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EFFECTIVENESS OF COPPER MINERALS LIBERATION FROM THE GANGUE THROUGH APPLICATION OF HRC PRESS IN COPPER ORE PROCESSING CIRCUITS

EFEKTYWNOŚĆ UWALNIANIA MINERAŁÓW MIEDZI ZE SKAŁY PŁONNEJ POPRZEZ ZASTOSOWANIE WYSOKOCIŚNIENIOWEJ PRASY HRC W UKŁADACH PRZERÓBKI RUD MIEDZI

The article concerns investigations over benefits of application of HRC devices into sulphide copper ore processing plant. High pressure comminution appears to be very effective technology in hard ore processing circuits, especially in terms of energy consumption. This can be particularly observed in downstream grinding and beneficiation operations. A series of pilot-scale crushing tests in HRC roller press for various levels of operating pressure, were performed. HRC crushing effectiveness along with downstream grinding process course for each crushing product were also under analysis. The investigations were supplemented by analysis of flotation process effectiveness and impact of the process of high-pressure comminution on environment (dust emission). The results of investigation show that operating pressure level influences the obtained comminution results (comminution degree, yield of finest particle size fractions). The grinding effectiveness, measured through production of the finest particle size fractions was significantly influenced by the operating pressure. The results show that higher values of operating pressure (4.0 and 4.5 N/mm^2) are not as efficient within this scope as the pressure 3.5 N/mm^2. Dust emission is also correlated with the operating pressure value.

Keywords: High-pressure comminution, copper ore, ball mill grinding, dust

Artykuł dotyczy badań nad możliwością wykorzystania prasy walcowej HRC w procesie przeróbki rud miedzi. Rozdrabnianie wysokociśnieniowe jest skuteczną technologią stosowaną w układach wzbogacania rud, zwłaszcza pod względem niższego zużycia energii, co jest szczególnie widoczne w kolejnych operacjach mielenia i separacji. Przeprowadzono serię testów rozdrabniania w prasie walcowej HRC w skali półtechnicznej, dla różnych poziomów ciśnienia roboczego. Badania uzupełniono analizą efektywności procesu flotacji i wpływu procesu rozdrabniania wysokociśnieniowego na środowisko (emisja pyłu).

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Wyniki badań wskazują, że poziom ciśnienia roboczego pozytywnie wpływa na uzyskane wyniki rozdrabniania (stopień rozdrobnienia, wychód ziaren najdrobniejszych). Skuteczność rozdrabniania w prasie, mierzona wychodem ziaren najdrobniejszych była w znacznym stopniu zależna od ciśnienia roboczego. Wyniki pokazują, że wyższe wartości ciśnienia roboczego (4,0 i 4,5 N / mm2) nie są tak skuteczne w tym zakresie jak ciśnienie 3,5 N/mm2. Emisja pyłu jest również skorelowana z wartością ciśnienia roboczego.

Słowa kluczowe: rozdrabnianie wysokociśnieniowe, ruda miedzi, mielenie w młynie kulowym, zapylenie

1. Introduction

The technology of high-pressure grinding was invented and developed by Professor Schoenert in 70's (Schoenert, 1979), and currently it is regarded as one of the most efficient methods of hard ore comminution. It was introduced into raw materials treatment in early 80's and since that time high-pressure devices has been applied in many mining and mining-related industrial sectors, including iron and non-ferrous metal ores processing (copper, platinum, gold), as well as cement and limestone flour production. Considerable number of works concerning modeling and optimization of HPGR operation were also presented (Daniel & Morell, 2004; Tavares, 2005; Saramak, 2012; 2013; Saramak & Kleiv, 2013). Nowadays high-pressure grinding rolls devices are considered as well know technology with over 500 sold machines, according to various sources.

The HRC, new solutions in ore comminution, based on high-pressure technology, was recently introduced by Metso. The company announces its new device as a kind of next step in high-pressure technology. The operation principle is analogous to HPGR operation (feed material is subjected to a particle-bed comminution between two counter rotating rolls, under force exerted by hydraulic pressure), but HRC devices have slightly different design and construction. The frame of machine was designed in an arch-shape, and it is believed that such a construction helps in maintain the pressure value along the roll's surface (especially on roll edges). Thanks to mutually pivoting housing the applied force can be magnified, what results in increasing the process effectiveness (Metso, 2013). Considering that HRC is a relatively new equipment, few works, describing the potential effects of mineral raw materials in HRC devices, can be found in literature. However there are more and more papers and presentations on international conferences and congresses (Knorr et al., 2013; Sandvik & Larsen, 2016).

2. Methodology and research programme

The main aim of the paper was to investigate the effects of ore comminution in HRC device. The liberation of useful mineral was directly linked to an increased recovery of flotation process and indirectly to the increase in yields of finest particle size fractions in downstream ball mill grinding process. Some research results, carried out for Polish copper ores, show (Potulska, 2008) that the optimum particle size for flotation feed ranges from 20 to 70 μm (Fig. 1). This material is considered as the one with the most favorable degree of useful mineral liberation, provided the lithologic composition is close to following share: sandstone 40-45%, carbonate 40-45%, slate 10-20%.

The material coarser than 70 μm is considered as not ready for flotation process, while the material finer than 20 μm is treated as over-ground. In both cases the effectiveness of flotation operation is lower, than for the material with particle size between 20 and 70 μm.

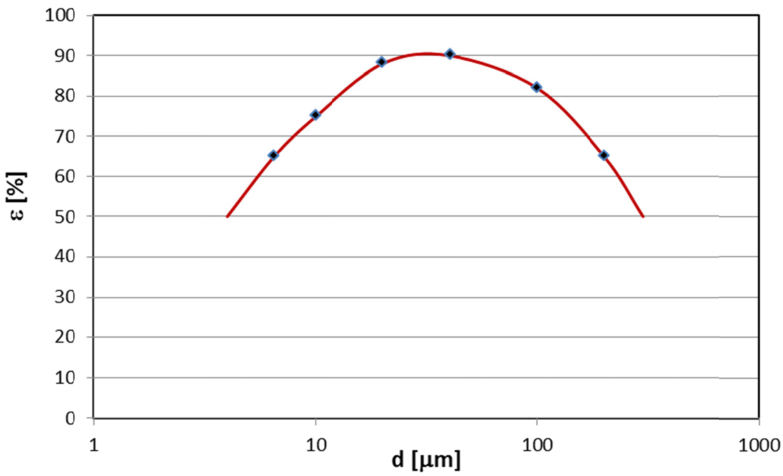

Fig. 1. Relationship between the metal recovery in flotation operations and particle size distribution for sulphide copper ores (Potulska, 2008)

Experimental programme included pilot plant tests of copper ore crushing in HRC device. The feed for HRC comminution was copper ore, constituting from three lithologic fractions (sandstone, carbonate, slate) with percentage shares 47%, 42% and 11%, respectively.

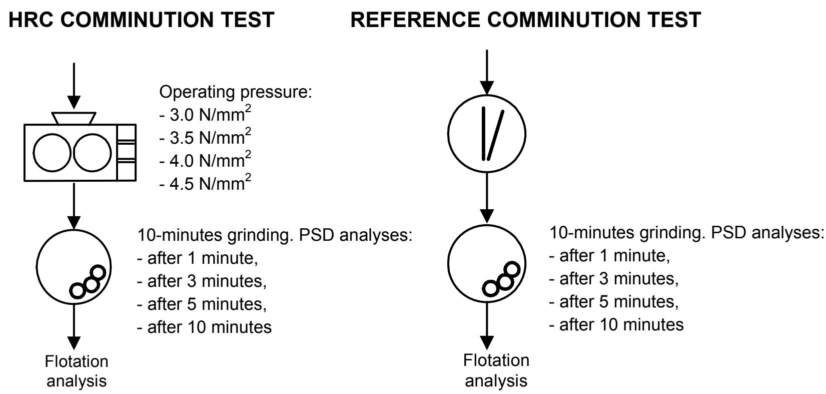

Fig. 2. Scheme of investigative programme

The entire sample of feed material was homogenized and divided into five samples with equal weight of about 50 kg each, and the same particle size composition. Four samples were crushed in HRC press under different values of operating pressure (F_{sp}), while the fifth one was treated as reference sample, and was crushed in a jaw crusher instead of HRC device. Each HRC crushing product was subjected to a batch grinding operation and further analyses, which helped in assessment of the HRC impact on effectiveness of downstream beneficiation operations. The scheme of investigations was presented in Figure 2.

3. Analysis of results

Particle size composition for feed and all HRC samples were determined (Fig. 3). Each HRC product was subjected to grinding tests in a ball mill in order to determine the grinding kinetics for each sample. Grinding operation of each sample lasted ten minutes, while PSD analyses were made after 1, 3, 5 and 10 minutes of grinding. One flotation test was then performed for the HRC sample crushed at operating pressure $F_{sp} = 4.0$ N/mm^2. The reference sample was crushed in a jaw crusher prior to grinding, in order to obtain the material with a particle size distribution similar to the ones obtained for HRC comminution products. The dust emission during crushing tests were also measured in order to determine an environmental footprint of the device, depending on the volume of operating pressure. Despite its critical significance, this issue is not so commonly presented in literature (Arrowsmith & Ashton, 1991; Saramak et al., 2016; 2017), therefore investigative programme presented in this paper includes this problem.

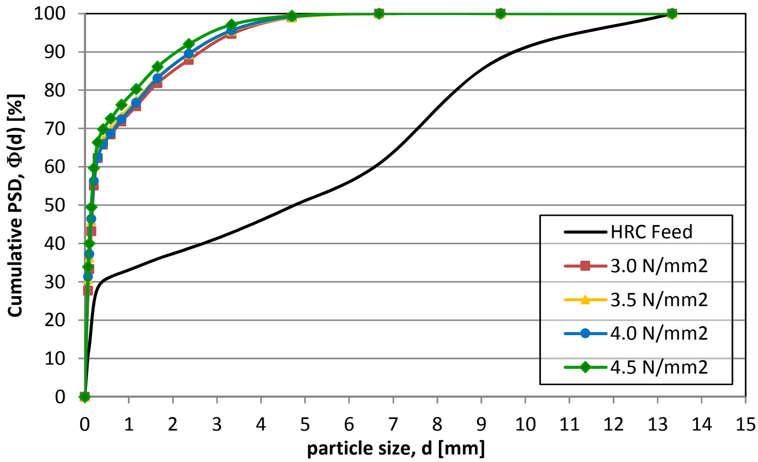

Fig. 3. Particle size distribution curves for HRC products crushed under various values of operating pressure

3.1. Results of high-pressure comminution

In the first stage the results obtained in HRC press was under the analysis. Energy consumption of high-pressure comminution, along with comminution degrees were investigated. Figure 4 presents values of Bond's work indices (W_i) obtained for each HRC product. Considering that for HRC feed $W_i = 14.13$ kWh/Mg, the energy savings in HRC ranges from 20 to 28%, depending the operating pressure value.

Analyzing Fig. 4 it can be observed that for two lowest pressure values, increases in energy savings were relatively low. For the pressure value 4 N/mm^2 a significant decrease in Bond's index value was observed (from 10.9 to 10.3 kWh/Mg). Further increasing in operating pressure value has resulted in less than proportional increase in savings of comminution energy consumption, therefore it might be true that for that type of ore the optimal operating pressure is between 3.5 and 4.0 N/mm^2.

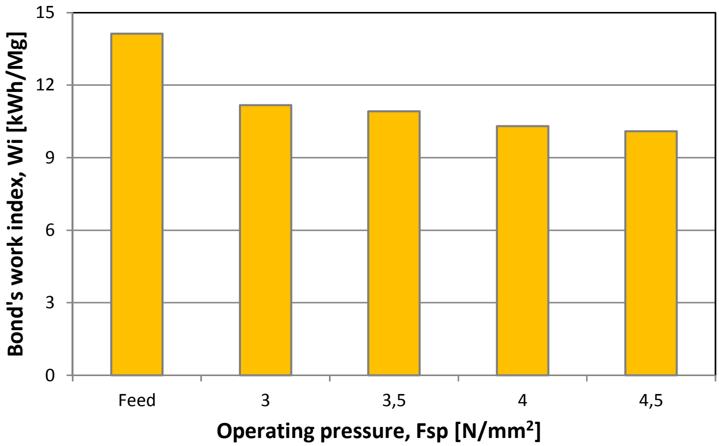

Fig. 4. Values of Bond's work indices obtained for HRC products in various operating pressure values

TABLE 1

Values of 50-ty, 80-ty and 95% comminution degrees (S_{50}, S_{80}, S_{95}) for HRC crushing products

Operating pressure (N/mm^2)	Comminution degree		
	S_{50}	S_{80}	S_{95}
3.0	26.1	5.7	3.4
3.5	28.0	6.2	3.6
4.0	28.1	6.1	3.6
4.5	31.7	7.5	4.0

Values of comminution ratios were presented in Table 1. As it can be seen from that Table, an application of high-pressure comminution significantly increases the fineness of crushing product. Average comminution ratio values range from 26 to 31, depending the operating pressure value. Another aspect worth mentioning is a relatively low change in comminution ratio values together with increasing the operating pressure value in HRC press. Some increases in S_x values can be observed together with increasing of F_{sp} from 3.0 to 3.5 N/mm^2. Further increase in F_{sp} results in insignificant improvements in S_x, while the course of crushing process with the highest operational pressure (4.5 N/mm_2) results in further improvement of comminution ratio values.

3.2. HRC effect in downstream operations

3.2.1. Ball mill grinding

The next stage of analysis involves research over the kinetics of downstream grinding process in a ball mill. Exemplary particle size distribution curves for the HRC product crushed under 3.5 N/mm^2, were presented in Fig. 5.

Analysing the figure 5 it can be noticed, that together with increasing the operating pressure value in HRC press, particle size distribution curves show higher contents of finest particle

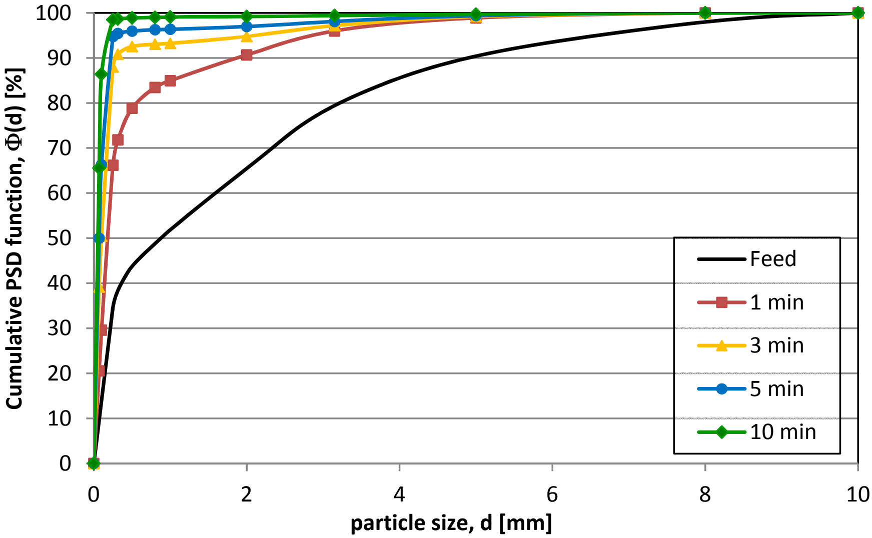

Fig. 5. PSD's of ball mill products for a prior comminution in HRC at 3.5 N/mm^2

size fractions. In order to compare the results more precisely, 50-ty, 80-ty and 95% comminution degrees were calculated for each grinding time. In order to determine the potential effects, an analogous analysis for the reference sample (crushed conventionally in a crusher), was also performed. Results are presented in Table 2. Potential benefits of HRC application can be seen especially when average comminution degrees are analysed (S_{50}). All these values obtained after three minutes of grinding were of a higher value than average comminution degree for conventionally upstream crushed product obtained after five minutes of grinding. What is more, the S_{50} value, obtained for HRC product for operating pressure values equal or higher than F_{sp} = 3.5 N/mm^2 after three minutes of grinding, was more favorable than the respective S_{50} value obtained after 10 minutes of grinding, for conventionally crushed product. It shows a potential energy savings in downstream grinding processes after application of high-pressure grinding technology in technological crushing and grinding circuits for Polish copper ores.

The main benefit from application of high-pressure comminution technology results from a more intense generation of finest particles, among which the liberated useful minerals constitute a significant share. Therefore, the next step of the analysis was to determine the yields of finest particles in each HRC products and in the reference sample. Figure 6 below shows the net production of particle size fraction below 0.07 mm ($\gamma_{-0.07}$) in each HRC product after 1, 3, 5 and 10 minutes of grinding.

Results show that the more intense generation of the finest particle size fractions were observed. In example, after one minute grinding of HRC products, crushed at operating pressure 4.0 and 4.5 N/mm^2, the $\gamma_{-0.07}$ value was comparable to the one obtained after three minutes grinding for conventionally crushed product.

As it was stated earlier, the highest potential recoveries in flotation processes can be obtained for particles from 20 to 70 μm. Nevertheless, in industrial practice the particles below 100 μm can be directed to rough flotation, where most of fully liberated minerals can be recovered. On the bases of the ball mill grinding tests there were estimated such durations of grinding processes

TABLE 2

Fifty, eighty and ninety five percent comminution degrees for HRC products

	Grinding time			
	1 min	**3 min**	**5 min**	**10 min**
	S_{50}			
Conventional crusher	2.3	4.2	6.9	11.3
HRC, 3.0 N/mm^2	4.6	8.1	11.6	15.8
HRC 3.5 N/mm^2	5.8	10.8	15.2	19.9
HRC 4.0 N/mm^2	7.5	15.2	21.2	23.7
HRC 4.5 N/mm^2	10.2	20.1	26.2	27.1
	Grinding time			
	1 min	**3 min**	**5 min**	**10 min**
	S_{80}			
Conventional crusher	1.4	2.1	5.1	8.4
HRC, 3.0 N/mm^2	3.9	7.5	10.3	15.5
HRC 3.5 N/mm^2	4.1	7.9	9.8	16.2
HRC 4.0 N/mm^2	6.2	12.1	10.8	17.4
HRC 4.5 N/mm^2	6.5	11.5	14.2	24.6
	Grinding time			
	1 min	**3 min**	**5 min**	**10 min**
	S_{95}			
Conventional crusher	1.1	1.5	1.8	1.9
HRC, 3.0 N/mm^2	1.7	2.2	2.5	2.6
HRC 3.5 N/mm^2	1.6	2.3	2.4	2.6
HRC 4.0 N/mm^2	1.9	2.4	2.6	2.7
HRC 4.5 N/mm^2	1.8	2.6	2.5	2.6

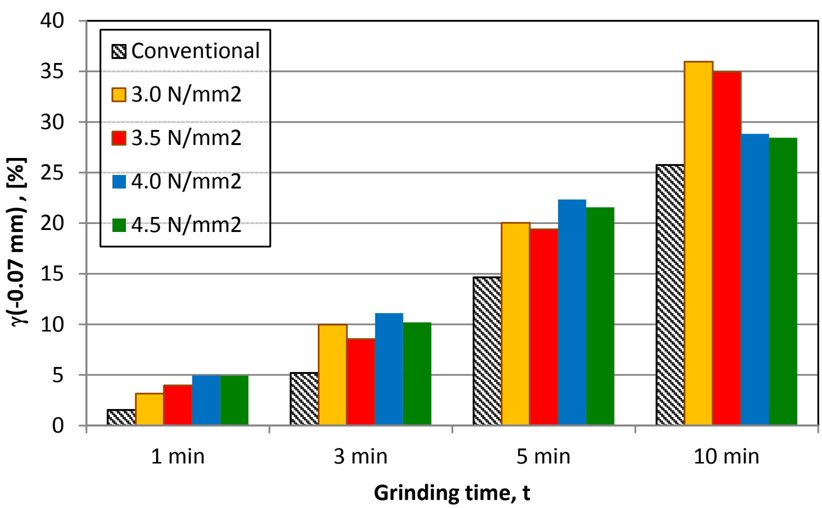

Fig. 6. Yields of finest size fraction $\gamma_{-0.07}$ in grinding operations depending on HRC operational pressure and grinding time

for all HRC products, where yields of particles below 0.1 mm were at least 50%. The same analysis was performed for the reference sample. Results were presented in Fig. 7. The results show that for conventionally crushed product it takes more than 8 minutes of grinding to obtain 50% particles finer than 0.1 mm. Analogous grinding times for HRC product drops significantly and range from a slightly more than two minutes (for F_{sp} = 4.5 N/mm^2) to nearly 3 and a half minute for F_{sp} = 3.0 N/mm^2.

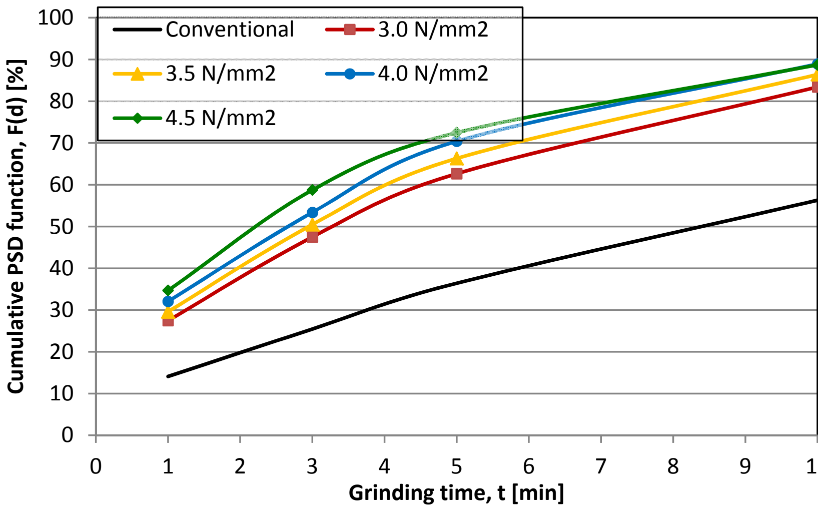

Fig. 7. Relationships between the yields of particles finer than 0.1 mm and the grinding time, obtained for different values of operating pressure

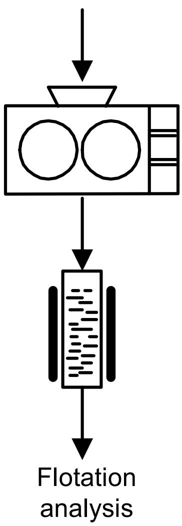

Fig. 8. Comminution circuit with HRC and electromagnetic mill

3.2.2. Grinding in electromagnetic mill

Application of HRC devices in ore comminution circuits might bring additional benefits through utilization of unconventional grinding technologies, especially in downstream fine grinding operations. One of the example can be an electromagnetic mill. The idea of its operation lies in different source of force, causing the movement of grinding media in mill's working chamber. An inductor with hidden poles generates the rotating electromagnetic field, which moves the grinding media. Comminution process takes part due to collision of the grinding media with the ore particles. Comminution in electromagnetic mill appears to be very effective. When additional weakening of the feed material in upstream comminution operations is carried out (micro-cracks being generated during high-pressure comminution), an entire comminution degree level of such a circuit might be even higher. The next stage of investigative programme is a series of grinding tests in electromagnetic mill for HRC products. The proposed scheme of joint operation of HRC device and electromagnetic mill was presented in Fig. 8. Initial tests has shown that benefits of such a configuration in terms of higher comminution degree are quite significant. More detailed results of investigations within this issue will be presented in separate publication.

3.2.3. Flotation process effectiveness

Table 3 shows chosen results of flash flotation process for both samples, while HRC product crushed at 4 N/mm^2 was taken as a feed for flotation tests.

TABLE 3

Main characteristics of flotation indices for both types of sample

Flotation index	HRC sample	Reference sample
Duration of flotation [min]	8	7
Concentrate yield g, [%]	4.2	7.5
Concentrate grade b, [%]	21.2	20.0
Copper content in final waste J, [%]	0.25 (after 45 minutes)	0.23 (after 75 minutes)

The main purpose of flotation test was to investigate the copper grade in tails. It was assumed that the higher level of copper liberation in flotation feed should correspond to lower useful mineral grade in tails. If copper minerals were sufficiently liberated from the gangue during comminution operations, these minerals should easily pass to the concentrate. If, on the other hand, there are ingrowths of copper with the gangue or some unliberated minerals, the higher amount of copper minerals will be lost in tails, because in flotation process these particles would not be able to pass into concentrate.

The results of the flotation test show that for HRC sample the tails with similar copper grade were obtained after much shorter time. It indicates a potential benefits in copper recovery through application of HRC technology in copper ore processes.

3.3. Environmental impact of high pressure comminution

Apart comminution effects also an environmental impact of HRC was investigated. For each single test the dust emission level was recorded with using the particle dust analyzer *Casella*. The background dust emission in laboratory, when no equipment was operating, was determined prior core measurement and the results are presented in Figure 8. It can be seen that average level of dust emission is stable and oscillates around 0.1-0.2 mg/m^3.

Values of dust emission for each single test, together with standard deviations, are presented in Table 4 and in Fig. 9. The measurements were carried out for three levels of operating pressure, namely 3.5, 4.0 and 4.5 N/mm^2. Each single value was registered every one second. The measurement for 4.0 N/mm^2 was a bit shorter (around 140 measurement points), while the two other ones recorded approximately 220 measurements.

Results show that there are significant differences in dust emission depending the operating pressure value in roller press. However it should be mentioned, that after completing each test, the

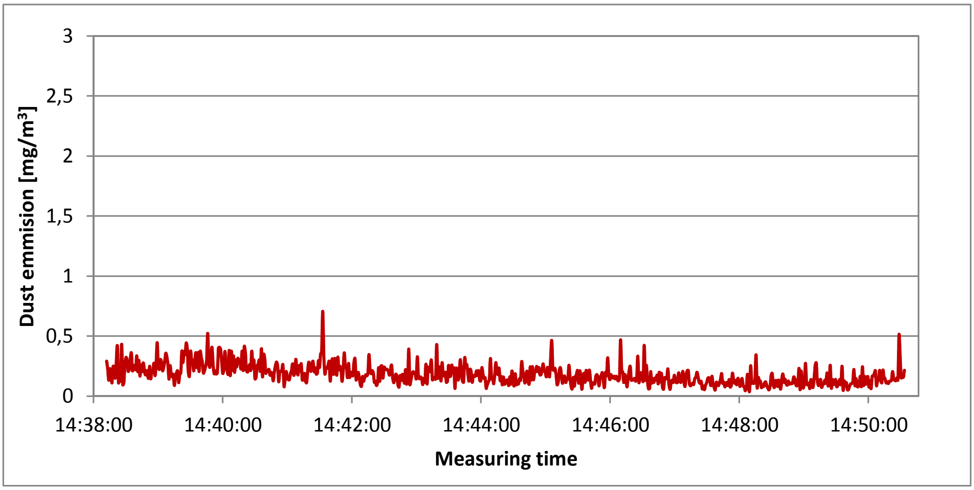

Fig. 8. Background dust emission

TABLE 4

Values of dust emissions for the roller press

HPGR operating pressure [N/mm^2]	**Average dust emission (with background) [mg/m^3]**	**Standard deviation**	**Average dust emission (without background) [mg/m^3]**
0 (background)	0.18	0.08	N/A
3.5	3.9	0.82	3.72
4.0	4.8	1.04	3.82
4.5	6.1	1.17	4.72

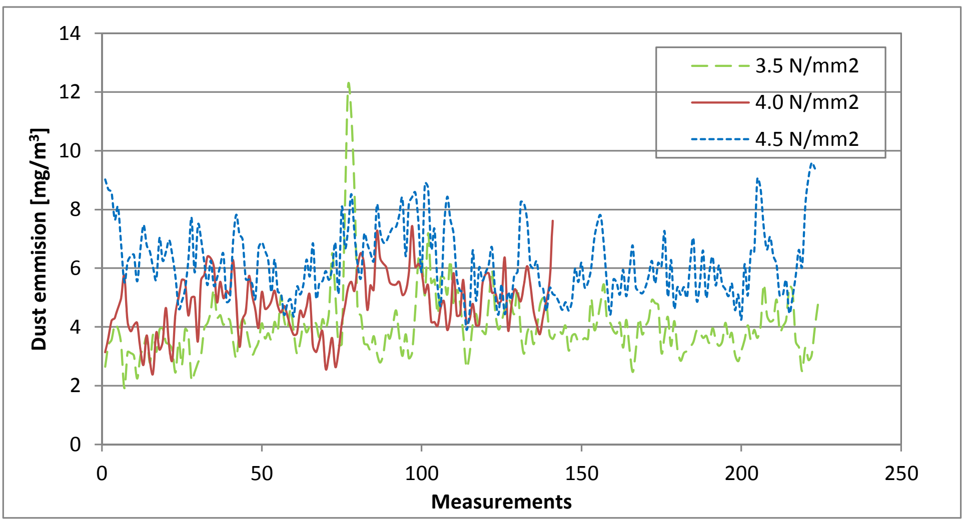

Fig. 8. Results of dust emission for HPGR operating at various pressure values

background dust emission was increased, due to the dust remains after the previous test. This new background emission was also measured and it equaled 0.8 mg/m^3 after first test and 1.2 mg/m^3 after the second one. Considering these values (last column in Table 4) it can be stated, that it is rather difficult to say clearly whether the operating pressure influences significantly on the dust emission. Values for operating pressure 3.5 and 4.0 N/mm^2 are similar, additionally the standard deviations for these measurements are high, what may indicate that differences between individual dust emissions can be insignificant. However, for the highest value of operating pressure (4.5 N/mm^2) the difference is significant on the accepted significance level $\alpha = 0.05$. However, further and more detailed investigations within this matter are recommended to determine some more clear relationships or models.

4. Summary

The aim of the paper was to show the potential benefits of HRC device operation in copper ore processing circuits. Investigative programme was carried out for sulphide copper ores, which occur in Poland. The obtained results show that utilization of HRC press in copper ore comminution operations may provide a measurable effect resulting from lowering the Bond's work index value. What is more, the Bond's index is closely correlated with operating pressure value, and the shape of this relationship is close to the third degree polynomial (significant decrease for lowest operating pressure, then a kind of stabilization, finally further decrease for highest values of operating pressure. There was also observed a more intense generation of finest particle size fractions during the ball mill grinding processes. HRC product characterize themselves in higher values of comminution degrees values S_x. It was also connected with shorter grinding time, due to the more intensive breakage of particles in the mill. This is also the result of the micro-crack formation during the high-pressure comminution process. Finally HRC devices influenced the higher flotation recoveries, while environmental impact of high-pressure technology can be to a some extend correlated with operational pressure value.

A good supplement of the above investigation would be a comparison of other alternative size reduction operations, in order to determine the most effective ore crushing method. The other option is to test the effectiveness of various downstream grinding technologies, like electromagnetic grinding. The suitable tests are under evaluation and the results will be a subject of separate publication.

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