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EFFECTS OF HIGH PRESSURE ORE GRINDING ON THE EFFICIENCY OF FLOTATION OPERATIONS

WPŁYW PROCESU WYSOKOCIŚNIENIOWEGO ROZDRABNIANIA RUD NA EFEKTYWNOŚĆ OPERACJI FLOTACJI

This article discusses issues related to the impact of the high pressure comminution process on the efficiency of the copper ore flotation operations. HPGR technology improves the efficiency of mineral resource enrichment through a better liberation of useful components from waste rock as well as more efficient comminution of the material. Research programme included the run of a laboratory flotation process for HPGR crushing products at different levels of operating pressures and moisture content. The test results showed that products of the high-pressure grinding rolls achieved better recoveries in flotation processes and showed a higher grade of useful components in the flotation concentrate, in comparison to the ball mill products. Upgrading curves have also been marked in the following arrangement: the content of useful component in concentrate the floatation recovery. All upgrading curves for HPGR products had a more favourable course in comparison to the curves of conventionally grinded ore. The results also indicate that various values of flotation recoveries have been obtained depending on the machine operating parameters (i.e. the operating pressure), and selected feed properties (moisture).

Keywords: comminution, high-pressure grinding rolls, ore flotation

Artykuł dotyczy zagadnień związanych z wpływem procesu wysokociśnieniowego rozdrabniania na efektywność przebiegu flotacji rud miedzi. Technologia HPGR poprawia efektywność wzbogacania surowców mineralnych poprzez lepsze uwolnienie składnika użytecznego ze skały płonnej oraz efektywniejsze rozdrobnienie materiału. Program badawczy obejmował przeprowadzenie laboratoryjnego procesu flotacji dla produktów rozdrabniania HPGR przy różnych wartościach ciśnienia operacyjnego i wilgotności materiału. Wyniki badań pokazały, że produkty rozdrabniania wysokociśnieniowej prasy walcowej osiągały lepsze uzyski w procesach flotacji oraz wykazywały się wyższą zawartością składnika użytecznego w koncentracie flotacyjnym w porównaniu z produktem rozdrabniania w młynach kulowych. Wyznaczone zostały także krzywe wzbogacalności w układzie: zawartość składnika użytecznego w koncentracie – uzysk flotacyjny. Wszystkie krzywe wzbogacalności dla produktów rozdrabniania w HPGR miały korzystniejszy przebieg w porównaniu z krzywymi wzbogacalności dla rudy kruszonej

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konwencjonalnie. Uzyskane wyniki wskazują także na fakt, że w zależności od parametrów operacyjnych urządzenia (tj. ciśnienia operacyjnego) oraz wybranych właściwości nadawy (wilgotność), otrzymywano różne wartości uzysków flotacyjnych.

Słowa kluczowe: rozdrabnianie, wysokociśnieniowe prasy walcowe, flotacja rud

1. Introduction

The High Pressure Grinding Rolls (HPGR) has been widely used in the mechanical processing of ore since the 1990s. Initially it was used for grinding less resistant materials, due to problems which arose during crushing harder metal ores. However, as technology developed high-pressure grinding rolls started being the standard used on processing kimberlites, iron ore, copper, gold and other mineral resources. The benefits of using the roller presses in ore processing systems can be divided into two main criteria:

– Savings resulting from reduced energy consumption of the HPGR grinding process (economic criterion),
– Improvement in the comminution degree of HPGR product, and improved useful product liberation due to the effects of huge compressive forces on the bed of comminuted material, resulting in the formation of micro-cracks in product particles, which in turn results in lower energy consumption in the downstream grinding stages and improves the efficiency of main beneficiation operations (technological criterion).

Industrial applications of high-pressure grinding presses significantly improve the efficiency of upgrading operations mainly with leaching extraction on heaps, leaching, gravitational beneficiation and flotation processes.

The results of research conducted by Klingmann (2005) compared the effectiveness of the leaching process on two types of gold ore, which was subjected to grinding in two different technological circuits: a triple-stage comminution circuit with HPGR at the third stage and a four-stage conventional arrangement, with Vertical Shaft Impactor operating at the fourth stage. Despite a finer final product of the four-stage circuit, better recoveries were obtained in the leaching process, from 7.7% to 10.7% in favour of HPGR. This was confirmed by other studies (Patzelt et al., 1996), in which the greatest improvement in the leaching process recovery for the HPGR-based circuit was obtained in respect of coarser particles. According to the authors, the reason for this may be the formation of micro-cracks in individual particles of HPGR products. Roller presses may also improve the effectiveness of gravitational beneficiation of gold, particularly for coarser mineral particles that are sufficiently liberated as a result of high-pressure grinding process. Pilot studies carried out for gold ore (Gray, 2005) showed that it was possible to increase the recovery from 60 to 90% using a roller press unit instead of a conventional tumbling mill. Other studies (Baum, 1997) indicated that concentrates with higher tin grades were obtained under gravitational upgrading of tin whilst, at the same time, metal payloss in the waste was reduced.

The article presents the impact of the high-pressure grinding process of copper ore on the useful component content in the flotation concentrate and the obtained flotation recovery. It is the first such publication in the country, though there have been studies carried out to evaluate the flotation processes for grinding HPGR by analyzing the yield obtained for concentrates in copper ore flotation processes (Saramak et al., 2014) as well as modelling the grinding process in HPGR (Saramak, 2013).

2. Flotation of copper ore

Research carried out by Anglo American in respect of copper ore (Smit, 2005) showed that the efficiency of the flotation process was higher for the HPGR product. The same study demonstrated that, if fully liberated minerals were proceeded to a ball mill instead of flotation, the recoveries in flotation decreased. This was associated with the occurrence of the over grinding material phenomenon. Other studies (Brozek & Młynarczykowska, 2010, 2012; Potulska, 2008) have shown that there is a correlation between the effectiveness of the flotation process of domestic sulphide copper ore and particle size distribution (Fig. 1).

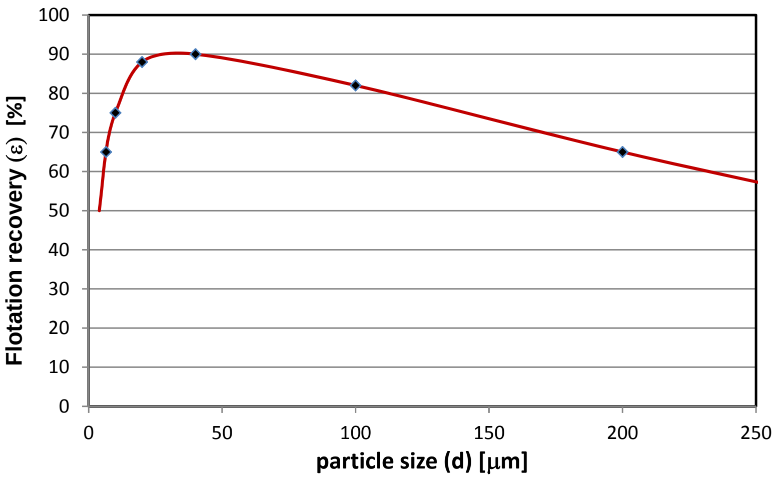

Fig. 1. Relationship between the metal recovery in flotation operations and particle size distribution for sulphide copper ore

In the multi-stage enrichment process in which the ore is prepared for flotation, the material with a particle size of between 20 and 70 μm may appear in the grinding circuit even at the stage of fine crushing of the material. If that yield is significant, these fine particle classes may be transferred from the grinding process directly to the rough flotation process, bypassing the grinding operations. This situation happens, for example, in the upgrading process of Polish copper ore, whereby the yield of the ball mill feed with a particle size less than 70 μm may even be over ten percent (Foszcz & Gawenda, 2012).

To put it simply, the flotation of sulphide minerals (not just copper) is an important factor associated with grinding:

- flotation recoveries are proportionally related to the liberation degree of useful mineral from ore,
- when the useful mineral particles are too finely grinded, despite the liberation, they pass on during flotation as waste, which worsen flotation recoveries,
- fine iron particles from worn grinding media and steel linings change the chemical properties of the flotation pulp and when oxidizing, influence the increased use of flotation reagents and interfere with the process.

The use of high-pressure grinding rolls in the technological process of ore flotation can have a positive impact on increasing flotation yields due to:

– achieving a high comminution degree of the grinding product,
– limiting the unfavorable phenomenon of material over grinding,
– elimination of grinding media (if the grinding roller replaces a ball mill or SAG), and the resulting reduction of fine iron particles content in the comminution product.

It is worth remembering that, despite its many advantages, the high-pressure grinding rolls is not an ideal and universal solution for every type of material. The potential benefits in a particular case should be verified in practice by carrying out appropriate tests.

3. The research program

3.1. Subject of research

The research presented in this paper included laboratory HPGR comminution tests carried out in the Norwegian University of Science and Technology in Trondheim. The unit used for this programme had a diameter of 200 mm and a width of 100 mm and the material was copper ore with a particle size of 0-8 mm and average feed copper grade α = 1.5%. Average yields for selected particle size fractions are presented in Table 1

TABLE 1

Particle size distribution of the feed led to flotation

Particle size [mm]	Yield [%]
0.1-0,125	1.03
0.071-0.1	11.17
0-0.071	87.80

3.2. Research methodology

Tests were carried out at an operating pressure of 2.5 N/mm^2, 3.5 N/mm^2, 4.5 N/mm^2 and 5.5 N/mm^2. For each pressure the material with regular (0%) and increased (2%) moisture content was tested. In the next stage, each product was subjected to grinding in a ball mill to obtain a particle size finer than 100 µm, after which a flotation analysis was carried out on the grinded products (Fig. 2).

In order to enable a comparison of the results obtained through the flotation process, each sample was equally prepared for flotation, i.e. particle composition was the same (Table 1). The flotation analysis was carried out using the fractional flotation method with a single cleaning of flotation concentrates. Flotation experiments were carried out in the manner that beyond the method of grinding particles, the other process conditions were kept constant. Each time the suspended particle matter density for flotation amounted to 1250 g/dm^3. A depressant mixture of ethyl xanthate sodium and Hostaflot was used in an amount of 120 g/mg, the Nasfroth frother reagent was fed in an amount of 30 g/mg. Agitation time after the addition of reagents was 5 minutes.

Flotation was carried out in two stages, with fractioned cleaning of flotation concentrates which were collected at the following intervals: 2, 5, 10, 15 minutes (K1, K2, K3, K4 respectively). The experimental diagram is shown in Figure 3

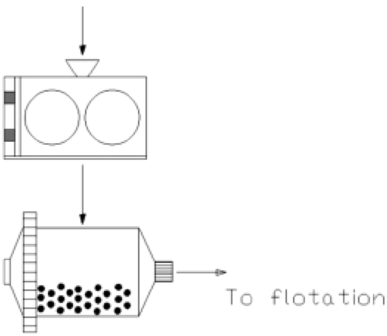

Fig. 2. Diagram of test circuit

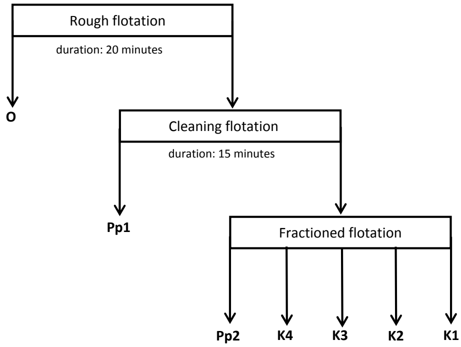

Fig. 3. Diagram of flotation experiment

3.3. Overview of the results

The effects of HPGR operating pressure on the copper grade in the flotation concentrate β and flotation recoveries ε were examined during the first stage. The results are shown in Table 2.

TABLE 2

Results for copper ore flotation of moisture contents of 0% and 2% grinded at different operating pressures

Operating pressure $[N/mm^2]$	Moisture content 0%		Moisture content 2%	
	β [%]	ε [%]	β [%]	ε [%]
2.5	14.2	82.6	13.6	78.3
3.5	13.7	83.9	13.5	88.4
4.5	13.8	83.7	13.9	84.9
5.5	13.1	81.1	14.7	78.8

In analyzing the results in Table 1, it can be seen that the highest recovery value for flotation concentrates was obtained at the operating pressure of 3.5 N/mm^2. For the remaining pressure values, the recoveries were lower. For moist material, the recovery for the best possible operating pressure was higher than for the dry material, but the recoveries achieved for other operating pressures were more favourable for dry material. Based on the above results, it can be concluded that the relationship between flotation recoveries and the operating pressure in the roller press unit can be represented by a parabolic curve. Interpretation of the obtained relationship is as follows: at lower values of operating pressure less intense comminution occurs, which results in lower levels of useful minerals liberation from the feed. In turn, it can be assumed that at too high pressure values, the over grinding phenomenon of completely liberated sulphide minerals occurred.

The energy consumption process E_{sp} and its productivity Q are presented in Table 3.

TABLE 3

Productivity and energy consumption of the grinding process of copper in HPGR

Operating pressure [N/mm^2]	Moisture content 0%		Moisture content 2%	
	E_{sp} [kWh/Mg]	Q [Mg/h]	E_{sp} [kWh/Mg]	Q [Mg/h]
2.5	2.16	1.51	2.09	1.55
3.5	2.57	1.34	2.53	1.45
4.5	2.86	1.38	2.98	1.42
5.5	3.41	1.33	3.53	1.42

In analyzing the results contained in Table 3, it can be noticed that better productivity indicators were obtained for moist materials than for dry ones. However, this resulted in higher energy consumption for the moist material, especially for operating pressures above 3.5 N/mm^2. The useful component content in flotation tailings presented in Figure 4 is interesting to analyze.

In general, the useful component in waste grew with increasing of HPGR operating pressure, and it was relatively higher for moist material. For dry material, the lowest copper content in the waste was obtained at a pressure of 3.5 N/mm^2.

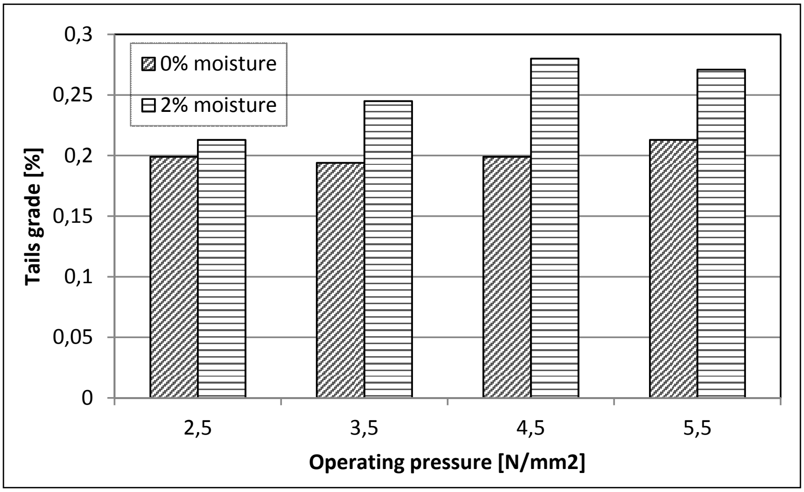

Fig. 4. Copper content in the tailings for HPGR comminution products

4. Analysis of the upgrading curves

For the purpose of ascertaining whether the results of flotation for HPGR product obtained in Chapter 3 are more favorable than for the material previously grinded in conventional tumbling mills, it is necessary to compare the beneficiation results obtained in the conventional technological process circuit with the one based on high-pressure grinding rolls. For this purpose, laboratory flotation tests for both variants of technological circuits were carried out. The final products of conventional circuit were prepared in the same way as the HPGR samples and the results obtained were comparable. The list in Table 4 includes the results obtained for the flotation of HPGR products with 0% moisture, grinded at the operating pressure of 3.5 N/mm^2 and the results of flotation for conventionally grinded material.

TABLE 4

Comparison of flotation results of material grinded conventionally and in HPGR

Technological indices	Mill-based circuit	HPGR-based circuit
β [%]	15.9	13.8
ε [%]	82.6	88.5

Due to the fact that the conventional tests were carried out in laboratory scale, it was difficult to accurately determine the energy consumption of the enrichment circuit. However, numerous studies carried out in pilot plant scale show that the energy consumption during comminution of raw minerals in HPGR is from several to 30% lower than in tumbling mills (Rule et al., 2008; Patzelt et al., 2001).

The flotation results obtained were also used to determine the upgrading curves for individual HPGR products. The Halbich upgrading curves, which represent the useful component content in the concentrate as a recovery function of $\varepsilon = f(\beta)$, were determined. Fig. 5 shows these curves for the dry material, and Figure 6 is for moist material. In comparison, Figure 5 also determines the upgrading curve for the material which was previously grinded in a tumbling drum. The results indicate that the HPGR unit is beneficial for this type of material, since all upgrading curves for HPGR products are situated above the curve for the products grinded in a ball mill.

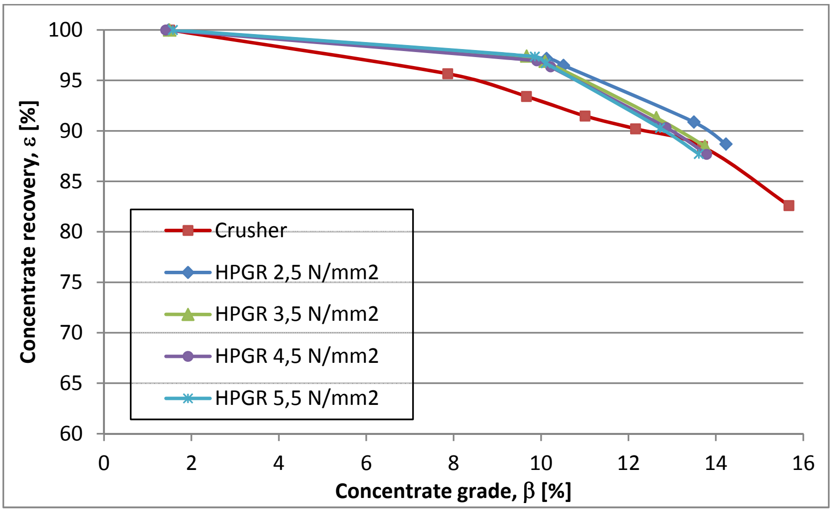

Fig. 5. Halbich upgrading curve for dry material

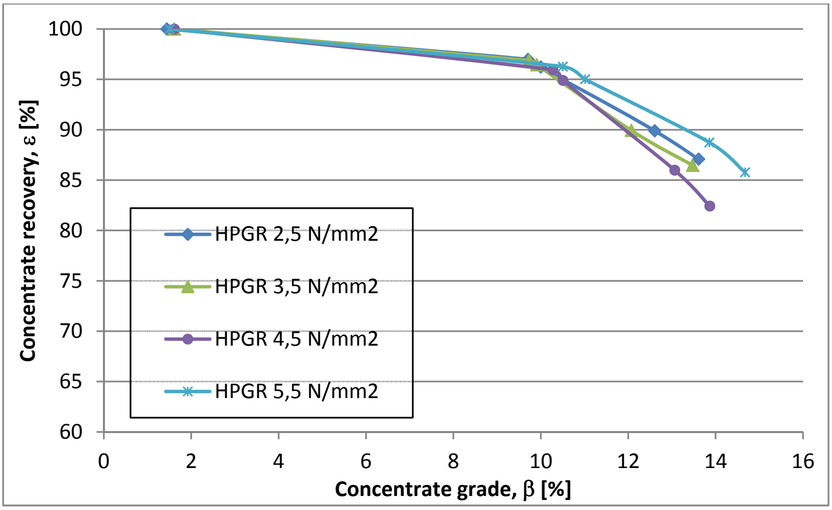

Fig. 6. Halbich upgrading curve for moist material

5. Modelling of the flotation process effectiveness

A general model can be built, based on the results obtained, in which the steering parameter will be the HPGR operating pressure and the objective function is the flotation recovery. Results of the experiments listed in Table 2 show that the relationship between the flotation recovery and the HPGR operating pressure is a parabolic function (Fig. 7). The fitting accuracy in both cases is statistically significant at the probability level of 95% and respectively amounts to: $R^2 = 0.995$ for the dry material and $R^2 = 0.916$ for moist one. The mathematical form of both approximation functions for dry and moist material are equations (1) and (2), respectively.

$$y = -0.979 \cdot x^2 + 7.336 \cdot x + 70.383 \tag{1}$$

$$y = -4.066 \cdot x^2 + 32.317 \cdot x + 23.477 \tag{2}$$

whereby:

y — flotation recovery, [%],
x — HPGR operating pressure, [N/mm^2].

Optimal operating pressure, i.e. those in which the highest flotation recoveries are to be achieved, may be determined on the basis of approximation results. For dry material, it is: $F_{sp\_opt\_0\%} = 3.7$ N/mm^2, and $F_{sp\_opt\_2\%} = 3.9$ N/mm^2 for moist material.

5. Summary

The test results presented in the paper show that the use of high-pressure grinding rolls in the technological circuits of copper ore comminution can improve efficiency of the flotation process

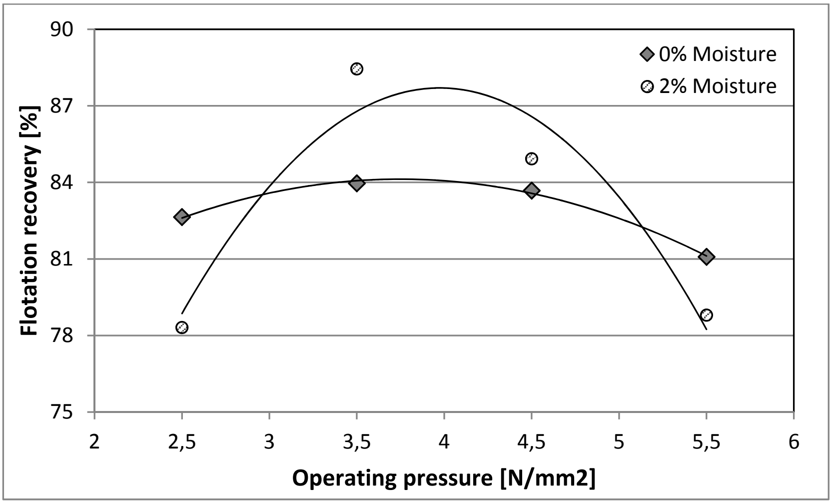

Fig. 7. The empirical values and approximation functions of flotation recoveries as a function of HPGR operating pressure

by increasing flotation recoveries and the useful component concentrate grades. The results also indicate that it is necessary to appropriately select the operating parameters of the roller press in order to ensure that suitable values of indices of the beneficiation process assessment are obtained. Inaccurate selection of these parameters will result in generation of unnecessary losses resulting from non-optimal use of the device.

The results presented in this article confirm those in previous worldwide studies, which talk about the measurable benefits of using the high-pressure grinding rolls in technological mineral processing circuits of metallic and non-metallic ore by:

– improving the comminution degree of the product,
– increasing the useful component liberation,
– reducing of energy consumption in the grinding process,
– increasing the technological effectiveness,
– reducing the paymetal loss and increasing the recovery.

It is also important to remember that final confirmation of the above results can be obtained after completing a full research program in a pilot plant scale; however, the results presented the above give hope that the potential benefits of high-pressure grinding rolls application in Polish copper ore processing can bring measurable results.

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