Ore Microscopy Characterization as a Mineral Processing Control

Rudolf TOMANEC[1], Vladimir ČABLIK[2], Ivana SIMOVIC[3], Radmila GACINA[4]

[1] Prof.; University of Belgrade, Faculty of Mining and Geology, 7, Djusina str. 11000 Belgrade, Serbia; email: tomanec@rgf.bg.ac.rs
[2] Doc. Ing., Ph.D.; VSB – Technical University of Ostrava, Faculty of Mining and Geology, Czech Republic; email: vladimir.cablik@vsb.cz
[3] Ing.; Mining Institute Zemun, Serbia
[4] University of Belgrade, Faculty of Mining and Geology, 7, Djusina str. 11000 Belgrade, Serbia

Summary

The mineral deposit Bor-Cerovo is a relatively simple Cu-(Fe)ore that is becoming poorer and more complex in texture with the depth of mining. The Bor Copper Mine has expanded mine workings to the Cerovo field margins, where the same type of porphyry copper ore was found for which the Bor Mine is known as one of largest in Europe. Under the oxidized zone in the vertical deposit section lie paragenetic mineral associations typical of the cementated zone, or a transitional layer from the primary mineralized rock. Average concentrations of sulphide copper and oxide copper in the primary rock range from 0.263% to 0.164% and from 0.102% to 0.008%, respectively. Concentration of the ore of simple mineral composition has given a product of unsatisfactory both concentrate quality and metal recovery. More study is felt necessary of the structural/textural properties, of the identified mineral relations, and of the rate of mineral product liberation for the given grind fineness. Mineralogical analyses were conducted in the course of laboratory (and technological) tests. It has been learned that chemical analyses of the floatation concentrated material alone were inadequate, especially where complex texture of intergrowths and poor ore were involved. Structural properties and complex integrowths, and concequently low liberation degree, were found to be the reason of poor concentration. This paper discusses importance of the mineral liberation measurement for the technological results of copper ore concentration at the Bor-Cerovo flotation plant, and explains the functional relation between the mineral liberation and the grind fineness. Data on the microscopy of ore texture and the mineral liberation degree presented in this paper are aimed at improving the recovery and grade of chalcopyrite concentrate in the Veliki Krivelj Flotation Plant. Ore microscopy in the laboratory and technological tests indicate that chemical analysis as a tool for monitoring ore flotation is insufficient, especially where the processed ore is complex-textured and poor.

Keywords: applied ore microscopy, copper ore, mineral liberation

Introduction

Margian areas of the Bor Copper Mine Cerovo deposit were recently explored by drilling for possible expansion of the mine workings. The mineral found in the new boreholes is typical porphyry, impregnated copper ore, like the rest of this deposit in Serbia, one of the largest in Europe. A paragenetic mineral association, typical of the cemented, transitional zone over the primary mineral, is extending under the oxidized zone.

By using the modal mineralogical analysis methods in solving the flotation concentration problem, the textural analysis was used, beside mineral identification and paragenetic analysis. The study of particle/crystal aggregates of ore is a very complex, comparaively long procedure that demands well educated staff in applicative ore microscopy and appropriate equipment. The characterization of textural properties of minerals is closely related to the process of their respective liberation. The degree to which a mineral will be liberated from accessory materials or another mineral is an important information in an economic evaluation of a technological scheme. Mineral processing technologies are continuously improved, because deposits of rich ore bodies have been exhausted, mineral concentrations depleted or, in other words, the complexity of lower grade ore is growing in terms of extremely fine mineral dispersions and very complex intergrowths. Therefore, liberation of useful minerals from a low grade and texturally complex ore necessitates very fine grinding and very high energy consumption.

Comminution (crushing and grinding) of ore is an energy-consuming operation; it must be performed to achieve two goals: (1) to have the product not finer than necessary for the desired liberation; and (2) to ensure that liberated product will not be further ground, that is to be removed from further grinding.

Samples and methods

Sample

Samples for the analysis were cores from different hole depths (mineralisation levels) classified into three characteristic groups: from the cemented ore (secondary sulphide enrichment), mineralised lumps from the transitional zone (with some secondary sulphide enrichment), and composite core samples with some secondary sulphide from the primary mineral. Average copper concentration through the three moneral zones varies from 0.203% at the top (cemented ore) to 0.258% in the transitional zone to only 0.164% in the primaty mineral. Oxidised copper as expected was highest (0.102%) in the cemented ore, much lower (0.026%) inthe transition, and vely low (0.008%) in the primary mineral (Tab. 1).

Representative samples from the three mineral zones were ground to approximately the same fineness (about mass 68 percent of the size class 0.074+0.000 mm), the fineness achieved in the concentration plant. Standard Tiler-screen undersizes of the samples gave six size classes, which were used to make polished sections and specimens for chemical analysis.

Tab.1 Essential ore minerals identified and sulphide and oxidised copper mean concentrations

Tab. 1 Podstawowe minerały rudne zidentyfikowane oraz zawartość siarkowodoru i średnie stężenie miedzi utlenionej

Mineral depth zone	Essential minerals	Accessory minerals	$Cu_{sulf.}$, (%) / L_m^* (%)	Cu_{ox}, (%)
Cemented (zone of secondary sulfide enrichment)	Pyrite, chalcopyrite, >>Covellite, >>Chalcocite, <pyrrhotite,	Spinel, Rutile, Hematite, Magnetite, Tetrahedrite (Ag), Tennantite (Ag), Native gold, Limonite, marmatite,	0,263 / 89,47 %	0,102
Transition	Pyrite, chalcopyrite, pyrrhotite, <<Covellite,	Spinel, Rutile, Magnetite, Hematite, Tetrahedrite (Ag), Tennantite (Ag), Native gold, marmatite,	0,258 / 88,16 %	0,026
Unaltered primary mineral (or hypogene minerals)	Pyrite, chalcopyrite, pyrrhotite,	Spinel, Rutile, Magnetite, <<Bornite, Limonite,	0,164 / 91,88 %	0,008

Tab. 2 Copper ore from Bor-Cerovo. Sample from cementation zone. Rate of chalcopyrite liberation, distribution of sulphide copper (chalcopyrite) in free and locked (middling) particles.

Tab. 2 Ruda miedzi z Bor-Cerovo. Próbka z stefy cementowania. Stopień uwolnienia chalcopiritu, rozklad i siarczku miedzi (chalkopiryt) w uwolnionych i zamkniętych ziarnach

Particle size (mm)	Weight (%)	Assay Cu_{sul} (%)	Distri-bution of Cu (%)	Rate of mineral liberati-on (L_m) (%)	Distribution of Cu in free particles	Distribution of Cu in middling particles	The locking types Bi–minerals locking types				Tree-minerals locking types		Poli–minerals
							$CuFeS_2 + FeS_2$	$CuFeS_2 + CuS$	$CuFeS_2 + SiO_2$	$CuFeS_2 + Cu_2S$	$CuFeS_2 + FeS_2 + SiO_2$	$CuFeS_2 + Cu_2S + FeS_2$	$CuFeS_2$ + polimin.
1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	15.
−0,208+0,147	15,76	0,246	14,74	64,29	9,48	5,26	2,27	0,39	2,30	-	0,17	-	0,13
−0,147+0,104	7,30	0,285	7,90	79,96	6,32	1,58	0,74	0,03	0,70	-	0,10	-	-
−0,104+0,074	7,23	0,252	6,91	85,33	5,90	1,01	0,27	0,41	0,28	-	0,06	-	-
−0,074+0,053	8,57	0,290	9,42	86,36	8,14	1,28	0,57	0,58	0,06	-	0,07	-	-
−0,053+0,038	10,57	0,275	11,06	87,50	9,68	1,38	0,58	0,53	0,12	-	-	-	0,15
−0,038+0,000	50,57	0,260	49,97	100,00	49,97	-	-	-	-	-	-	-	-
Feed:	100,00	0,263	100,00	L^*_m =89,47	0,235	0,028							-

Tab. 3 Copper ore from Bor-Cerovo. Sample of Transition zone. Rate of chalcopyrite liberation, distribution of sulphide copper (chalcopyrite) in free and locked (middling) particles.

Tab. 3 Ruda miedzi z Bor-Cerovo. Próbka z sterfy przejściowej. Stopień uwolnienia chalkopirytu, rozkladu siarczku miedzi (chalkopiryt) w uwolnionych i zamkniętych ziarnach

Particle size (mm)	Weight (%)	Assay Cu_{sul} (%)	Distri-bution of Cu (%)	Rate of mineral liberati-on (L_m) (%)	Distribution of Cu in free particles	Distribution of Cu in middling particles	The locking types Bi–minerals locking types				Tree-minerals locking types		Poli–minerals
							$CuFeS_2 + FeS_2$	$CuFeS_2 + CuS$	$CuFeS_2 + SiO_2$	$CuFeS_2 + Cu_2S$	$CuFeS_2 + FeS_2 + SiO_2$	$CuFeS_2 + Cu_2S + FeS_2$	$CuFeS_2$ + polimin.
1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	15.
−0,208+0,147	13,45	0,180	9,40	60,64	5,70	3,70	1,83	0,27	1,21	-	0,39	-	-
−0,147+0,104	10,07	0,228	8,93	65,15	5,82	3,11	0,26	1,31	1,20	-	0,34	-	-
−0,104+0,074	8,58	0,246	8,19	76,40	6,26	1,93	0,40	0,81	0,50	-	0,17	-	0,05
−0,074+0,053	9,90	0,177	6,79	76,54	5,20	1,59	0,46	0,63	0,30	-	0,13	-	0,07
−0,053+0,038	9,78	0,214	8,11	81,57	6,62	1,49	0,27	0,69	0,38	-	0,09	-	0,06
−0,038+0,000	48,22	0,313	58,58	100,00	58,58	-	-	-	-	-	-	-	-
Feed:	100,00	0,258	100,00	L^*_m=88,16	0,227	0,031							-

Ore microscopy identified essential minerals, their textural features, intergrowth patterns; lberation rate of chalcopyrite (and partly covellite with chalcocite), and integral liberation rate for each representative sample were calculated. The integral liberation rate of chalcopyrite as the essential copper mineral was 91.88% in the primary mineral (largest chalcopyrite crystal aggregates), 88.16% in the transitional zone, and 89.47% in the cemented mineral zone where chalcopyrite was mostly (over 30%) replaced by covellite. Identified essential and accessory minerals, sulphide and oxidised mineral mean concentrations and rates of the total (integral) chalcopyrite liberation in the three zones are given in Table 1.

Methods of investigation

The three average (drill core) samples from the cemented, transition and primary mineral zones were ground to the approximately even fneness, about 68% undersize screen 0.0074 mm., the ultimate fineness of the industrial plant. Each sample was size classified by standard Taylor screens. Specimens for chemical analysis and ore microscopy were selected from each of the six size classes. Gran size and chemical composition, and copper distribution for each of the three sample groups are given in Tabs. 2, 3 and 4.

Degree of mineral liberation

Specimens of each class size – briquetted polished sections – were optically examined by polarising microscope for identification of minerals in the paragenetic sequence, textural features and morphology of the ground ore grains. Liberated valuable mineral (chalcopyrite and partly covellite+chalcocite) is determined by Fleet's procedure using the Schand integration table (the multi-micrometre linear measuring system). Specimens of polished sections are analysed by the folowing procedures: all particles in the selected fields of view are counted; these fields are taken in a regular pattern across the wole specimen. Mineral liberation was registered using the Rosiwal-Schand method. Particle counting was performed on an Ernest Leitz integration table, and control counts by an image analyzer. The rate of chalcopyrite liberation, or the rate and mode of chalcopyrite intergrowth with accessory minerals are determined for

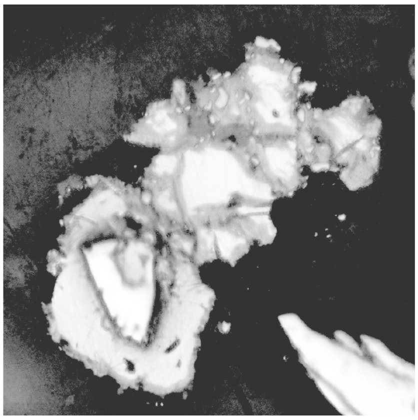

Fig. 1 Alteration of chalcopyrite in the processes of secondary enrichment, Covellite replacing chalcopyrite

Rys. 1 Alteracja chalkopirytu w procesach wtórnego wzbogacania, kowelin zastępuje chalkopiryt

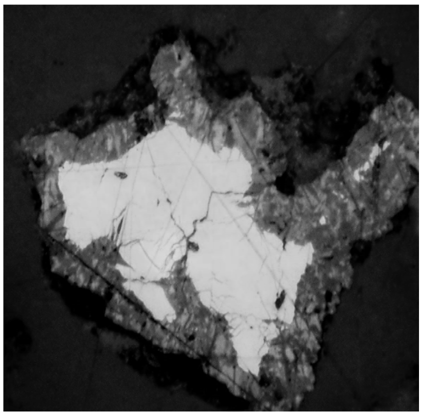

Fig. 2 Covellite replacing chalcopyrite along grain boundaries

Rys. 2 Kowelin zastępujący chalcopiryt wzdłuż granic ziaren

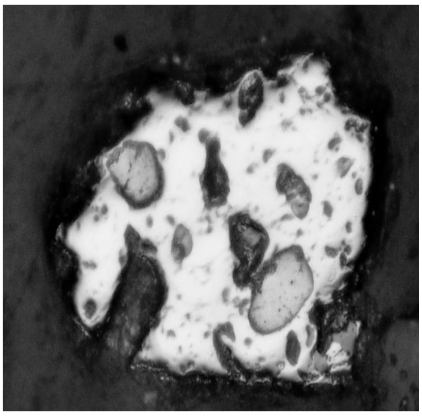

Fig. 3 Pyrite grain with inclusions. Chalcopyrite and pyrrhotite inclusions of high contiguitty index make this crude ore difficult for mineral liberation

Rys. 3 Ziarna pirytu z wtrąceniami. Chalkopirytowe i pirhotytowe wtrącenia o wysokim współczynniku styczności utrudniają wydzielenie minerałów z rudy surowej

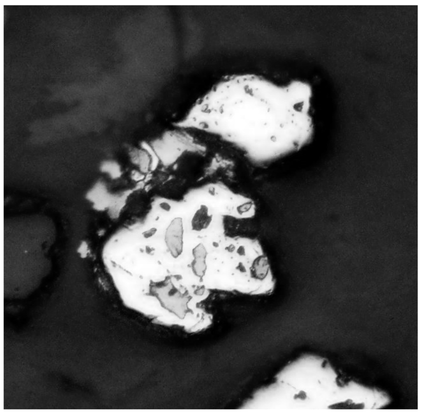

Fig. 4 Pyrite and chalcopyrite intimately intergrown

Rys. 4 Występowanie pirytu i chalkopirytu

Tab. 4. Copper ore from Bor-Cerovo. Sample from unaltered primary zone. Rate of chalcopyrite liberation in particle sizes, distribution of sulphide copper (chalcopyrite, Covellite+Chalcocite) in free and locked (middling) particles

Tab. 4 Ruda miedzi z Bor-Cerovo. Próbka z podstawowej niezmienionej strefy. Stopień uwolnienia chalkopirytu, rozkład siarczku miedzi (chalkopiryt, kowelin+chalkozyn) w uwolnionych zamkniętych ziarnach

Particle size (mm)	Weight (%)	Assay Cu_{sul} (%)	Distri-bution of Cu (%)	Rate of mineral liberati-	Distribution of Cu in free particles	Distribution of Cu in middling particles	The locking types Bi–minerals locking types				Tree-minerals locking types		Poli–minerals
				on (L_m) (%)			$CuFeS_2$ + FeS_2	$CuFeS_2$ + CuS	$CuFeS_2$ + SiO_2	$CuFeS_2$ + Cu_2S	$CuFeS_2$ + FeS_2 + SiO_2	$CuFeS_2$ + Cu_2S + FeS_2	$CuFeS_2$ + polimin. zrna
1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	15.
–0,208+0,147	13,20	0,137	11,03	61,02	6,73	4,30	1,30	-	1,62	-	0,83	-	0,55
–0,147+0,104	9,64	0,147	8,65	78,93	6,83	1,82	0,51	-	1,02	-	0,19	-	0,11
–0,104+0,074	9,13	0,147	8,17	87,69	7,16	1,01	0,58	-	0,25	-	0,10	-	0,08
–0,074+0,053	8,50	0,116	6,03	88,32	5,33	0,70	0,36	-	0,20	-	0,05	-	0,09
–0,053+0,038	10,47	0,155	9,87	90,08	8,89	0,98	0,77	-	0,15	-	0,06	-	-
–0,038+0,000	49,06	0,188	56,25	100,00	56,25	-	-	-	-	-	-	-	-
Feed:	100,00	0,164	100,00	L^*_m=91,88	0,151	0,013							-

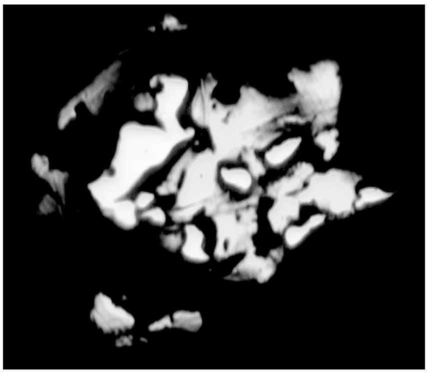

Fig. 5 Pyrite and chalcopyrite intimately intergrown.

Rys. 5 Występowanie pirytu i chalcopirytu

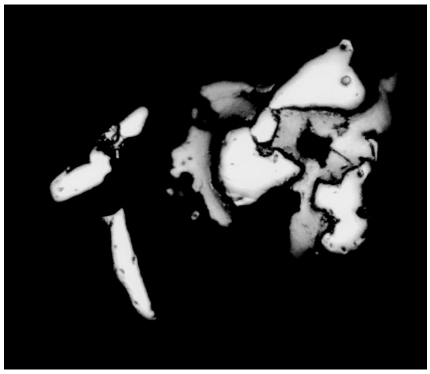

Fig. 6 Pyrite and chalcopyrite intimately intergrown.

Rys. 6 Występowanie pirytu i chalcopirytu

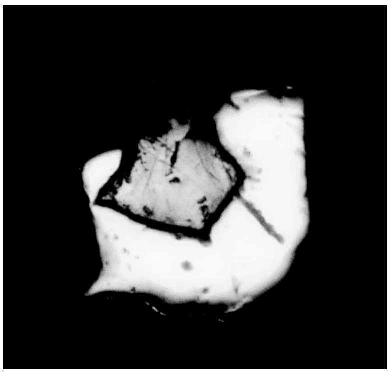

Fig. 7 Pyrite and chalcopyrite with external free surface

Rys. 7 Piryt i chalkopiryt z zewnętrzną powierzchnią uwolnioną

Tab. 5 Chemical composition and contents in samples from drill cores in Bor-Cerovo

Tab. 5 Skład chemiczny i zawartości próbek z odwiertów w Bor-Cerovo

Zone	Cu (%)	Cu_{ox} (%)	S (%)	Fe (%)	Fe_3O_4 (%)	Al_2O_3 (%)	CaO (%)	K_2O (%)	SiO_2 (%)	TiO_2 (%)	Au (g/t)	Ag (g/t)
Cementation	0.32	0.11	4.45	2.39	0.092	19.56	0.64	3.61	59.24	0.55	0.10	1.0
Transition	0.27	0.039	2.80	3.47	0.145	19.70	1.59	3.20	58.94	0.58	0.20	1.2
Primary	0.17	0.03	2.14	2.81	0.198	18.40	10.43	2.85	44.92	0.50	0.07	0.7

each size class of each of the three samples. Measurements were adjusted by ubtroducing Goden correction coefficient (ki); the data processing results are given in Tabs. 2, 3 and 4.

Results and Discussion

Microscopy of this quite simple ore revealed textural features more coplex in the transitional than in the other two zones. The mean value of chalcopyrite liberation (average liberation for the whole sample, or the total liberation) was 88.16%. The rate of chalcopyrite liberation in the coarsest size class was 60.64%; At the nominal ground fineness 0.074 mm in the plant, chalcopyrite liberation in the coarsest size class was 60.64%. Chalcopyrite is mainly intergrown with pyrite and gangue minerals (Tab. 3).

With the grain size decreasing, chalcopyrite commonly occurs in intergrowths with covellite,more rarely with pyrite (Figs. 3 and 4). Covellite and chalcocite, the products of secondary sulphide enrichment, occur in thin skins over chalcopyrite grains.

The cemented zone is more complex in mineral composition and thereby the pattern of valuable mineral intergrowths is more complex as well. The mass proportion of secondary sulphides in the zone varies from 24% to 32% and the concentration of chalcopyrite is low. Te rate of liberatedchalcopyrite is 89.47% and that of covellite, the prevailing secondary mineral in the zone, excedes 94%. The complex texture is the reason why the recovery of copper is lower and its waste high. Fine-grained primary pyrite was optically analysed by microscopy in chalcopyrite grains, or it was possibly secondary pyrite in form of the relict structures (Fig. 1). The textural features suggest that ore from the cemented zone should be finer grained. Optimum grind fineness is expected to support liberation of some chalcopyrite inclusions locked in coarse-grained pyrite (Figs. 3 and 4), which, however, will cause attrition of the secondary sulphide thin crust and its (and in part oxide copper) inversion into very fine particles, into sludge.

This will lead to the escape of copper into spoil and its loss. Average liberation rate (total liberation) of chalcopyrite is the highest (91.88%) from the primary mineral zone, because chalcopyrite grains are fairly large and sulphide copper is low (0.164%). Common intergrowths are with silicate minerals, less with pyrite. Chalcopyrite proportion in mineral intergrowths decrease with the reducing grain sizes; this proportion was highest in the intergrowths with pyrrhotite (Tab. 5). It has been concluded on the basis of the ore microscopy data that primary pyrite, replaced by younger, coarser chalcopyrite, is difficult to liberate from the fine-ground ore. A low amount of copper in the concentrate is often the consequence of a notable amount of pyrite in the ore.

Conclusion

Problems of the mineral separation by flotation - copper loss to the spoil, low copper concentration and recovery – are not to be solved with the help of chemical analysis alone, however it may seem possible. Solution of the problems necessitates microscopic examination, characterization of the ore texture, monitoring the rate of mineral liberation at the given grind fineness.

Principal features of the considered typical porphyric copper mineral is the texture, or the intergrowth of the essential chalcopyrite mineral and accessory pyrite. Very small inclusions or coarser grains of pyrite locked in pyrite crystal aggregates control the behaviour of the impregnated porphyric copper during the processing. Any finer grind, for better liberation of chalcopyrite, would not much increase the recovery without increasing the cost of grinding. Part of the unliberated chalcopyrite would be lost with the spoil. A high-quality copper concentrate is neither to be expected, because it would contain intergrown pyrite grains with chalcopyrite enclosed without free external surfaces that would allow contact with the reagents during the flotation.

Microscopic analysis, of both concentrate and spoil, can be helpful with the problems of mineral concentration where chemical analysis alone is inadequate. A section through the copper ore deposit shows three zones. The upper is cemented ore zone domnantlyof pyrite and subordinate chalcopyrite. Pyrite grains are mainly "free" (without external free surface), bearing inclusions of minute chalcopyrite that is impossible to liberate or float into the concentrate. Some inclusions in pyrite are of pyrrhotite. Chalcopyrite is the essential copper mineral which occurs in free grains or in wide covellite+chalcocite boundaries that may fill narrow cracks. Secondary sulphides are deposited on chalcopyrite grains replacing and reducing it even to relics in the core of the intergrowths. Covellite proportion in the polished sections varies from about 27% in the coarsest to some 35% in the finest size class in relation to the total amount of chalcopyrite in the ore. The average covellite/chalcopyrite ratio is 30/70. Identified tetrahedrite and tennantite are the likely silver-bearers in the ore. Average rate of the oxide copper in the ore is 0.102%. Oxide minerals (malachite, azurite, tenorite) as microcrystal powder products over sulphide surface and in fine cracks, unidentified under the microscope, are transformed by attrition into the finest size class and carried into spoil.

Pyrite occurrence in the transitional zone is almost identical. The mean sulphide copper is still high (0.258%), whilst the proportion of covelite (and other secondary sulphides) is meagre (negligible in the rank of occurrence); chalcopyrite grains are somewhat larger and of higher liberation rate. It is interesting to note that gold (in contact with chalcopyrite) and minor amounts of tetrahedrite and tennantite, the likely silver-bearers, are identified in the polished sections from the transitional zone. Pyrite is dominant also in the primary mineral zone, frequently with enclosed chalcopyrite (rarely pyrrhotite). Primary chalcopyrite is fresh, without secondary sulphides (covellite, chalcocite, tenorite), very rarely with bornite, and unobserved oxide copper minerals (oxide copper rate 0.008%). While the mean amount of copper is the lowest (0.164%), the chalcopyrite liberation rate is the highest (91.88%).

By using the method presented, the assumption that the chemical analysis as a tool for raw material monitoring during the flotation concentration is simply not sufficient was confirmed, especially for complex texture and poor ores.

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Mikroskopowa charakterystyka rudy jako kontrola przetwarzania minerału

Złoże mineralne Bor-Cerovo jest stosunkowo prostą rudą Cu-(Fe), która staje się uboższa i bardziej złożona w teksturze wraz z głębokością wydobywania. Kopalnia miedzi Bor rozszerzyła prace wydobywcze do granic obszaru Cerovo gdzie znaleziono ten sam typ porfirowej rudy miedzi, z którego kopalnia Bor jest znana jako największa w Europie. Poniżej strefy utlenionej w pionowej strefie złoża znajduje się zespół paragenetycznego minerału typowego dla strefy cementacji, lub warstwa przejściowa ze skały pierwotnie zmineralizowanej. Średnie stężenie siarczanu miedzi i tlenku miedzi w skale pierwotnej znajduje się w przedziale kolejno od 0,263% do 0,164% oraz od 0,102% do 0,008%. Stężenie w rudzie niezłożonego minerału daje produkt niezadowalający pod względem zarówno jakości koncentratu jak i odzysku metalu. Koniecznych jest więcej badań na temat właściwości strukturalnych/tekstury, identyfikacji zależności minerału, oraz na temat stopnia wyzwalania produktu mineralnego dla danego stopnia rozdrobnienia. Przeprowadzono analizę mineralogiczną podczas badań laboratoryjnych (i technologicznych). Dowiedziano się, że analiza chemiczna i flotacja koncentratu mineralnego była nieadekwatna, szczególnie gdy zaangażowana była skomplikowana struktura narostów między ziarnami i uboga ruda. Odkryto, że właściwości strukturalne i skomplikowane narosty, a co za tym idzie niski stopień uwalniania, były powodem ubogiej koncentracji. Artykuł ten omawia znaczenie pomiarów uwalniania minerału dla wyników technologicznych koncentracji miedzi w rudzie w zakładzie flotacyjnym Bor-Cerovo, i wyjaśnia funkcjonalną zależność miedzi uwalnianiem minerału a stopniem rozdrobnienia. Dane mikroskopowe tekstury rudy i stopnia uwalniania minerału prezentowane w tym artykule mają na celu polepszenie odzyskiwania i stopnia koncentratu chalkopirytu w zakładzie flotacyjnym VelikiKrivelj. Laboratoryjne i technologiczne badania mikroskopowe rudy wykazują, że analiza chemiczna jako narzędzie monitorowania flotacji rudy jest niewystarczająca, szczególnie jeśli przetwarzana ruda ma skomplikowaną teksturę i jest uboga.

Słowa kluczowe: mikroskopia rudy, rudy miedzi, minerały uwolnione