле

Table 3. **Comparative flotation results for anode slime from Test *6* according to the flowsheet "flotation – concentrate regrinding", with and without bulk concentrate regrinding**

Таблица 3. Сравнительные показатели обогащения шлама из опыта *6* по схеме «флотация – доводка концентрата» без измельчения и с доизмельчением коллективного концентрата

Product	Yield, %	Mass fraction, %		Recovery, %	
		Au	Ag	Au	Ag
Without bulk concentrate regrinding					
Concentrate	41.77	1.34	29.8	72.54	76.09
Second cleaner tails	8.80	0.89	20.16	10.15	10.85
First cleaner tails	12.97	0.58	10.46	9.75	8.29
Bulk flotation	**63.54**	–	–	**92.44**	**95.23**
Flotation tails	36.46	0.16	2.14	7.56	4.77
Feed (slime)	100.00	0.77	16.36	100.00	100.00
With bulk concentrate regrinding in a bead mill					
Concentrate	25.76	1.71	35.61	60.14	59.50
Second cleaner tails	5.34	0.97	21.78	7.09	7.54
First cleaner tails	30.31	0.58	14.09	24.06	27.70
Bulk flotation	**61.41**	–	–	**91.29**	**97.74**
Flotation tails	38.59	0.165	2.1	8.71	5.26
Feed (slime)	100.00	0.73	15.42	100.00	100.00

Discussion

The results indicate that through the use of hydrometallurgical operations — namely aeration decopperization and flotation processing — the degree of concentration of copper anode slime can be increased by a factor of 2.5—3.0, with a corresponding rise in gold and silver content. In addition, the flotation tails represent an oxide concentrate rich in lead and antimony.

The concentrate after cleaner flotation and the final tails were examined using a Carl Zeiss EVO MA15 scanning electron microscope with X-Max EDX system (Germany). The results are presented in Fig. 4.

The obtained concentrate of precious metals and chalcogenides requires further upgrading and subsequent separation of gold, silver, and selenium. Its main constituent is refractory silver selenide, and the separation of these components necessitates the application of specialized, potentially unique, technological operations. The recovery of antimony, lead, and other non-ferrous metals present in copper anode slimes has been addressed in a number of publications [20; 21]. For processing flotation tails, which consist mainly of oxide compounds of lead and antimony, a previously developed integrated technology may be applied: in stage 1, leaching of lead sulfate with conventional complexing agents; in stage 2, electrolysis of an antimony — lead anode in an alkaline — glycerate solution, producing commercial antimony while simultaneously precipitating lead from the electrolyte as

Table 4. **Process and reagent regimes for flotation processing of copper anode slime samples (see Table 1) according to the flowsheet “bulk flotation – ultrafine regrinding of the bulk concentrate – cleaner flotation of the bulk concentrate”**

Таблица 4. Технологический и реагентный режимы обогащения образцов шлама (см. табл. 1) по схеме «основная флотация – ультратонкое измельчение концентрата основной флотации–перечистка концентрата основной флотации»

Stage	Slurry pH	Reagent consumption, g/t					Duration, min
		H_2SO_4 (1 :1)	$CuSO_4$	Aeroflot (sodium butyl xanthate)	MIBK (methyl isobutyl carbinol)	Water glass	
Slime sample from Test *3*							
Agitation		25 335	66.7	–	–	–	–
Bulk flotation	1.49	–	–	450	50	–	52
Regrinding of bulk concentrate	–	–	–	–	–	–	12
1st cleaner flotation of the bulk concentrate	1.57	–	–	50	10	–	22
2nd cleaner flotation of the bulk concentrate	1.6	–	–	–	–	300	21
3rd cleaner flotation of the bulk concentrate	1.6	–	–	–	–	300	14
4th cleaner flotation of the bulk concentrate	1.7	–	–	–	–	300	13
5th cleaner flotation of the bulk concentrate	1.7	–	–	–	–	300	10
Slime sample from Test *4*							
Agitation	–	22 520	66.7	–		–	–
Bulk flotation	1.49	–	–	450	50	–	52
Regrinding of bulk concentrate	–	–	–	–	–	–	12
Agitation	–	16 890	–	–	–	–	–
1st cleaner flotation of the bulk concentrate	1.55	–	–	120	30	–	18
2nd cleaner flotation of the bulk concentrate	1.62	–	–	–	–	300	13
3rd cleaner flotation of the bulk concentrate	1.6	–	–	–	–	300	11
4th cleaner flotation of the bulk concentrate	1.7	–	–	–	–	300	10
5th cleaner flotation of the bulk concentrate	1.7	–	–	–	–	–	10
Slime sample from Test *5*							
Agitation	–	22 520	66.7	–	–	–	–
Bulk flotation	1.5	–	–	450	50	–	52
Regrinding of bulk concentrate	–	–	–	–	–	–	12
Agitation	–	19 705	–	–	–	–	–
1st cleaner flotation of the bulk concentrate	1.64	–	–	230	60	–	38
2nd cleaner flotation of the bulk concentrate	1.57	–	–	100	10	300	24
3rd cleaner flotation of the bulk concentrate	1.6	–	–	–	–	300	20
4th cleaner flotation of the bulk concentrate	1.7	–	–	–	–	300	17
5th cleaner flotation of the bulk concentrate	1.7	–	–	–	–	300	10
Slime sample from Test *6*							
Agitation	–	33 780	66.7	–	–	–	–
Bulk flotation	1.5	–	–	470	65	–	61
Regrinding of bulk concentrate	–	–	–	–	–	–	12
Agitation	–	7037	–	–	–	–	–
1st cleaner flotation of the bulk concentrate	1.7	–	–	–	–	–	18
2nd cleaner flotation of the bulk concentrate	1.6	–	–	–	–	300	15
3rd cleaner flotation of the bulk concentrate	1.6	–	–	–	–	300	13
4th cleaner flotation of the bulk concentrate	1.7	–	–	–	–	300	11
Agitation	–	33 780	66.7	–	–	–	–
Bulk flotation	1.5	–	–	450	50	–	52
Agitation	–	28 150	66.7	–	–	–	–
Bulk flotation	1.5	–	–	450	50	–	52
1st cleaner flotation of the bulk concentrate	1.7	–	–	–	–	300	15
2nd cleaner flotation of the bulk concentrate	1.7	–	–	–	–	–	8

Table 5. **Technological performance indicators of slime flotation processing**

Таблица 5. Технологические показатели флотационного обогащения шлама

Product	Yield, %	Metal content in product, % / metal recovery to product, %			
		Au	Ag	Pb	Sb
Slime sample from Test 3					
Concentrate	22.59	1.36 / 54.23	35.97 / 60.45	1.63 / 8.03	2.9 / 4.52
5th cleaner tails	7.35	1.22 / 15.83	31.29 / 17.11	3.2 / 5.13	5.3 / 2.69
4th cleaner tails	4.17	0.97 / 7.14	22.7 / 7.04	5.4 / 4.90	7.8 / 2.24
3rd cleaner tails	3.50	0.73 / 4.51	14.98 / 3.90	5.7 / 4.35	13.5 /3.26
2nd cleaner tails	6.80	0.57 /6.84	11.94 / 6.04	6.1 / 9.04	14.2 / 6.66
1st cleaner tails	16.91	0.166 / 4.96	2.44 /3.07	6.7 / 24.7	21.1 /24.61
Bulk flotation stage	**61.32**	**93.51** (recovery)	**97.61** (recovery)	–	–
Final tails	38.68	0.095 / 6.49	0.83 / 2.39	5.2 / 43.85	21.0 / 56.02
Feed (slime)	100.00	0.57 / 100.00	13.44 / 100.00	4.59 / 100.00	14.50 / 100.00
Slime sample from Test 4					
Concentrate	21.67	1.69 / 55.15	36.31 / 57.12	3.00 / 11.41	2.90 / 4.19
5th cleaner tails	5.18	1.23 / 9.60	31.95 / 12.01	2.9 / 2.64	4.4 / 1.52
4th cleaner tails	3.04	1.06 / 4.85	24.94 / 5.50	4.9 / 2.62	7.5 / 1.52
3rd cleaner tails	4.38	0.90 / 5.94	19.90 / 6.33	6.1 / 4.69	11.5 / 3.36
2nd cleaner tails	8.49	0.70 / 8.95	14.63 / 9.02	6.1 / 9.09	15.2 / 8.60
1st cleaner tails	17.13	0.311 / 8.02	5.27 / 6.55	6.5 / 19.55	20.2 / 23.06
Bulk flotation stage	**59.89**	**92.51** (recovery)	**96.53** (recovery)	–	–
Final tails	40.11	0.124 / 7.49	1.19 / 3.47	7.1 / 50.00	21.6 / 57.75
Feed (slime)	100.00	0.66 / 100.00	13.78 / 100.00	5.70 / 100.00	15.00 / 100.00
Slime sample from Test 5					
Concentrate	30.75	1.35 / 63,04	36.29 / 69.19	1.68 / 7.38	2.9 / 5.94
5th cleaner tails	1.34	1.01 / 2,06	23.22 / 1.93	6.6 / 1.26	7.8 / 0.70
4th cleaner tails	3.38	1.24 / 6,36	28.68 / 6.01	4.3 / 2.08	7.1 / 1.60
3rd cleaner tails	6.27	1.02 / 9,71	24.31 / 9.45	6.2 / 5.56	10.6 / 4.43
2nd cleaner tails	8.33	0.6 / 7,59	14.4 / 7.44	15.5 / 18.45	15.3 / 8.49
1st cleaner tails	19.25	0.152 / 4,44	2.89 / 3.45	8.9 / 24.49	21.2 / 27.16
Bulk flotation stage	**69.32**	**93.20** (recovery)	**97.47** (recovery)	–	–
Final tails	30.68	0.146 / 6,80	1.33 / 2.53	9.3 / 40.78	25.3 / 51.68
Feed (slime)	100.00	0.66 / 100.00	16.13 / 100.00	7.00 / 100.00	15.02 / 100.00
Slime sample from Test 6					
Concentrate	64.80	1.09 / 90.85	23.78 / 94.58	–	–
Final tails	35.20	0.202 / 9.15	2.51 / 5.42	–	–
Feed (slime)	100.00	0.78 / 100.00	16.29 / 100.00	–	–
Concentrate	41.77	1.34 / 72.54	29.8 / 76.09	–	–
2nd cleaner tails	8.80	0.89 / 10.15	20.16 / 10.85	–	–
1st cleaner tails	12.97	0.58 / 9.75	10.46 / 8.29	–	–
Bulk flotation stage	**63.54**	**92.44** (recovery)	**95.23** (recovery)	–	–
Final tails	36.46	0.16 / 7.56	2.14 / 4.77	–	–
Feed (slime)	100.00	0.77 / 100.00	16.36 / 100.00	–	–
Concentrate	23.34	1.77 / 56.54	36.9 / 55.86	2.6 / 8.12	2.3 / 3.78
4th cleaner tails	0.94	1.02 / 1.31	20.94 / 1.28	7.1 / 0.89	7.7 / 0.51
3rd cleaner tails	1.48	1.13 / 2.29	24.57 / 2.36	6.6 / 1.31	8.4 / 0.87
2nd cleaner tails	5.34	0.97 / 7.09	21.78 / 7.54	7.1 / 5.07	10.5 / 3.95
1st cleaner tails	30.31	0.58 / 24.06	14.09 / 27.70	10.3 / 41.76	12.7 / 27.08
Bulk flotation stage	**61.41**	**91.29** (recovery)	**97.74** (recovery)	–	–
Final tails	38.59	0.165 / 8.71	2.1 / 5.26	8.3 / 42.85	23.5 / 63.81
Feed (slime)	100.00	0.73 / 100.00	15.42 / 100.00	7.48 / 100.00	14.21 / 100.00

Table 6. **Flotation results for decopperized slime**

Таблица 6. Результаты флотации обезмеженного шлама

Test No.	Metal content in the bulk concentrate, %			Metal recovery to the bulk concentrate, %		Metal content in flotation tails, %		
	Au	Ag	Σ Pb + Sb	Au	Ag	Au	Ag	Σ Pb + Sb
3	1.36	35.97	4.53	93.51	97.61	0.095	0.83	26.2
4	1.69	36.31	5.90	92.51	96.53	0.124	1.19	28.7
5	1.35	36.29	4.58	93.20	97.47	0.146	1.33	34.6
6	1.09	23.70	4.90	91.29	97.75	0.165	2.1	31.8

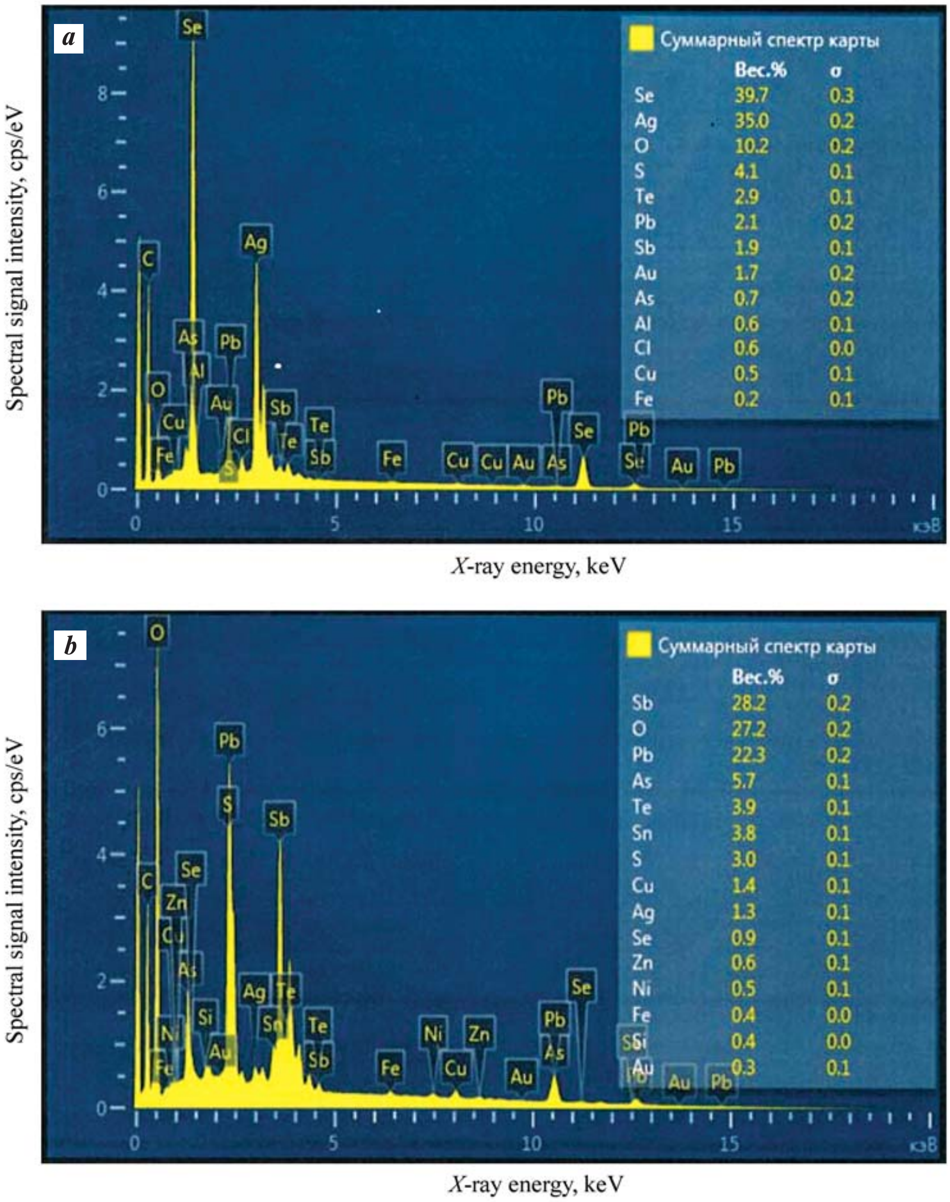

Fig. 4. Results of semi-quantitative chemical analysis of (***a***) the flotation concentrate after cleaner flotation and (***b***) the final flotation tails

Рис. 4. Результаты полуколичественного химического анализа концентрата флотации после перечисток (***a***) и отвальных хвостов обогащения (***b***) lead sulfide concentrate [22]. Alternatively, integrated pyro- and hydrometallurgical technologies for antimony and lead recovery, developed and implemented at JSC "Uralelektromed" [23], or other established methods [24] may be employed.

Conclusions

1. Technological operations — namely aeration decopperization followed by flotation — have been developed, enabling the processing of copper anode slimes without the use of costly autoclave leaching.

2. The conditions and equipment configuration required for deep decopperization of slime (to less than 0.5—0.8 % residual copper) have been determined.

3. The method of aeration decopperization using oxygen in sulfuric acid solution (200 g/dm^3) is suitable for deep copper removal, while simultaneously suppressing the undesirable dissolution of tellurium. This substantially reduces the formation of slags and dust, thereby minimizing gold and silver losses during Doré smelting.

4. An acceptable degree of separation between chalcogenides of precious metals and oxide compounds of lead and antimony was achieved, allowing for the production of commercial products from the respective concentrates in subsequent processing.

5. The results obtained contribute to the development of an integrated hydrometallurgical technology for processing copper anode slimes.

References

1. Hait J., Jana R.K., Sanyal S.K. Processing of copper electrorefining anode slime: a review. *Mineral Processing and Extractive Metallurgy.* 2009;118(4):240—252. https://doi.org/10.1179/174328509x431463
2. Cooper W.C. The treatment of copper refinery anode slimes. *JOM.* 1990;8:45—49. https://doi.org/10.1007/BF03221054
3. Meyerovich A.S., Meretukov M.A. Technique and technology of processing electrolytic sludge abroad: Review information. Moscow: TsNIITsvetmet of Economics and Information, 1988. 52 p. (In Russ.).
Мейерович А.С., Меретуков М.А. Техника и технология переработки электролитных шламов за рубежом: Обзорная информация. М.: ЦНИИцветмет экономики и информации, 1988. 52 с.
4. Meretukov M.A., Orlov A.M. Metallurgy of precious metals (Foreign experience). Moscow: Metallurgiya, 1990. 416 p. (In Russ.).
Меретуков М.А., Орлов А.М. Металлургия благородных металлов (Зарубежный опыт). М.: Металлургия, 1990. 416 с.
5. Wei Dong Xing, Seong Ho SohnMan Seung Lee. A Review on the recovery of noble metals from anode slimes. *Mineral Processing and Extractive Metallurgy Review.* 2019; 2:1—14. https://doi.org/10.1080/08827508.2019.1575211
6. Lobanov V.G., Polygalov S.E., Mamyachenkov S.V., Khmelev N.B., Melnik F.F. On the problem of intensifying the demineralization of copper electrolyte sludge. *Tsvetnye metally.* 2023;12:35—40. (In Russ.). https://doi.org/ 10.17580/tsm.2023.12.02
Лобанов В.Г., Полыгалов С.Э., Мамяченков С.В., Хмелев Н.Б., Мельник Ф.Ф. К проблеме интенсификации обезмеживания медеэлектролитного шлама. *Цветные металлы.* 2023;12: 35—40. https://doi.org/ 10.17580/tsm.2023.12.02
7. Greiver T.N., Zaitseva I.G., Kosover V.M. Selenium and tellurium. Moscow: Metallurgiya, 1977. 296 p. (In Russ.).
Грейвер Т.Н., Зайцева И.Г., Косовер В.М. Селен и теллур. М.: Металлургия, 1977. 296 с.
8. Hoffman J.E., Sutcliff K.E., Wells B.A., George D.B. Hydrometallurgical processing of kennecott refinery slimes. In: *COPPER 95 — COBRE 95: Electrorefining and Hydrometallurgy of Copper.* Canada. Montreal: Canadian Institute of Mining, Metallurgy and Petroleum, 1995. Vol. 3. P. 41—57.
9. Komori K., Ito S., Okada S., Iwahori S. Hydrometallurgical process of precious metals in naoshima smelter and refinery. *Processing of Copper.* 2010;4:1403—1411.
10. Jarvinen O., Virtanen H. A new hydrometallurgical process for treating copper anode slimes. In: *Proc. of COBRE 2003.* Chili: Santiago, 2003. P. 221—232.
11. Chuanyan Lei, Peihua Zhu. Recovery of precious metals from copper anode slime by combined metallurgy and beneficiation. In: *Mineral processing and extractive metallurgy:* Proc. of Int. Conf. China: Kunming, 1984. P. 699—705.
12. Dong Li, XueyiGuo, Zhipeng Xu, Runze Xu, Qiming Feng. Metal values separation from residue generated in alkali fusion-leaching of copper anode slime. *Hydrometallurgy.* 2016;165(2):290—294. https://doi.org/10.1016/j.hydromet.2016.01.021
13. Yasin K., Guldem K., Servet T. An investigation of copper and selenium recovery from copper anode slimes. *International Journal of Mineral Processing.* 2013;124(11):75—82. https://doi.org/10.1016/j.minpro.2013.04.006
14. Dong Li, XueyiGuo, Zhipeng Xu, Qinghua Tian, Qiming Feng. Leaching behavior of metals from copper anode slime using analkali fusion-leaching process. *Hydrometallurgy.* 2015;157(10):9—12.

15. Chen A., Peng Z., Hwang J-Y., Ma Y., Liu X., Chen X. Recovery of silver and gold from copper anode slimes. *JOM*. 2015;67(2):493—502. https://doi.org/10.1007/s11837-014-1114-9
16. Lastochkina M.A., Greiver T.N., Vergizova T.V., Mastyugin S.A., Ashikhin V.V., Krayukhin S.A., Krestyaninov A.T. Method for processing lead sludge from copper electrorefining (variants): Patent 2451759 (RF). 2012. (In Russ.).
Ласточкина М.А., Грейвер Т.Н., Вергизова Т.В., Мастюгин С.А., Ашихин В.В., Краюхин С.А., Крестьянинов А.Т. Способ переработки свинцовистых шламов электрорафинирования меди (варианты): Патент 2451759 (РФ). 2012.
17. Chen T.T., Dutrizac J.E. Mineralogical characterization of anode slimes. *Canadian Metallurgy Quarterly*. 1993;32(4):267—279.
18. Yanliang Zeng, Chunfa Liao, Fupeng Liu, Xun Zhou. Occurrence behaviors of As/Sb/Bi in copper anode slime and their separation by compound leaching followed by stepwise precipitation. *ACS Omega*. 2023;8: 10022—10029.
19. Mastyugin S.A., Lastochkina M.A., Naboychenko S.S., Voinkov R.S. Use of disintegration techniques in processing copper electrolyte sludge. *Tsvetnye metally*. 2014;(11):35—40. (In Russ.).
Мастюгин С.А., Ласточкина М.А., Набойченко С.С., Воинков Р.С. Использование приемов дезинтеграции при переработке медеэлектролитных шламов. *Цветные металлы*. 2014;(11):35—40.
20. Ugorets M.Z., Glazkova T.I. Hydrometallurgical extraction of lead and antimony from copper electrolyte sludge. In: *Complex use of raw materials of non-ferrous metallurgy*. Sverdlovsk: House of the Ural Scientific Center of the USSR Academy of Sciences, 1980. P. 63—66. (In Russ.).
Угорец М.З., Глазкова Т.И. Гидрометаллургическое извлечение свинца и сурьмы из медеэлектролитных шламов. В кн.: *Комплексное использование сырья цветной металлургии*. Свердловск: УНЦ АН СССР, 1980. С. 63—66.
21. Khlomanskikh Yu.B., Cherkasov G.F., Savin V.M., Lobanov E.N. On the removal of Sb, As and Bi during the processing of copper electrolyte sludge. *Tsvetnye metally*. 1970;(7):30—31. (In Russ.).
Хломанских Ю.Б., Черкасов Г.Ф., Савин В.М., Лобанов Е.Н. О выводе Sb, As и Bi при переработке медеэлектролитных шламов. *Цветные металлы*. 1970;(7):30—31.
22. Voinkov R.S. Complex processing of flotation tailings of copper electrolyte sludge: Abstract of the dissertation of Cand. Sci. (Eng.). Yekaterinburg: UrFU, 2015. (In Russ.).
Воинков Р.С. Комплексная переработка хвостов флотации медеэлектролитных шламов: Автореф. дис. канд. техн. наук. Екатеринбург: УрФУ, 2015.
23. Timofeev K.L., Korolev A.A., Krayukhin S.A., Maltsev G.I., Voinkov R.S., Shunin V.A., Sergeychenko S.V., Kokshin A.A. Development of tin and antimony production at Uralelectromed JSC. In: *Modern technologies for the production of non-ferrous metals:* Proceedings of the International Scientific Conference dedicated to the 80th anniversary of S.S. Naboychenko (March 24, 2022). Yekaterinburg: UrFU, 2022. P. 159–165. (In Russ.).
Тимофеев К.Л., Королев А.А., Краюхин С.А., Мальцев Г.И., Воинков Р.С., Шунин В.А., Сергейченко С.В., Кокшин А.А. Освоение производства олова и сурьмы в АО «Уралэлектромедь». В сб.: *Современные технологии производства цветных металлов*: Материалы междунар. науч. конф., посвященной 80-летию С.С. Набойченко (24 марта 2022 г.). Екатеринбург: УрФУ, 2022. С. 159—165.
24. Baole Li, Juhai Deng, Wenlong Jiang, Guozheng Zha, Bin Yang Removal of arsenic, lead and bismuth from copper anode slime by a one-step sustainable vacuum carbothermal reduction process. *Separation and Purification Technology*. 2023;310:123059. https://doi.org/10.1016/j.seppur.2022.123059

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R.S. Voinkov – prepared initial samples, participated in decopperization tests of slimes (at JSC Uralelektromed), performed chemical analyses, contributed to the discussion of experimental results, revised the manuscript.

S.V. Volkova – conducted flotation experiments (at JSC "Uralmekhanobr") on decopperized slime, including bead milling, performed analyses, including scanning electron microscopy.

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