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COMPARATIVE RESULTS OF COPPER FLOTATION FROM SMELTER SLAG AND GRANULATED SMELTER SLAG****

Abstract

Smelter slag is obtained in the process of metallurgical converting of copper concentrate in the Smelter Plant in Bor, Serbia. Today, the reserves of this material are evaluated at about more of a year, with the average copper content of 0.6-0.9%. Production of copper concentrate by flotation of smelter slag has started in 2001. Flotation concentrate goes to the Copepr Smelter once more for production of copper cathodes and the rough flotation tailings go to the flotation tailing dump. Copper recoveries in the flotation process of smelter slag reaches the value of about 45- 50%. Slag in RTB plants is processed in a facility that is not designed for slag processing but it is only adapted to these conditions. The obtained results are worser than the expected ones and testing that could improve them will continue.

This paper shows the way of obtaining the flotation concentrate of smelter slag with realization better total copper recovery. One of the possibilities is the slag granulation process that provides a range of courses to investigate the impact on process of comminution and concentration of copper. For this purpose, on a specially constructed laboratory granulator, large amounts of granulated smelter slag are obtained, necessary for further testing the process of flotation concentration. This paper presents the achieved comparative results from the flotation concentration process of smelter slag and granulated smelter slag of reverberatory furnace.

Keywords: *smelter slag, granulation, grinding, flotation, Cu recovery*

1 INTRODUCTION

Metal production in the future could be substantially lower than the present due to a fact that metal reserves in a natural form in the run-of-mine ores are rapidly decreased from year to year. The other reason, limited metal productions are present by stricter laws on environmental protection due to the waste generated by the mass processing of low-grade ore. Huge amounts of metals, trapped in tailing

dumps and slag dumps, for the future can be a potential raw materials for the production the new metal amounts. For these reasons, the tailing dumps and slag dumps, as a source of large amounts of metals, have increasing economic importance. All over the world there are attempts for slag recycling and further recovery of useful metals from it. Mineralogical composition of slag, obtained

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from metallurgical treatments, depends on many factors, and it is one of the most important technologies of metallurgical treatment. Depending on the above mentioned, the content of useful component varies within the limits that present higher content than the presence of this component in the run-of-mine ores. The main components of slag, obtained from the copper metallurgy, are Fe and SiO_2 . Copper content in almost all slags of metallurgical copper treatment ranges from 0.5 to 4.0%, which is significantly more than copper content in the ore of copper deposits, which are nowadays in exploitation. Slags, obtained by metallurgical treatment of copper, usually with different methods of preparation and concentration, are treated for recovery of copper.

Smelter slag of reverberatory furnace is obtained in the process of metallurgical converting of flotation copper concentrates in the Smelter in Bor. Experimental production of copper concentrate by flotation from smelter slag has begun in 2001. Slag in RTB plants is processed in a facility that was not designed for slag processing, but it was only adapted to these conditions. Flotation Plant in Bor was originally designed for a different type of raw material, and it is now only adapted for slag processing [1]. Slag is less suitable than ore for comminution from the point of view of energy consumption, cover and grinding media, and also for metal recovery (copper, Cu). The obtained flotation concentrate from smelter slag once again goes to smelting in the Copper Smelter for production of copper cathodes, while the definitive flotation tailings from copper smelter slag goes to disposal on flotation tailing dump. Ten years ago, the mentioned useful metals are obtained by flotation concentration in the plant in Bor but with a series of difficulties and less successful than in the world with similar raw materials. Regarding to this, there are a number of difficulties, such as high power consumption and poor technological results of some similar plants in the world. Copper recovery in the

process of flotation copper concentration from smelter slag hardly reaches the value of around $I_{\text{Cu}} = 50\%$. This value is much lower than that usually achieved by standard flotation process of sulfide minerals $I_{\text{Cu}} = 75\text{--}85\%$ holder of metal copper, Cu, which are present in the ores. Also, at the same time, high value of copper content was detected in the final flotation tailings. The obtained results are worse than the expected and testing that could improve them will be continued.

Practice has shown that the secondary raw materials differ from the primary raw materials, ores, in terms of mineralogical, physico-chemical and mechanical characteristics. The current global research in the field of processing the mineral raw materials, were based on research the processing of primary raw materials (ores). Therefore, all results, theories and conclusions obtained by research the primary raw materials, can not be fully accepted and applied in the process of treatment the secondary raw materials.

Smelter slag from the process of metallurgical treatment of concentrates by their mineralogical, physical - chemical and mechanical properties is quite different from primary raw materials. Behavior of smelter slag in the process of crushing, grinding and flotation is different from the behavior of ores that are essential for obtaining a copper rich concentrate. Characteristics of smelter slag, such as bulk density and hardness, have impact that the process of ore processing cannot be applied without any changes in treatment of smelter slag.

The existing differences in physico-chemical and mechanical properties of the primary raw materials, ore and secondary raw materials, smelting slag, impose a need for basic research due to introduction a behavior of smelting slag in treatment process and possibility of process optimization to improve the technological results and reduce the treatment costs [2]. For all these reasons, any work that indicates the direction of possible solutions to achieve better technological results of

copper recovery in the flotation process from smelter slag has a great importance.

One possibility is slag granulation process that provides a number of possible ways to test the impact on the process of comminution and concentration of copper. For this purpose, a laboratory device was designed and a laboratory technological line with a help of which will receive large amounts of granulated smelter slag necessary for further investigations.

By the Project TR 33023, titled "*Development of Technologies for Flotation Processing of Copper Ore and Precious Metals in Order to Achieve Better Technological Results*", funded by the Ministry of Science and Technological Development within the Program of Technological Development, the certain studies were implemented in the field of granulation of smelter slag of fire furnace. Previous studies, related to the necessary degree of comminution [2;3] have shown that the coarseness of input that is grain-size distribution of input into the rod mill may be compensated by granulation process [4].

This is actually simple and inexpensive process that can avoid the technological method of three stage crushing and sieving. Granulation process has to be explored as well as to test the impact of granulation and the way of performing the granulation on technological indicators of flotation concentration of copper from granulated smelterslag. In order for further

testing, a laboratory facility for slag granulation was established with which large amounts of granulated slag will be obtained, required for the experiments [5].

2 SEPARATION, PREPARATION AND PHYSICO-CHEMICAL CHARACTERIZATION OF THE SAMPLE

a) Sampling and physic-chemical characterization of the sample from reverberatory furnace slag

The sample for this study was taken from the crushed slag of reverberatory furnace in the Smelte Bor. By stopping the conveyor belt under the bunker of finished crushing product at the input of grinding mill, sampling was carried out in the Flotation Plant. Sample of finished product of grinding the smelte slag was first homogenized by standard laboratory method and then fragmented to 100% -12.7 mm. Upon determination the Bond Index in the mill with rods, the sample was fragmented to 100% -3.327 mm, homogenized, and then used to determine the Bond Index in the ball mill and other necessary technological investigations. Physico-chemical characteristics of the starting sample of slag were determined by common laboratory methods. These characteristics are presented in Table 1. Samples were taken from the same sample of smelter slag for mineralogical characterization and X-ray analysis.

Table 1 Physico-chemical characteristics of smelter slag sample

Physical characteristics	Values and measuring units:
Slag density and natural pH value	$\rho = 3\,575.0 \text{ kg/m}^3$; pH 6.75
Bond Index	$W_i \text{ (KWh/t)}$
Rod mill; Ball mill	19.13 ; 31.96
<i>Grain-size distribution</i>	Analytical represented (RRS equation):
Final crushing product, starting sample Class size -12.7 mm+0.0 mm	$R = 100 \cdot e^{-\left(\frac{d}{23474}\right)^{1.020}}, \%$
Sample ready for flotation (grinding) Class size -3.327 mm+0.0 mm	$R = 100 \cdot e^{-\left(\frac{d}{1859}\right)^{1.036}}, \%$

Chemical characteristics:	Content :
Cu-total	0.89 %
Cu-elem.	0.45 %
Cu-ox	0.246 %
Cu-sulphide	0.214 %
S	0.82 %
SiO ₂	34.87 %
Fe	38.55 %
FeO	37.00 %
Fe ₃ O ₄	8.98 %
Al ₂ O ₃	4.84 %
Au	< 1.0 g/t
Ag	< 1.0 g/t
MgO	1.10 %
Na ₂ O	0.45 %
K ₂ O	1.54 %
CaO	3.77 %

X-ray analysis

X-ray analysis was carried out in the Mining and Metallurgy Institute Bor on "Siemens" apparatus using Cu anticathode with filtered radiation with Ni filters, at voltage of 40 kV and current intensity of 20 mA. Bydiffraction analysis on samples

of smelter slag, the following quantitative compositions were determined: fayalite (Fe₂SiO₄), magnetite (Fe₃O₄) and quartz (SiO₂) as the main phase. Figure 1 presents a roentgenogram taken on a sample of smelter slag.

Microscopic description

Samples are approximately of the same size and very similar in color and shape, suggesting a common origin. Visible on the surface of the sample are nearly spherical cavities, which indicates that samples are product of ore – slag smelting. Dark gray, matte color, with blue-green and red-brown hue is dominated.

Mineralogical composition: fayalite, magnetite, chalcopyrite, bornite, copper matte, native copper, pyrite, chalcopyrite, coveline ... Base of preparation consists of fayalite, which appears in the form of blades (usually) and in the form of stars (rarely), where it forms a mercuritic structure. Fayalite presents an isomorphic series, occurring naturally in the mineral olivine. ((Mg, Fe) 2SiO_4). Olivine is an isomorphic mixture of forsterite (Mg_2SiO_4) and fayalite (Fe_2SiO_4). For olivine is characterized by metamorphosis in serpentine with simultaneous leaching of magnetite and hematite. This fayalitic base supports other mineral phases [3]. Mainly magnetite occurs independently, rarely intergrown with copper minerals. Bornite is the most present from copper minerals. It occurs in the form of xeromorphic grains, and sporadically appears in the form of nearly isometric spherical grains. These grains can be seen as transformation of chalcopyrite into bornite and bornite into chalcocite or copper matte representing an intermediate phase. Coveline is rarely observed in this transformation. The final product is native copper, which is locally observed in bornite grains. It is observed very rarely as self-contained. Pyrite occurs in the form of hypidiomorphic grains, mostly independent and rarely intergrown with copper minerals.

b) Obtaining and physico-chemical characterizations of granulated smelter slag sample

For laboratory experiment of granulated smelter slag of reverberatory furnace in the Smelter Bor, the slag was used slag which is taken from the crushing and sieving plant from conveyor belt, before the process of tertiary crushing. Slag was exposed on the landfills to the atmospheric conditions and contained a certain amount of moisture due to which it was pre-dried at room temperature. In order to characterize the taken sample, the physico-chemical analyses of slag were carried out and the results are shown in Table 2.

At laboratory technological line, specially formed or in a granulator constructed for these purposes, a granulation process of smelter slag in the Smelter Bor was carried out [4;5]. Slag was subjected to melting in a laboratory induction furnace for melting, power of 100 kW, in a pot volume $V = 10 \text{ l}$, manufacturer ELING - Loznica. Granulation was done in the laboratory conditions in the newly designed device-granulator for fast cooling of hot slag. During the experiment, 250 kg of slag was melted, and temperature, at which the slag was poured, $t = 1250^\circ\text{C}$. Temperature measurement of slag was performed using a submersible pyrometer.

In this way, a sample of granulated slag was obtained which was used for further testing of grain-size distribution, chemical composition, the possibilities of copper flotation, etc. Thus, granulated smelter slag was produced in laboratory conditions and the functionality of laboratory equipment design for granulation was confirmed. The following Figures 2 and 3, respectively, present the smelter slag granulator in operation and schematic view of the newly established laboratory technological line for the production of granulated smelter slag.

Figure 2 Granulator of smelter slag in operation

Figure 3 Technological scheme of laboratory procedure for granulation of smelter slag

The new laboratory device and laboratory technological line should provide further research in several directions:

- Testing of smelter slag granulation in order to obtain as much as possible finer granules.
- Creation of various granulated slag for technological testing of copper flotation concentration with regard to that.
- Modification the existing technological process of flotation copper concentration from smelte slag of reverberatory furnace and energy efficient

process of flotation concentration of granulated smelter slag.

At the same time, a new laboratory device granulator of smelter slag was designed and it presents a model that will be used in addition to the testing for construction of larger semi-industrial or industrial smelter slag granulator.

Produced granulated smelter slag by the method of rapid cooling in granulator is with altered physico-chemical characteristics compared to the primary smelter slag. The results of physico-chemical characterization

of granulated smelter slag are present in Table 2. The observed changes are primarily related to: different grain-size distribution of the finished product of grinding the smelter slag and granulated smelter slag, then difference in determined Bond work index between samples of smelter slag and granulated smelter slag that can contribute in saving the grinding energy in comminution or grinding of granulated smelter slag for the process of flotation concen-

tration. This will be the subject of a separate study. Also, there is a very glassy fayalitic structure of granulated slag with copper matte and copper within it, separated in elemental form.

Figure 4 and 5 present a separated elemental copper in smelter slag and granulated smelter slag, respectively, according to the given figures, that could determine further research in a flotation direction.

Figure 4 *Intergrowing of chalcopyrite, pyrite and copper matte with allocations of elemental copper*

Figure 5 *Copper matte in fayalite base, 50x lens, II Nikoli*

Table 2 *Physico-chemical characteristics of granulated smelte slag sample*

Physical characteristics		Values and measuring units:
Slag density and natural pH value		$\rho = 3230 \text{ kg/m}^3$; pH 7.5
Bond index		Wi (KWh/t)
Ball mill: Standard/Shortened		12.20 / 10.13
Grain size distribution		Graphically represented:
Granulated sample of smelter slag Input into industrial grinding of smelter slag (crushed slag)
Chemical characteristics:		Content:
Cu-total		1.05%
S		0.56%
SiO ₂		36.28 %
Fe		26.25 %
FeO		28.65 %
Fe ₃ O ₄		0.092 %
Al ₂ O ₃		12.67 %
Au		< 1.0 g/t
Ag		< 1.0 g/t
CaO		15.50 %

3 EXPERIMENTAL PART

As it was mentioned in the abstract of this paper, here will be present the realized results of flotation concentration of smelter slag and granulated smelt slag of reverberatory furnace under the same laboratory conditions.

a) Results of flotation copper concentration from smelter slag

Preliminary grinding experiments were carried out to determine the grinding kinetics

of smelter slag samples. The experiments were conducted in an ellipsoidal ball mill, volume 15.2 dm^3 . Mass of ball batch at the beginning of testing was 12 kg. For an experiment, 0.6613 g of ore was ground, with a solid content of 75%. All milling conditions were held constant while only changing the grinding time was done. The achieved results of experiment of grinding kinetics the smelter slag sample will serve to determine the grinding time, i.e. to achieve a certain

percentage participation in size class -75 +0.0 μm in the finished product of grinding for the given experiment of flotation. Due to this comprehensive work, the results of grinding kinetics will not be separately present.

All experiments of flotation concentration, basic flotation of smelter slag were carried out according to the standard experimental procedure in "Denver" laboratory flotation machine with chamber volume of 2.4 dm^3 and increased r.p.m. of rotor of 1300 min^{-1} . During testing, a series of experiments was carried out of basic flotation in order to select the best result of technological recovery, I_{Cu} of copper or the highest copper content in the basic flotation concentrate of smelter slag.^[2;3] Based on these results of experiments of smelter slag flotation, a de

pendence of copper recovery in basic flotation concentrate is given from fineness of grind that is, the content of given size-class - 0.075 mm in the grinding product of appropriate experiment. The achieved results of copper recovery in basic concentrate, obtained in the base flotation experiments, are shown in Table 3. The experiments were carried out on a previously prepared sample of smelter slag, according to the protocol and scheme of the experiment, given in Figure 6 with previous preparation of the following reagents:

1. Lime- CaO – aqueous solution in the form of $\text{Ca}(\text{OH})_2$,
2. Potassium methyl xanthate -KAX – 1 % aqueous solution 100 ml,
3. Dowfroth - D-250-1 % aqueous solution 100 ml.

Protocol of flotation experiments

Grinding:

- Ore: Smelter slag, final grinding product: $m=0.6613 \text{ kg}$
- Water: $v=220.43 \text{ ml}$
- Solid content: $S=75 \%$
- Grinding time: $t=8; 9; 11; 15 \text{ and } 20 \text{ min}$
- Class content -75 μm approximately to the times $\gamma=50; 60; 70; 80; 90 \%$
- Lime: $\text{CaO}=1.5 \text{ g}$

Conditioning:

- Conditioning time: $t=5 \text{ min}$
- Solid content: $S=23 \%$
- Lime: $\text{CaO}= / , \text{ g}$
- pH value: $\text{pH}=11.3$
- Collector: $\text{KAX}=25 \text{ g/t (1.653 ml)}$
- Water (Addition to 2.4 l of pulp) $v=220.43 \text{ ml}+1993.45 \text{ ml}=2214 \text{ ml}$
- Frother: (added 1 min before flotation) $\text{D-250}=15 \text{ g/t (0.992 ml)}$

Basic flotation :

- Solid content $S=23 \%$
- pH value: $\text{pH}=11.3$
- Flotation time: $t_{\text{Total}}=20 \text{ min (5 + 5 + 10) min}$
- Collectors: $\text{R}=12.5(0.826 \text{ ml}) + 12.5(0.826 \text{ ml}) \text{ g/t}$
- Frother: D-250(as required) approximately $=10(0.661 \text{ ml}) + 10(0.661 \text{ ml}) \text{ g/t}$
- Lime: $\text{CaO}= / \text{ g}$

Scheme of flotation experiments

Figure 6 Protocol and scheme of flotation experiments

Weak industrial Cu recoveries, obtained by slag flotation in the Smelter Bor, Flotation Plant Bor, which are up to the level of $I_{Cu} = 45-50 \%$, have caused a number of attempts to achieve better technological results and finding out possible ways to more successful treatments of these raw materials. Preliminary testing the impact of **grinding fineness** on copper recovery in the flotation process of smelter slag through a comparative test was conducted on a laboratory scale. In this way, during the experiments, all technological parameters were kept constant except fineness of ground samples, submitted to the flotation process.

Fineness of grind is regulated on the basis of required grinding time from grinding kinetics of smelter slag that was previously done in order to obtain a product of grinding with the certain percentage participation of size class -0.075 mm. So the only difference is in the fineness of grind. Industrial conditions for the smelter slag flotation process are that this raw material is usually ground to fineness 60% of size class participation - 75 μm . For these experiments, those are the grinding parameters of 90% of size class participation - 75 μm , which are recorded as the most suitable from the

standpoint of reached copper recovery, $I_{Cu}(\%)$.

The resulting concentrates and tailings of flotation slag, according to the protocol of experiments with the given parameters, are further processed and analyzed in laboratory conditions. The results are present in Table 3 where technological parameters are calculated of realized experiments for mutual comparison with actual industrial parameters, i.e. the results. From present technological results, flotation experiments, Table 3, it is evident that a direct correlation between the content of -75 μm size class in the final product of grinding and realized flotation Cu recovery was established. Namely, with increasing fineness of grind (increase in the amount of accounted size class - 75 μm in the final product of grinding, given for a sample for flotation experiment), copper recovery also increases, Cu in the basic flotation concentrate.

The present Table 3 shows that the best recovery $I_{Cu} = 60.12\%$ in the basic flotation was achieved with maximum fineness of grind used in these experiments, i.e. with participation of given class-size -75 $\mu m + 0.0 \mu m$ of 93.2 % in grinding product of the sample for experiment.

Table 3 Results of copper flotation of smelting slag generated at different fineness of grinding

Technological results of smelter slag flotation (Total time of basic flotation t = 20 ')					
Vreme mlevenja	t=8 min -75µm 53.4 %	Product	m(g)	m(%)	I Cu(%)
		U	665.8	100	100
		K	51.2	7.69	49.99
	t=9min -75µm 60.6%	J	614.6	92.31	50.01
		U	663.8	100	100
		K	59.2	8.92	53.33
		J	604.6	91.08	46.67
	t=11min- 75µm 71.0 %	U	665.8	100	100
		K	62.8	9.43	54.98
		J	603	90.57	45.02
	t=15min- 75µm 86.0 %	U	665.7	100	100
		K	75.3	11.31	56.8
		J	590.4	88.69	43.2
	t =20min -75µm 93.2 %	U	663.5	100	100
		K	80.1	12.07	60.12
		J	583.4	87.93	39.88

a) Results of copper flotation from granulated smelter slag

Flotation concentration of granulated smelter slag under the same laboratory conditions and in the same laboratory devices, with previously adopted the same operation and technological parameters of the experiment, was carried out. This was done for two reasons. First, in order to enable comparison of the obtained results and the second because that is how the conditions are

kept that were given the best technological results on previously treated smelter slag sample, i.e. the experiment parameters are kept that have given the best results of copper recovery, $I_{Cu}(\%)$. The achieved, as well as protocol of realized experiment of flotation concentration of copper from granulated smelter slag are given slag as follows in Figure 7 and in Table 4.

Figure 7 Scheme of experiment of flotation copper concentration of granulated copper slag

Table 4 Results of experiment of flotation copper concentration of granulated copper slag

	T(g)	T(%)	Cu(%)	I(%)
U	665.6	100.00	0.77	100.00
K	47.3	7.11	7.92	73.37
J	618.3	92.89	0.22	23.63

The achieved results of flotation experiment of copper concentration of granulated copper slag from reverberatory furnace are the highest achieved so far. The realized copper recovery is: $I_{Cu} = 73.37\%$.

Such result is expected by the certain way regarding to the previously established physico-chemical and mineralogical change on granulated copper slag. Due to a safety

reason of the achieved results as well as checking the finality of flotation experiment of copper concentration, a previous experiment of copper concentration was repeated with additional extended copper flotation. Protocol of the experiment and achieved results are present in next Figure 8 and Table 5.

Figure 8 Scheme of extended experiment of flotation copper concentration of granulated copper slag

Table 5 Results of extended experiment of flotation concentration of granulated smelter slag

	T(g)	T(%)	Cu(%)	I(%)
U	666.1	100.00	0.92	100.00
K1	47.9	7.19	10.30	80.65
K2	19.5	2.93	0.85	2.71
K+K2	67.4	10.12	7.56	83.36
J	598.7	89.88	0.17	16.64

The achieved results of extended flotation experiment of copper concentration of granulated copper slag from reverberatory

furnace are maximum achieved so far. The realized copper recovery is: $I_{Cu} = 83.36\%$.

Such result is expected by the certain way regarding to the previously realized experiment. So, due to a reason of improvement the realized results as well as a consequence of realization the extended experiment of flotation, i.e. finiteness of flotation experiment of copper concentration of granulated copper slag from reverberatory furnace in the Copper Smelter in Bor.

In this way through the experimental work and experimentally obtained results, the method and procedure of the new treatment of technogenic waste - smelter slag were found, in order to obtain as favorable as possible or maximum technological results of copper recovery from this technogenic raw material.

The given protocol of experiments and tables of achieved results in Figure 8 and Table 5, present an argument prior to that ascertainment.

CONCLUSION

Based on the present results in this paper, titled "Comparative Results of Copper Flotation from Smelter Slag and Granulated Smelter Slag" general conclusions can be derived, including:

- On the new laboratory line for smelter slag granulation of reverberatory furnace in the Smelter in Bor, Figure 3, i.e. on newly designed granulator smelter slag, Figure 2, a new material was obtained for these investigations: "Granulated Smelter Slag."
- Granulated smelter slag is distinguished by its physic-chemical, mineralogical characteristics from primary smelter slag in the Smelter in Bor. The primary and the most important differences are reflected in the grain-size distribution, slag resistance to comminution of so-called the Bond work index, W_i , and increased presence of copper matte or elemental copper in a sample of granulated smelter slag.
- On this type of new material – raw material, there may be various further advanced investigations, for example: research the conditions for achieving a finer grain-size distribution of granulated smelter slag to obtain granulated smelter slag, which can be directly implemented in an industrial ball mill. Then, due to the natural affinity of copper and copper matte to sulfur and due to high content of the same in the obtained sample of granulated smelter slag, it is possible to conduct a research of sulfurization the granulated smelter slag and obtaining a new material: "New Sulfurized Smelter Slag", i.e. making conditions for an even more successful flotation concentration of copper, regarding to the known fact that copper sulphides are the best floated. Also, a calcination of granulated smelter slag is possible which would also present a new material for technological testing, and all of this with a goal for more successful copper recovery or use of these new materials for other purposes, for example in construction, etc.
- In this paper, a flotation of smelter slag of reverberatory furnace in Bor was tested with previously determined optimum parameters of comminution the same in order to obtain the most favorable technological results of copper, I_{Cu} (%). The most favorable results were obtained with the following parameters present in Table 3, as follows:
 - Participation of size class $-75 \mu m$ $+0.0 \mu m$ in the final product of sample grinding for the experiment of 93.2%, gives the best copper recovery in the basic flotation of $I_{Cu} = 60.12 \%$.
- Then, flotation concentration of granulated smelter slag of reverberatory furnace in the Smelter in B or was

tested with the same optimum parameters of comminution and more favorable results of copper recovery were obtained of $I_{Cu} = 73.37\%$.

- For finiteness of flotation experiment, a flotation experiment was carried out with additional time of flotation process - extended flotation process and the most favorable technological results of copper recovery were obtained of $I_{Cu} = 83.36\%$. Such result is quite adoptable and allows the creation of a new technological scheme for treatment the smelter slag in the Smelter in Bor, and getting large amounts of copper from this technogenic raw material. Proposal for the new technological scheme of smelter slag treatment for successful copper recovery from this secondary material will be the subject of a separate work.
- Here established a new process of smelting slag treatment is also applicable in other pyrometallurgical methods of treatment the flotation copper concentrates wherever such waste material creates smelter slag. A conclusion is made that this procedure is also applicable for treatment of smelter slag which will be obtained from a New Copper Smelter in Bor that should be put into operation in the next years.
- All these investigations will be continued in the future period per all here given basis.

Based on clearly stated conclusions, it can be considered that these investigations is fully justified part of the Project TR 33023 of the Ministry of Science and Technology of the Republic of Serbia, which in this segment of the project dealt with the smelter slag of reverberatory furnace of the Copper Smelter in Bor, particularly through development of new processing technology of smelter slag, which gives better technological results. Re

searchers believe that this is not the end point of the achieved results and, as it was mentioned in the conclusions of this study, it will be continued to achieve maximum values of technological results.

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UPOREDNI REZULTATI FLOTACIJE BAKRA IZ TOPIONIČKE ŠLJAKE I GRANULIRANE TOPIONIČKE ŠLJAKE****

Izvod

Topionička šljaka se dobija u procesu metalurškog konvertovanja koncentrata bakra u topionici u Boru - Srbija. Danas su rezerve ovog materijala procenjene na oko više od godinu dana, sa prosečnim sadržajem bakra od 0.6-0.9%. Proizvodnja koncentrata bakra flotacijom topioničke šljake je započeta u 2001. Flotacijski koncentrat još jednom odlazi u topionicu bakra radi proizvodnje bakarnih katoda a definitivna flotacijska jalovina odlazi na depo flotacijske jalovine. Iskorišćenje bakra u procesu flotiranja topioničke šljake dostiže vrednost od oko 45 - 50%. Šljaka u pogonima RTB-a prerađuje se u postrojenju koje nije projektovano za preradu šljake već samo prilagođeno tim uslovima. Dobijeni rezultati su lošiji od očekivanih pa se nastavljaju ispitivanja koja bi mogla da ih unaprede.

Ovaj rad prikazuje način dobijanja flotacijskog koncentrata topioničke šljake sa ostvarivanjem boljeg ukupnog iskorišćenja bakra. Jedna od mogućnosti je proces granuliranja šljake koji daje čitav niz pravaca za ispitivanje uticaja na proces usitnjavanja i koncentracije bakra. Za ove potrebe na specijalno konstruisanom laboratorijskom granulatoru dobijene su veće količine granulata topioničke šljake neophodne za dalja ispitivanja procesa flotacijske koncentracije. Ovaj rad prikazuje ostvarene uporedne rezultate procesa flotacijske koncentracije topioničke šljake i granulirane topioničke šljake plamene peći.

Ključne reči: topionička šljaka, granuliranje, mlevenje, flotiranje, iskorišćenje Cu

1. UVOD

Proizvodnja metala bi u budućnosti mogla biti značajno manja u odnosu na sadašnju, zbog činjenice, da se rezerve metala u prirodnom obliku u rovnim rudama ubrzano iz godine u godinu smanjuju. Drugi razlog, limitirane proizvodnje metala predstavljaju sve strožiji zakoni o zaštiti životne sredine, zbog otpada koji nastaje masovnom preradom siromašnih ruda. Ogromne količine metala zarobljene u jalovištima i šljakištima, za naredni period mogu predstavljati potencijalne sirovine za

dobijanje novih količina metala. Iz tih razloga jalovišta i šljakišta kao izvor velikih količina metala imaju sve veći ekonomski značaj. Sve više pokušaja u svetu ima da se šljaka reciklira i dodatno valorizuju korisni metali iz nje. Mineraloški sastav šljake dobijen iz metalurške prerade zavisi od mnogih faktora, a jedan od značajnih je tehnologija metalurške prerade. U zavisnosti od gore napomenutog, sadržaj korisne komponente varira u granicama koje predstavljaju veći sadržaj nego prisustvo te

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komponente u rovnim rudama. Glavne komponente šljaka dobijenih iz metalurgije bakra su Fe i SiO₂. Sadržaj bakra u skoro svim šljakama metalurške prerade bakra kreće se u rasponu od 0,5 do 4,0 %, što je znatno više od sadržaja bakra u rudama ležišta bakra, koja se danas eksploatišu. Šljake dobijene metalurškom preradom bakra, najčešće se različitim postupcima pripreme i koncentracije tretiraju radi ponovnog dobijanja bakra.

Topionička šljaka plamene peći dobija se i u procesu metalurškog konvertovanja flotacijskih koncentrata bakra u topionici u Boru. Eksperimentalna proizvodnja koncentrata bakra, flotacijom, od topioničke šljake je započeta u 2001 god. Šljaka u pogonima RTB-a prerađuje se u postrojenju koje nije projektovano za preradu šljake već samo prilagođeno tim uslovima. Pogon „Flotacija” u Boru je prvobitno projektovan za drugačiju vrstu sirovine a sada je samo prilagođen za preradu šljake[1]. Šljaka je manje pogodna od rude za usitnjavanje sa stano- višta potrošnje energije, obloga i meljućih tela a takođe i iskorišćenja metala (bakra, Cu). Dobijeni flotacijski koncentrat od topioničke šljake još jednom ide na topljenje u topionicu bakra radi proizvodnje bakarnih katoda, dok definitivna flotacijska jalovine od topioničke šljake odlazi na deponovanje na flotacijsko jalovište. Desetak godina unazad, flotacijskom koncentracijom u pogonu u Boru se dobijaju pomenuti korisni metali ali sa nizom poteškoća i manje uspešno nego u svetu na sličnim sirovinama. Sa tim u vezi, javlja se niz poteškoća koje se ogledaju kroz veliku potrošnju električne energije i lošije tehnološke rezultate od nekih sličnih pogona u svetu. Iskorišćenje bakra u procesu flotacijske koncentracije bakra iz topioničke šljake jedva dostiže vrednost od oko $I_{Cu}=50\%$. To je dosta niža vrednost od one koja se uobičajeno postiže standardnim flotacijskim postupkom na mineralima sulfida $I_{Cu}=75-85\%$ nosioca metala bakra, Cu, koji su prisutni u rudama. Takođe, je istovremeno detektovana visoka vrednost sadržaja bakra u finalnoj flota-

cijskoj jalovini. Dobijeni rezultati su lošiji od očekivanih pa se nastavljaju ispitivanja koja bi mogla da ih unaprede.

Praksa je pokazala, da se sekundarne sirovine razlikuju od primarnih sirovina, ruda, u pogledu mineraloško fizičko-hemij- skih i mehaničkih karakteristika. Dosadašnja svetska istraživanja u oblasti prerade mine- ralnih sirovina, bazirala su se na istraživanju prerade primarnih sirovina (ruda). Samim tim, svi rezultati, teorije i zaključci dobijeni istraživanjima primarnih sirovina, ne mogu se u potpunosti prihvatiti i primenjivati u procesu tretmana sekundarnih sirovina.

Topionička šljaka iz procesa metalurške prerade koncentrata se po svojim minera- loškim, fizičko – hemijskim i mehaničkim osobinama dosta razlikuje od primarnih sirovina. Ponašanje topioničke šljake u procesima drobljenja, mlevenja, flotiranja, različito je od ponašanja ruda koje su osnov za dobijanje koncentrata bogatog bakrom. Karakteristike topioničke šljake, kao što su specifična masa i tvrdoća, utiču da se sam proces prerade rude ne može bez ikakvih promena primeniti u preradi topioničke šljake. Razlike koje postoje u fizičko- hemijskim i mehaničkim osobinama prima- rne sirovine, rude i sekundarne sirovine, topioničke šljake, nameću potrebu za temeljnim istraživanjima, radi upoznavanja ponašanja topioničke šljake u procesu pre- rade i mogućnost optimizacije procesa radi poboljšanja tehnoloških rezultata i smanjenja troškova prerade[2]. Iz svih navedenih razloga, svaki rad koji upućuje na pravac mogućih rešenja, za postizanje boljih techno- loških rezultata iskorišćenja bakra u postupku flotacije koncentracije bakra iz topioničke šljake, ima velikog značaja.

Jedna od mogućnosti je proces granu- liranja šljake koji daje čitav niz mogućih pravaca za ispitivanje uticaja na proces usitnjavanja i koncentracije bakra. Za te potrebe konstruisan je laboratorijski uređaj if ormirana je laboratorijska tehnološka linija uz pomoć koje će se dobiti veće količine granulata topioničke šljake neophodne za dalja ispitivanja.

2. IZDVAJANJE PRIPREMA I FIZIČKO - HEMIJSKA KARAKTERIZACIJA UZORKA

a) Uzorkovanje i fizičko-hemijska karak-terizacija uzorka šljake plamene peći

Projektom TR 33023 pod naslovom: „Razvoj tehnologija flotacijske prerade ruda bakra i plemenitih metala radi postizanja boljih tehnoloških rezultata“, koji finansira Ministarstvo za nauku i tehnološki razvoj u okviru Programa tehnološkog razvoja sprovedena su određena istraživanja u oblasti granuliranja topioničke šljake plamene peći. Ranija istraživanja koja se odnose na neophodni stepen usitnjavanja [2;3] pokazala su, da krupnoća ulaza odnosno, granulometrijski sastava ulaza u mlin sa šipkama može da se kompezira postupkom granuliranja [4]. To je ustvari, jedan jednostavan i jeftin proces kojim može da se izbegne tehnološki postupak trostepenog drobljenja i prosejavanja. Proces granulacije tek treba istražiti, ispitati uticaj granuliranja i način izvođenja postupka granuliranja na tehnološke pokazatelje flotacijske koncentracije bakra iz topioničke granulirane šljake. U cilju daljih ispitivanja formirano je laboratorijsko postrojenje za granuliranje šljake uz pomoć kojeg će se dobiti veće količine granulirane šljake neophodne za eksperimente [5].

Uzorak za ovo istraživanje izuzet je od izdrobljenog materijala šljake plamenih peći topionice Bor. Zaustavljanjem transportne trake ispod bunkera gotovog proizvoda drobljenja, na ulazu u mlin za mlevenje, izvršeno je uzorkovanje u flotaciji Bor. Uzorak gotovog proizvoda drobljenja topioničke šljake je prvo homogenizovan standardnim laboratorijskim postupkom a potom usitnjen do 100% -12,7 mm. Posle određivanja Bondovog Indeksa u mlinu sa šipkama, uzorak je usitnjen do 100% -3,327 mm, homogenizovan i posle toga korišćen za određivanje Bondovog Indeksa u mlinu sa kuglama i za druga neophodna tehnološka istraživanja. Fizičko hemijske karakteristike polaznog uzorka topioničke šljake su određene uobičajenim laboratorijskim metodama. Ove karakteristike su predstavljene u tabeli 1. Uzorci – specimeni su uzeti iz istog uzorka topioničke šljake za mineralošku karakterizaciju i rendgensku X-ray analizu.

Tabela 1. Fizičko hemijske karakteristike uzorka topioničke šljake

Fizičke karakteristike	Vrednosti i merne jedinice:
Gustina šljake i prirodna pH vrednost	$\rho = 3\,575,0 \text{ kg/m}^3$; pH 6,75
Bondov indeks	$W_i \text{ (KWh/t)}$
Mlin sa šipkama; Mlin sa kuglama	19.13 ; 31.96
<i>Granulometrijski sastav</i>	Predstavljen analitički (RRS jednačina):
Finalni proizvod drobljenja, polazni uzorak Klasa krupnoće -12,7 mm+0,0 mm	$R = 100 \cdot e^{-\left(\frac{d}{23474}\right)^{1.020}}, \%$
Uzorak spreman za flotaciju (mlevenje) Klase krupnoće -3,327 mm+0,0 mm	$R = 100 \cdot e^{-\left(\frac{d}{1859}\right)^{1.036}}, \%$

Hemijske karakteristike	Sadržaj :
Cu-total.	0.89 %
Cu-elem.	0.45 %
Cu-ox	0.246 %
Cu-sulphid.	0.214 %
S	0.82 %
SiO ₂	34.87 %
Fe	38.55 %
FeO	37.00 %
Fe ₃ O ₄	8.98 %
Al ₂ O ₃	4.84 %
Au	< 1.0 g/t
Ag	< 1.0 g/t
MgO	1.10 %
Na ₂ O	0.45 %
K ₂ O	1.54 %
CaO	3.77 %

X-ray analiza

X-ray analiza je izvedena u Institutu za rudarstvo i metalurgiju Bor na "Simens" aparaturi uz korišćenje Cu antikatode sa filtriranim zračenjem Ni filtrima, pri naponu od 40 kV i jačini struje od 20 mA. Difrakcionom analizom uzorka topioničke

šljake, određene su sledeće kvalitativne kompozicije: fajalita (Fe₂SiO₄), magnetita (Fe₃O₄), i kvarca (SiO₂) kao glavne faze. Na slici 1., predstavljen je rendgenogram snimljen na uzorku topioničke šljake.

Mikroskopski opis

Uzorci su približno istih dimenzija i veoma slični po boji i obliku, što ukazuje na isto poreklo. Na površini uzorka uočljive su skoro sferične šupljine, što ukazuje da su uzorci proizvod topljenja rude - šljaka. Dominira tamno siva, mat boja, sa zelenoplavom i crveno-braon nijansom.

Mineraloški sastav: fajalit, magnetit, halkopirit, bornit, bakrenac, samородni bakar, pirit, halkozin, kovelin. Osnova preparata se sastoji od fajalita, koji se pojavljuje u vidu lamela (najčešće) i u vidu zvezdica (ređe), pri čemu formira mermitsku strukturu. Fajalit predstavlja izomorfni niz, koji se u prirodi javlja u mineralu olivinu. $(\text{Mg,Fe})_2\text{SiO}_4$. Olivin je izomorfna smeša forsterita $(\text{Mg}_2\text{SiO}_4)$ i fajalita $(\text{Fe}_2\text{SiO}_4)$. Za olivin je karakteristična metamorfoza u serpentini sa istovremenim izlučivanjem magnetita i hematita. Na ovu fajalitsku osnovu naležu ostale mineralne faze.[3] Uglavnom se magnetit javlja samostalno, ređe je srastao sa mineralima bakra. Od minerala bakra najzastupljeniji je bornit. Javlja se u vidu ksenomorfih zrna, a mestimično se javlja u vidu skoro izometričnih sfernih zrna. U ovim zrnima se vidi transformacija halkopirita u bornit, a bornita u halkozin odnosno bakrenac koji predstavlja međufazu. Ređe se uočava u ovoj transformaciji i kovelin. Krajnji produkt je samородni bakar, koji se lokalno uočava u zrnima bornita. Kao samostalan se uočava vrlo retko. Pirit se javlja u vidu hipidiomorfih zrna, uglavnom samostalan, a ređe srastao sa mineralima bakra.

b) Dobijanje i fizičko-hemijska karakterizacija uzorka granulirane topioničke šljake

Za laboratorijski eksperiment granuliranja topioničke šljake plamene peći

topionice u Boru, korišćena je šljaka koja je izuzeta iz pogona drobljenja i prosejavanja sa transportne trake, pre procesa tercijernog drobljenja. Šljaka je na deponiji bila izložena atmosferilijama, pa je sadržala određenu količinu vlage zbog čega je prethodno osušena na sobnoj temperaturi. Radi karakterizacije izuzetog uzorka urađene su fizičko-hemijske analize šljake i rezultati su prikazani u tabeli 2.

Na laboratorijskoj tehnološkoj liniji specijalno formiranoj odnosno, u granulatoru konstruisanom za ove namene, sproveden je postupak granuliranja topioničke šljake plamene peći topionice u Boru[4;5]. Šljaka je podvrgnuta topljenju u laboratorijskoj indukcionoj peći za topljenje, snage 100 kW, u loncu zapremine $V=10$ l, proizvođača ELING - Loznica. Sama granulacija izvedena je u laboratorijskim uslovima unovokonstruisanom uređaju-granulatoru za naglo hlađenje usijane šljake. Prilikom eksperimenta istopljeno je 250 kg šljake, a temperatura pri kojoj je šljaka izlivena je bila $t=1250$ °C. Merenje temperature šljake obavljeno je potapajućim pirometrom.

Na taj način, dobijen je uzorak granulirane topioničke šljake na kojem je sprovedeno dalje ispitivanje granulometrijskog sastava, hemijskog sastava, mogućnosti flotacije bakra itd. Dakle, u laboratorijskim uslovima je proizvedena granulirana topionička šljaka i potvrđena je funkcionalnost konstrukcije laboratorijskog uređaja za granuliranje. Na narednim slikama 2 i 3., predstavljeni su respektivno, granulator topioničke šljake u radu i šematski prikaz novoformirane laboratorijske tehnološke linije za proizvodnju granulirane topioničke šljake.

Sl. 2. Granulator topioničke šljake u radu

Sl. 3. Tehnološka šema laboratorijskog postupka za granuliranje topioničke šljake

Novi laboratorijski uređaj i laboratorijska tehnološka linija treba da omogućiti nastavak istraživanja u nekoliko pravaca:

- Ispitivanje granuliranja topioničke šljake u cilju dobijanja što finijeg granulata.

- Stvaranje raznih granuliranih šljaka radi tehnoloških ispitivanja flotacijske koncentracije bakra i sa time u vezi
- Izmenu postojećeg tehnološkog procesa flotacijske koncentracije bakra iz topioničke šljake plamene peći

energetski i tehnološki efikasnijim procesom flotacijske koncentracije granulirane topioničke šljake.

Ujedno, konstruisani novi laboratorijski uređaj - granulator topioničke šljake predstavlja model koji će poslužiti pored navedenih ispitivanja i za konstrukciju većeg poluindustrijskog ili industrijskog granulatora topioničke šljake.

Proizvedena granulirana topionička šljaka postupkom naglog hlađenja u granulatoru je sa izmenjenim fizičko hemijskim karakteristikama u odnosu na primarnu topioničku šljaku. Rezultati fizičko hemijske karakterizacije granulirane topioničke šljake su predstavljeni u tabeli 2. Uočene izmene se prvenstveno odnose na: Različiti granulometrijski sastav gotovog proizvoda drob-

ljenja topioničke šljake i granulirane topioničke šljake zatim, razlika u utvrđenom Bondovom radnom indeksu između uzoraka topioničke šljake i granulirane topioničke šljake koja može doprineti uštedi u energiji mlevenja pri usitnjavanju tj. mlevenju granulirane topioničke šljake za proces flotacijske koncentracije. To će biti predmet posebnog istraživanja. Takođe, uočena je izrazito staklasta fajalitska struktura granulirane šljake sa bakrencom i bakrom unutar nje izdvojenim u elementarnom obliku.

Na slici 4 i 5. predstavljen je izdvojeni elementarni bakar u topioničkoj šljaci i granuliranoj topioničkoj šljaci respektivno prema navedenim slikama, koji može opredeliti naredna istraživanja u flotacijskom pravcu.

Sl. 4. Sraslac halkopirita, pirit i bakrenac sa izdvajanjima elementarnog bakra

Sl. 5. Bakrenac u fajalitskoj osnovi, Objektiv50x, II Nikoli

Tabela 2. Fizičko-hemijske karakteristike uzorka granulirane topioničke šljake

Fizičke karakteristike	Vrednosti i merne jedinice:
Gustina šljake i prirodna pH vrednost	$\rho = 3230 \text{ kg/m}^3$; pH 7,5
Bondov indeks	$W_i \text{ (KWh/t)}$
Mlin sa kuglama: Standardni/Skraćeni	12,20 /10,13
Granulometrijski sastav	Predstavljen grafički:
Granulirani uzorak topioničke šljake Ulaz u industrijsko mlevenje topioničke šljake (izdrobljena šljaka)	
Hemijske karakteristike	Sadržaj :
Cu-total.	1.05%
S	0.56%
SiO ₂	36.28 %
Fe	26.25 %
FeO	28.65 %
Fe ₃ O ₄	0.092 %
Al ₂ O ₃	12.67 %
Au	<1.0 g/t
Ag	< 1.0 g/t
CaO	15.50 %

3. EKSPERIMENTALNA PROCEDURA

Kako je u izvodu ovoga rada napomenuto biće ovde prikazani ostvareni rezultati procesa flotacijske koncentracije topioničke šljake i granulirane topioničke šljake plamene peći izvedeni pod istim laboratorijskim uslovima.

a) Rezultati flotacijske koncentracije bakra iz topioničke šljake

Predhodno su izvršeni eksperimenti mlevenja radi određivanja kinetike mlevenja uzorka topioničke šljake. Eksperimenti su rađeni u elipsoidnom mlinu sa

kuglama zapremine $15,2 \text{ dm}^3$. Masa šarže kugli na početku ispitivanja bila je 12 kg.

Za jedan eksperiment mleveno je 0,6613 g rude, pri sadržaju čvrstog od 75%. Svi uslovi mlevenja su dakle zadržani konstantnim dok je samo vršena promena vremena mlevenja. Ostvareni rezultati ogle-da kinetike mlevenja uzorka topioničke šljake poslužiće za određivanje vremena mlevenja tj. za postizanje određenog procentualnog učešća klase krupnoće $-75 + 0,0 \mu\text{m}$ u gotovom proizvodu mlevenja za dati ogled flotiranja. Zbog preobim-

nosti ovoga rada rezultate kinetike mlevenja nećemo posebno prikazivati.

Svi ogledi flotacijske koncentracije, osnovnog flotiranja topioničke šljake izvršeni su po standardnoj eksperimentalnoj proceduri u „Denver” laboratorijskoj flotacijskoj mašini zapremine komore $2,4 \text{ dm}^3$ i sa povećanom brzinom obrtanja rotora od 1300 min^{-1} . Tokom ispitivanja izvedena je serija eksperimenata osnovnog flotiranja u cilju odabira najboljeg rezultata tehnološkog iskorišćenja, I_{Cu} bakra odnosno, najvišeg sadržaja bakra u osnovnom koncentratu flotacije topioničke šljake.[2;3] Na osnovu tih rezultata oglada flotiranja topioničke šljake data je zavisnost iskorišćenja bakra u osnovnom flotacijskom koncentratu od

finoće mliva odnosno, od sadržaja date klase krupnoće $-0,075 \text{ mm}$ u proizvodu mlevenja odgovarajućeg oglada. Ostvareni rezultati, iskorišćenja bakra u osnovom koncentratu dobijenim u ogledima flotacijske koncentracije, prikazani su u tabeli 3. Ogledi su izvedeni na predhodno pripremljenom uzorku topioničke šljake, po protokolu i šemi oglada datoj na sl. 6 uz predhodnu pripremu sledećih reagenasa:

1. Kreč - CaO – vodeni rastvor u obliku Ca(OH)_2 ,
2. Kalijumetilksantat - KAX – 1% vodeni rastvor 100 ml,
3. Dowfroth - D-250-1 % vodeni rastvor 100 ml.

Protokol flotacijskih oglada

Mlevenje :

- Ruda: Topionička šljaka, gotov proizvod drobljenja: $m=0.6613 \text{ kg}$
- V o d a: $v=220,43 \text{ ml}$
- Sadržaj čvrstog: $\check{C}=75 \%$
- Vreme mlevenja: $t=8;9;11;15 \text{ i } 20 \text{ min}$
- Sadržaj klase $-75\mu\text{m}$ orjentaciono prema vremenima $\forall=50;60;70;80;90 \%$
- Kreč: $\text{CaO}=1,5 \text{ g}$

Kondicioniranje :

- Vreme kondicioniranja: $t=5 \text{ min}$
- Sadržaj čvrstog: $\check{C}=23 \%$
- Kreč: $\text{CaO}= / , \text{ g}$
- pH vrednost : $\text{pH}=11,3$
- Kolektor: $\text{KAX}=25 \text{ g/t (1,653 ml)}$
- Voda (Dopuna do $2,4 \text{ l}$ pulpe) $v=220,43\text{ml}+1993,45\text{ml}=2214 \text{ ml}$
- Penušač: (dodati 1 min pre flotiranja) $\text{D-250}=15 \text{ g/t (0.992 ml)}$

Osnovno flotiranje :

- Sadržaj čvrstog $\check{C}=23 \%$
- pH vrednost: $\text{pH}=11,3$
- Vreme flotiranja: $t_{\text{Ukupno}}=20 \text{ min (5 + 5 + 10) min}$
- Kolektori : $R=12,5 (0,826 \text{ ml}) + 12,5 (0,826 \text{ ml}) \text{ g/t}$
- Penušač: D-250 (prema potrebi) orjentaciono= $10 (0.661 \text{ ml}) + 10 (0.661 \text{ ml}) \text{ g/t}$
- Kreč: $\text{CaO}= / \text{ g}$

Šema flotacijskih ogleda

Sl. 6. Protokol i šema flotacijskih ogleda

Slaba industrijska iskorišćenja Cu dobijena postupkom flotacije šljake plamene peći topionice Bor, u flotaciji Bor, koja se kreću do nivoa od $I_{Cu} = 45 - 50 \%$, uslovala su brojne pokušaje postizanja boljih tehnoloških rezultata i iznalaženja mogućih pravaca uspješnijeg tretmana ove sirovine. Preliminarno ispitivanje *uticaja finoće mlevenja na iskorišćenje bakra pri procesu flotiranja topioničke šljake* kroz uporedni test je sprovedeno na laboratorijskom nivou. Na taj način, pri izvođenju eksperimenata, svi tehnološki parametri ogleda su zadržavani konstantnim sem finoće mliva uzoraka koji se izpostavljaju postupku flotacije. Finoća mliva je regulisana na osnovu izbora neophodnog vremena mlevenja iz kinetike mlevenja topioničke šljake koja je predhodno urađena, da bi se dobio proizvod mlevenja sa određenim procentualnim učešćem klase krupnoće -0,075 mm. Dakle, jedina razlika je učinjena u finoći mliva. Industrijski uslovi za proces flotacije topioničke šljake su, da se ova sirovina uobičajeno melje do finoće 60 % učešća klase krupnoće - 75 μm . Za naše ogleda to su parametri mlevenja od 90 % učešća klase krupnoće - 75 μm koji su evidentirani kao

najpovoljniji sa stanovišta postignutog iskorišćenja bakra, $I_{Cu}(\%)$.

Dobijeni koncentri i jalovine flotacije šljake, po protokolu ogleda sa datim parametrima, su u laboratorijskim uslovima dalje rađeni i analizirani. Rezultati su predstavljeni u tabeli 3. gde su sračunati i tehnološki parametri sprovedenih ogledaradi međusobnog poređenja i poređenja sa ostvarenim industrijskim parametrima tj. rezultatima. Iz prikazanih tehnoloških rezultata, flotacijskih ogleda tabela 3., se vidi, da je ustanovljena direktna zavisnost između sadržaja klase krupnoće -75 μm u gotovom proizvodu mlevenja i postignutog flotacijskog iskorišćenja bakra, Cu. Naime, sa porastom finoće mliva (porast sadržaja obračunske klase krupnoće - 75 μm u gotovom proizvodu mlevenja datog uzorka za flotacijski eksperiment) raste i iskorišćenje bakra, Cu u osnovnom flotacijskom koncentratu.

Iz predstavljene tabele 3, se vidi da je u osnovnom flotiranju najbolje iskorišćenje $I_{Cu} = 60,12 \%$ postignuto sa maksimalnom finoćom mliva korišćenoj u ovim eksperimentima odnosno, sa učešćem date klase krupnoće -75 μm +0,0 μm od 93,2 % u proizvodu mlevenja uzorka za eksperiment.

Tabela 3. Rezultati flotacije bakra topioničke šljake ostvareni na različitim finoćama mlevenja

Tehnološki rezultati flotacije topioničke šljake (Ukupno vreme osn. flotiranja t = 20 ')					
Vreme mlevenja	t=8 min -75µm 53,4 %	Proizvod	m(g)	m(%)	I Cu(%)
		U	665,8	100	100
		K	51,2	7,69	49,99
	t=9min -75µm 60,6%	J	614,6	92,31	50,01
		U	663,8	100	100
		K	59,2	8,92	53,33
	t=11min- 75µm 71,0 %	J	604,6	91,08	46,67
		U	665,8	100	100
		K	62,8	9,43	54,98
	t=15min -75µm 86,0 %	J	603	90,57	45,02
		U	665,7	100	100
		K	75,3	11,31	56,8
	t =20min -75µm 93,2 %	J	590,4	88,69	43,2
		U	663,5	100	100
		K	80,1	12,07	60,12
		J	583,4	87,93	39,88

**a) Rezultati flotacijske koncentracije
bakra iz granulirane topioničke šljake**

Flotacijska koncentracija granulirane topioničke šljake pod istim laboratorijskim uslovima i u istim laboratorijskim uređajima, sa predodno usvojenim istim radnim i tehnološkim parametrima ogleda, je izvedena. To je urađeno iz dva razloga. Prvi, radi mogućnosti komparacije dobijenih rezultata i drugi, jer su na taj način zadržani uslovi koji su i na predhodno tretiranom

uzorku topioničke šljake dali najpovoljnije tehnološke rezultate odnosno, zadržani su parametri ogleda koji su dali najpovoljnije rezultate iskorišćenja bakra, $I_{Cu}(\%)$. Ostvareni rezultati, kao i protokol izvedenog ogleda flotacijske koncentracije bakra iz granulirane topioničke šljake dati su kako sledi, na slici 7. i u tabeli 4.

Sl. 7. Šema flotacijskog ogleda koncentracije bakra granulirane topioničke šljake

Tabela 4. Rezultati oglada flotacijske koncentracije granulirane topioničke šljake

	T(g)	T(%)	Cu(%)	I(%)
U	665,6	100,00	0,77	100,00
K	47,3	7,11	7,92	73,37
J	618,3	92,89	0,22	23,63

Ostvareni rezultati oglada flotacijske koncentracije granulirane topioničke šljake plamene peći su do sada najviši ostvareni. Postignuto iskorišćenje bakra je: $I_{Cu}=73,37\%$.

Ovakav rezultat je na izvestan način očekivan, obzirom na predhodno ustanovljene fizičko-hemijsko mineraloške promene

na granuliranoj topioničkoj šljaci. Iz razloga sigurnosti ostvarenih rezultata kao i provere konačnosti flotacijskog oglada koncentracije bakra ponovljen je predhodni ogled samo sa dodatnim produžnim flotiranjem bakra. Protokol oglada i ostvareni rezultati predstavljeni su na narednoj slici 8., i u tabeli 5.

Sl. 8. Šema produžnog oglada flotacijske koncentracije bakra granulirane topioničke šljake

Tabela 5. Rezultati produžnog oglada flotacijske koncentracije granulirane topioničke šljake

	T(g)	T(%)	Cu(%)	I(%)
U	666,1	100,00	0,92	100,00
K1	47,9	7,19	10,30	80,65
K2	19,5	2,93	0,85	2,71
K+K2	67,4	10,12	7,56	83,36
J	598,7	89,88	0,17	16,64

Ostvareni rezultati produžnog oglada flotacijske koncentracije granulirane topioničke šljake plamene peći su maksimalno do sada ostvareni. Postignuto iskorišćenje bakra je: $I_{Cu}=83,36\%$. Ovakav rezultat je na

izvestan način očekivan, obzirom na predhodno izvedeni ogled. Odnosno, iz razloga poboljšanja ostvarenih rezultata kao posledice izvođenja produžnog oglada flotacijske koncentracije tj. konačnosti flotacijskog

ogleda koncentracije bakra iz granulirane topioničke šljake plamene peći topionice bakra u Boru.

Na ovaj način kroz eksperimentalan rad i eksperimentalno dobijene rezultate utvrdili smo način i postupak novog tretmana tehnogenog otpada – topioničke šljake, sa ciljem dobijanja što povoljnijih tj. maksimalno mogućih tehnoloških rezultata iskorišćenja bakra iz ove tehnogene otpadne sirovine.

Dati protokol ogleda i tablica ostvarenih rezultata slika 8. i tabela 5., predstavljaju argument predhodno navedenoj konstataciji.

ZAKLJUČAK

Na osnovu rezultata prikazanih u ovom radu pod nazivom “Uporedni rezultati flotacije bakra iz topioničke šljake i granulirane topioničke šljake” možemo izvesti nekoliko generalnih zaključaka i to:

- Na novoj laboratorijskoj liniji za granulaciju topioničke šljake plamene peći topionice u Boru, sl. 3., tj. Na novokonstruisanom granulatoru topioničke šljake sl. 2., dobijen je nov materijal za ova istraživanja: „Granulirana topionička šljaka“.
- Granulirana topionička šljaka, se razlikuje po svojim fizičko, hemijsko, mineraloškim karakteristikama od primarne topioničke šljake plamene peći topionice u Boru. Osnovne i najbitnije razlike se ogledaju u granulometrijskom sastavu, otpornosti šljake na usitnjavanje tzv. Bondovom radnom indeksu W_i , i povišenom prisustvu bakrenca odnosno, elementarnog bakra u uzorku granulirane topioničke šljake.
- Na ovoj vrsti novog materijala-sirovine, moguća su razna dalja napredna istraživanja npr.: Istraživanje uslova za postizanje finijeg granulometrijskog sastava granulirane topioničke šljake radi dobijanja granulirane topioničke šljake koja može direktno da se sprovede u industrijski mlin sa kug-

lama. Zatim, zbog prirodnog afiniteta bakra i bakrenca prema sumporu, a zbog povišenog sadržaja istih u dobijenom uzorku granulirane topioničke šljake moguće je sprovesti istraživanje nasumporavanja granulirane topioničke šljake te dobijanja novog materijala: „Nove nasumporisane topioničke šljake“ tj., stvaranje uslova za još uspješniju flotacijsku koncentraciju bakra, obzirom na poznatu činjenicu da sulfidi bakra najbolje flotiraju. Takođe, moguća je i kalcinacija granulirane topioničke šljake što bi takođe predstavljalo novi materijal za tehnološka ispitivanja a sve sa ciljem uspješnije valorizacije bakra ili upotrebe ovih novih materijala u druge svrhe npr. u građevinarstvu itd.

- U ovom radu, ispitivana je flotacijska koncentracija topioničke šljake plamene peći u Boru sa predhodno utvrđenim optimalnim parametrima usitnjavanja iste radi dobijanja najpovoljnijih tehnoloških rezultata iskorišćenja bakra, I_{Cu} (%). Dobijeni su najpovoljniji rezultati sa sledećim parametrima predstavljeni u tabeli 3., a to su:
Učešćem klase krupnoće $-75 \mu m + 0,0 \mu m$ u gotovom proizvodu mlevenja uzorka za eksperiment od 93,2 %, daje u osnovnom flotiranju najbolje iskorišćenje bakra od $I_{Cu} = 60,12 \%$.
- Ispitivana je zatim, flotacijska koncentracija granulirane topioničke šljake plamene peći topionice u Boru sa istim optimalnim parametrima usitnjavanja i dobijeni su sada povoljniji tehnološki rezultati iskorišćenje bakra od $I_{Cu} = 73,37 \%$.
- Radi konačnosti eksperimenta flotiranja, izveden je ogled flotiranja sa dodatnim vremenom flotacijskog postupka - produžno flotiranje i dobijeni su do sada najpovoljniji tehnološki rezultati iskorišćenje bakra od

$I_{Cu} = 83,36 \%$. Ovakav rezultat je sasvim prihvatljiv i omogućuje kreaciju nove tehnološke šeme za preradu topioničke šljake pleamen peći topionice bakra u Boru, te dobijanje veće količine bakra iz ove tehnogene sirovine. Predlog nove tehnološke šeme prerade topioničke šljake radi uspešnije valorizacije bakra iz ove sekundarne sirovine biće predmet posebnog rada.

- Ovde ustanovljen novi postupak tretmana topioničke šljake je primenljiv i kod drugih pirometalurških postupaka prerade flotacijskih koncentrata bakra gde god se kao otpadni materijal stvara topionička šljaka. Izvodimo zaključak da je ovakav postupak primenljiv i za preradu topioničke šljake koja će se dobijati iz nove topionice bakra u boru koja narednih godina treba biti puštena u rad.
- Sva ova istraživanja će se nastaviti i u narednom periodu po svim ovde navedenim osnovama.

Na osnovu taksativno navedenih zaključaka možemo smatrati da je ovim istraživanjima u potpunosti opravdan deo projekta TR 33023 Ministarstva za nauku i tehnološki razvoj Republike Srbije koji se u ovom segmentu projekta bavio topioničkom šljakom plamene peći topionice bakra u Boru, i to posebno kroz razvoj nove tehnologije prerade topioničke šljake koja daje bolje tehnološke rezultate. Istraživači smatraju da ovo nije krajnji domet ostvarenih rezultata te će se kako je već navedeno u zaključcima ova istraživanja

nastaviti do postizanja max. vrednosti tehnoloških rezultata.

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