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INFLUENCE OF COPPER ORE COMMINUTION IN HPGR ON DOWNSTREAM MINERALLURGICAL PROCESSES

Crushing processes taking place in high-pressure grinding rolls devices (HPGR) are currently one of the most efficient methods of hard ore size reduction in terms of the energy consumption. The HPGR products are characterized by a fine particle size and the micro-cracks formation in individual particles, which appears in downstream grinding processes, decreasing their energy consumption. The purpose of the paper was to analyze the effectiveness of a ball mill grinding process and flotation operations depending on the changeable conditions of run of the HPGR crushing process. The research programme carried out included crushing tests in the laboratory scale HPGR device at various settings of the operating pressure volume and selected qualitative properties of the feed material (i.e. particle size distribution).

On the basis of obtained results the models, defining the grinding process effectiveness as a function of changeable conditions of HPGR process run, were determined. Based on these models the optimal grinding time in a ball mill was specified which is, in turn, the basis for optimization of operation the technological comminution circuits for a given material type. The obtained results proved that the application of HPGR devices in given copper ore comminution circuit may improve the effectiveness of downstream grinding process what leads to improvement of the entire circuit work efficiency through decreasing the process energy consumption and enhancing the product size reduction.

Keywords: copper ore beneficiation, comminution, HPGR technology

1. Introduction

The crushing technology based on HPGR presses application is currently one of the most efficient methods of hard ore comminution from the scope of the energy consumption, and the development of HPGR applications in ore preparation circuits is presently the world trend. A significant energy savings can be obtained by application the HPGR devices on secondary or tertiary crushing stages instead of conventional crushers or by combining the roller press with a ball mill. In such a circuit, the value of Bond's work index in grinding operations for HPGR products can be lower from 20-30% (see also section 3.2. below). Tumble mills, operating on a grinding stage after the HPGR device, usually utilize less energy due to the high crushing efficiency of HPGR, what is also the result of a finer feed for the ball mill [5]. The circuit's energy consumption is lower as a result of moving back the particle breakage process intensity from the downstream grinding (ball mill) to upstream crushing (HPGR) stage. HPGR's are also very efficient devices from the scope of the particle size distribution of crushed product. In roller presses the most favourable mass recovery of product fraction size (0.1-1.0 mm) [1] can be obtained, comparing to conventional crushing devices. It is very desirable feature of product not only in ore processing industry (limitation of material over-grinding phenomenon) but also in a limestone powder production, used as fillers in plaster mass production.

Amongst main benefits of HPGR application, apart from the energy savings [6,13,14], following should be mentioned: high process efficiency due to the greater comminution effect and relatively low operating costs [11], positive influence on higher effectiveness of downstream beneficiation processes [4,8,17], relatively small footprints, stable throughput, low noise and dust emissions comparing to conventional crushing devices [15]. While technological and energetic effects of HPGR operation were widely covered in literature [10-12], there are reasonably small number of publication concerning the environmental impact of HPGR work. Results of investigations within this scope, are also presented in the paper.

1.1. Literature review

Many works draw attention to the potential benefits of HPGR units applications in downstream grinding processes as well as upgrading operations like flotation or leaching. According to various investigations HPGR products need less time for downstream ball mill grinding process in order to reach a desired particle size composition, comparing to conventional

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crushing devices [9,16] There are also more intense increases in yields of finest particle size fraction for HPGR products at the beginning stage of grinding process. This effect results from a better liberation of useful minerals, which takes part during the high-pressure comminution. This generally leads to increasing the recovery of useful mineral in concentrate, and the effect can be enhanced when the fully liberated particles will be earlier discharged from the mill.

Some works [2,18] show that effects of downstream upgrading processes can be improved by adjusting the value of HPGR operating pressure. Too low pressure causes insufficient mineral liberation which result in lower concentrates recovery, while too high pressure values may leads to the overgrinding phenomenon, which reflects in increased grade of useful mineral in tail and, as a result, the higher paymetal loss. This is presented in Fig. 1.

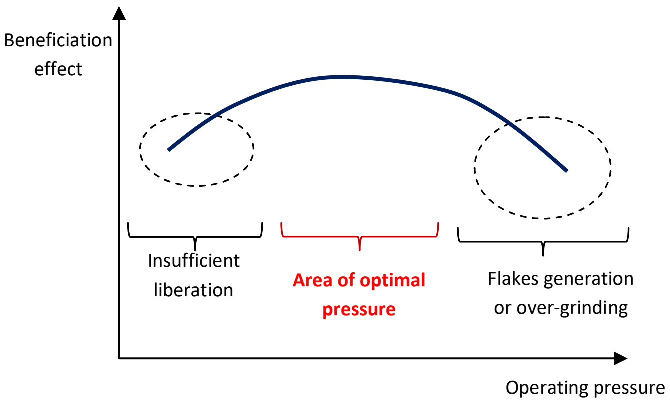

Fig. 1. Parabolic relationship between the operating pressure and beneficiation effect

Considering the above, it might be reasonable to test the relationship between main operating parameters of HPGR and potential benefits in downstream technological operations of grinding. These relationship would be the basis for possible control of HPGR operation leading towards optimization of entire comminution circuit.

2. Methodology and research programme

All tests were conducted in a laboratory HPGR unit with roll diameter 200 mm and the width 100 mm. The feed material for comminution tests was a sulphide copper ore, consisted of three lithological types: sandstones (47%), carbonates (42%) and slates (11%). The material consisted of following main cupriferous minerals: chalcocite 67%, bornite 9% and chalcopyrite 4%. Particle size composition of the feed material was presented in Fig. 2.

In the first stage of the research programme, the grinding kinetics for the material crushed under various operating pressure of HPGR, was investigated. Four identical samples of ore were crushed under four different values of operating pressing force: 4 kN, 6 kN, 8 kN and 10 kN, what corresponds to 2 N/mm^2, 3 N/mm^2, 4 N/mm^2 and 5 N/mm^2, respectively. Roll speed

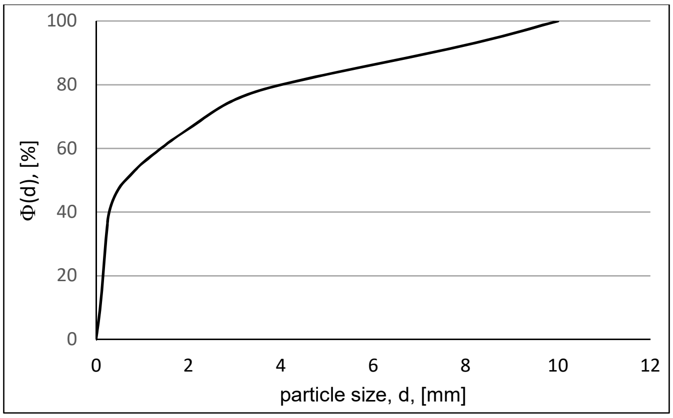

Fig. 2. Particle size composition of HPGR feed material

value was 0.4 m/s and was constant for each single test. Bond's working index value was determined for each sample [3], and five analyses were performed in total (one for the feed and four for HPGR products). Each HPGR product was then subjected to dry ball mill grinding process in a standard Bond's ball mill (305 mm × 305 mm),with 20.1 kg of grinding media (steel balls) and 1 kg of feed material. Grinding media diameter has ranged from 15.2 to 38.1 mm. For each single grinding test, the particle size distributions of grinding product were performed after 1, 2, 4, 6, 10 and 15 minutes of grinding.

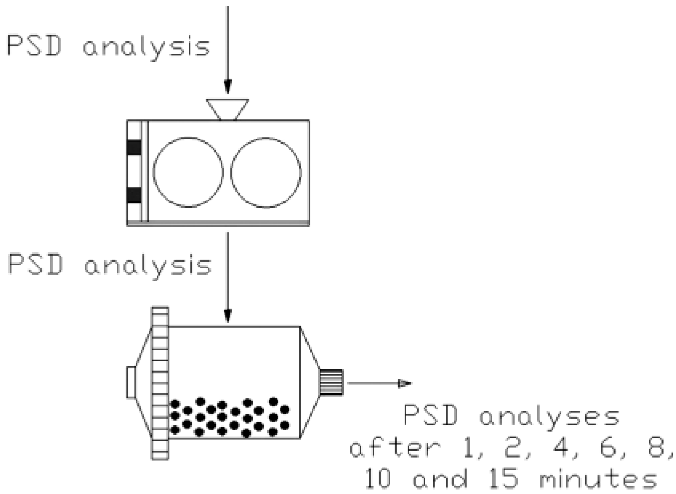

Fig. 3. Scheme of investigative programme

Product from each test of ball mill grinding were then subjected to flotation tests, which are regarded as a supplementary analyses and the verification of potential benefits in useful mineral recovery. Flotation feed was the ball mill grinding product and flotation analyses were carried out using the fractional flotation method with a single cleaning of flotation concentrates and the suspended particle matter density amounted to 1250 g/dm^3. Flotation tests were performed with using laboratory device Denver D 12 with cell volume 2.5 dm^3 for main flotation test and 1.5 dm^3 for cleaning the concentrate. In each flotation step a collector's 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 scheme was presented in Fig. 4. Symbol "O" means final tails, Pp1 – intergrowths of copper and gangue from the cleaning stage, while Pp2 – intergrowths of copper and gangue from fractioned flotation. Concentrates (fractions) K1 to K4 were collected after following time periods: K1 – 2 minutes, K2 – 5 minutes, K3 – 10 minutes and K4 – 15 minutes of flotation. Each fraction has various copper grade and the final value is an average from each concentrates K1 to K4.

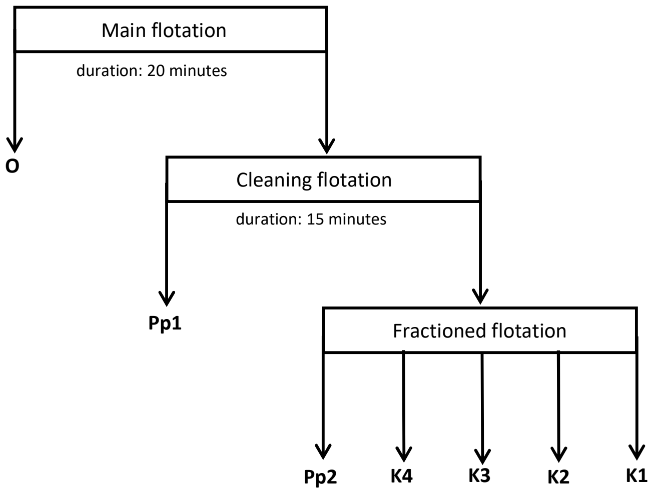

Fig. 4. Scheme of flotation tests

Dust emission during each (crushing and grinding) test was also registered in order to investigate potential relationship between operating pressure value and dust emission degree.

3. Results and discussion

Potential benefits were analysed in terms of grinding effectiveness and potential energy savings. Additionally the effect of flotation together with selected environmental impacts defined as dust emission, were under investigations.

3.1. Analysis of grinding effect

Figures 5 and 6 present exemplary particle size distributions of grinding products after one and fifteen minutes of grinding, respectively.

Analyzing the results it can be seen that during the first and second minute of grinding the most favourable size reduction was observed for HPGR product crushed under 10 kN pressing force. Together with increasing the grinding time, the HPGR product at 6 kN appeared to be the finest. Comparing the results obtained after longer grinding time we can also see that rather insignificant changes in particle size distribution of individual HPGR products were observed. It may indicate that further grinding process is of a reasonably lower effectiveness as its kinetics decreases.

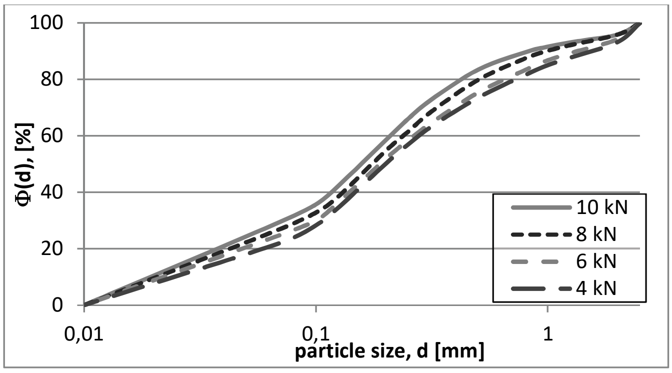

Fig. 5. Particle size distribution curves for products after one minute grinding time

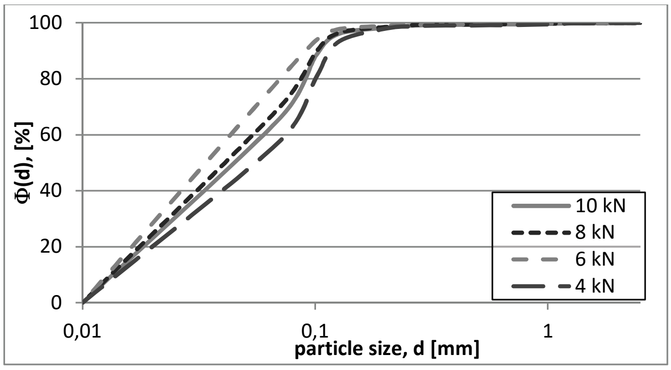

Fig. 6. Particle size distribution curves for products after fifteen minutes of grinding

However, it needs to be pointed out, that the HPGR products comminuted under various operating pressures have different particle size distribution, therefore analysis of grinding kinetics might be incomplete to a some extend. It results from the fact, that each ball mill feed has various particle size characteristics, thus if each ball mill feed varies in terms of particle size composition, the results of grinding of four samples may not be fully comparable. There is, however, a method to overcome this problem, namely a comparative analysis of size reduction ratios of each product of comminution. In the next stage of analysis the comminution degrees S_{50}, S_{80} and S_{90} were calculated and compared. Comminution degree is here understood as a relationship of particle size of feed (D) to particle size product (d):

$$S_x = \frac{D_x}{d_x} \tag{1}$$

where x denotes the characteristic particle, i.e. average – 50% (d_{50} and D_{50}), 80% (d_{80} and D_{80}) or 95% (d_{95} and D_{95}). Referring to these values we can talk about average comminution degree (S_{50}), eighty per cent comminution degree (S_{80}) or maximum comminution degree, respectively. Suitable results are presented in Fig. 7 (S_{50} – average comminution degree) and Fig. 8 (S_{80} – eighty per cent comminution degree).

Analyzing the Figs. 7,8 it can be observed that for grinding time below 4 minutes the highest comminution ratios were obtained for the pressing force 10 kN. This may results from

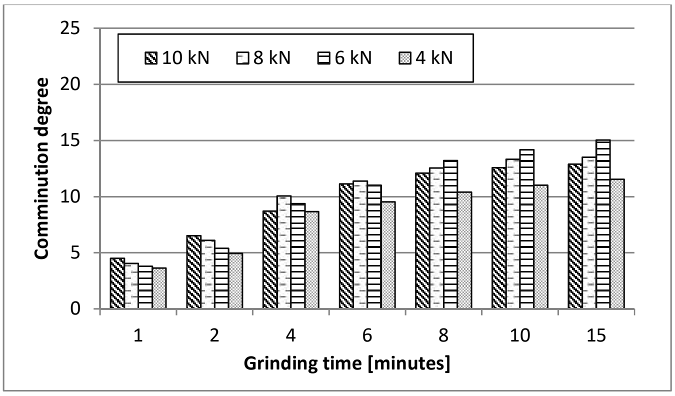

Fig. 7. Average comminution ratios for ball mill products after certain grinding time

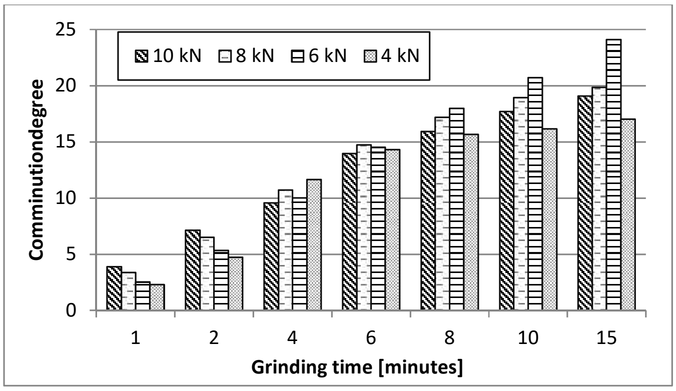

Fig. 8. Eighty per cent comminution ratios for ball mill products after certain grinding time

de-agglomeration of material flakes. The flakes formation is the more intense for higher values of operating pressure and these conglomerates are disintegrated rather at the early stage of grinding. However, the highest pressure does not produce the most favourable comminution ratios after 10 and 15 minutes of grinding. The material under investigation shows the highest comminution ratio for average pressing force (6 kN). For this case it is rather uneconomically to treat the ore with higher pressure.

3.2. Energetic aspects-possible energy savings

One of the main benefits of application the HPGR devices into ore comminution circuits are potential energy savings, which can be measured through Bond's work index values (W_i). For each HPGR product Bond's values were determined, and the results are presented in Figure below (W_i value for HPGR feed was 14.1 kWh/Mg):

Analyzing the results presented in Fig. 9 it can be seen that considerable reduction in Bond index value were obtained. Savings reached from 20 to as high as 30% of Bond values for HPGR product crushed at 10 kN. It can be also noticed that reduction does not increases together with increasing the HPGR pressing force in consecutive tests. Bond values for highest forces (8 and 10 kN) are very similar, what may indicate increasing of HPGR operating force above that value has relatively low influence on further decreasing of Bond index value. The real savings of energy consumption in grinding process can be calculated from the formula developed by Bond [3]:

$$W = 10W_i\left(\frac{1}{\sqrt{d_{80}}} - \frac{1}{\sqrt{D_{80}}}\right) \text{ [kWh/Mg]} \qquad (2)$$

where:

W_i – Bond's work index value [kWh/Mg],
D_{80} – eighty percent particle for feed [mm],
d_{80} – eighty percent particle for grinding product [mm].

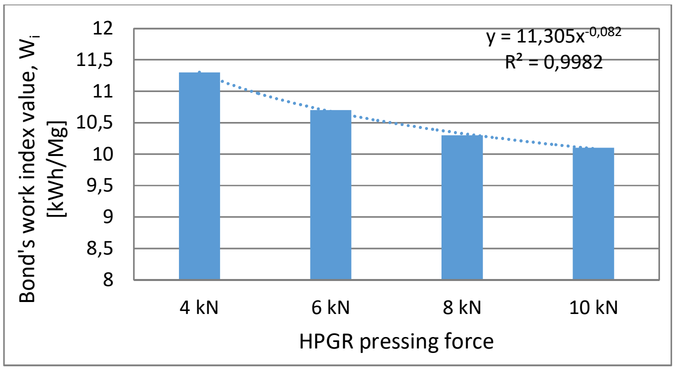

Fig. 9. Bond's work index value for HPGR products crushed at various operating pressure

If we assume certain values of d_{80} and D_{80} (i.e. d_{80} = 1 mm, D_{80} = 3 mm), then we can expect the following percentage decrease in energy consumption for HPGR products, calculated according to formula (2) (Table 1).

TABLE 1

Percentage decrease of grinding energy consumption for HPGR products

No HPGR (base case)	HPGR, 4 kN	HPGR, 6 kN	HPGR, 8 kN	HPGR, 10 kN
100%	80.1%	75.9%	73.0%	71.7%

3.3. Effect of flotation

In order to verify an influence of HPGR operating conditions on beneficiation results, each sample has been subjected to flotation test. As it was mentioned earlier, the flotation feed was the ball mill product after 15 minutes of grinding and fractional flotation method with a single cleaning of flotation concentrate was applied. Characteristics of flotation concentrates have been presented in Table 2, where b denotes concentrate grade, ε — concentrate recovery and ϑ — copper content in tails.

Analyzing the results of flotation tests it can be noticed, that the lowest losses of copper in tails (ϑ) were obtained for HPGR pressing force 6 kN and 8 kN. At the same time the most favorable value of flotation recovery (ε) was obtained for the pressing force 6 kN: 86.4%. The obtained results confirm, that

TABLE 2

Results of flotation for HPGR products crushed under various operating pressure (β – concentrate grade, ε – concentrate recovery, J – copper content in tails)

HPGR pressing force, [kN]	Flotation results		
	ϑ [%]	β [%]	ε [%]
4	0.23	13.6	78.3
6	0.19	13.5	86.4
8	0.20	13.9	84.9
10	0.21	14.7	78.8

various operating condition of HPGR might result in different levels of copper recovery in flotation operations. Comparing the obtained values of flotation recovery with the HPGR pressing force it might indicate the operator what level of operational parameters should be set in order to maximize the effects in terms of flotation recoveries. Figure 10 presents values of flotation recoveries obtained for HPGR product comminuted under various values of pressing force. Analyzing the results it can be stated that for this case an optimal value of pressing force in terms of maximization the flotation effectiveness, should be around 6 kN.

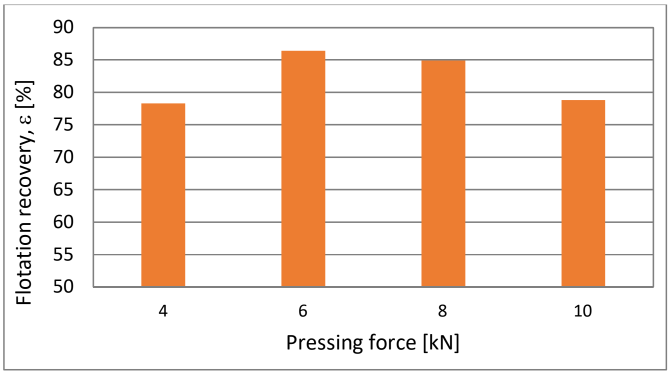

Fig. 10. Values of flotation recovery for specific HPGR pressing force

The results presented in this figure are convergent with the Figure 1. We can observe a range of operating pressing force for which the beneficiation results are the most favorable. Too high or too low HPGR pressure leads to decreasing the effectiveness of flotation, what results in lowering of overall metallurgical efficiency.

3.4. Dust emission analysis

During the experimental programme also an environmental effect of HPGR was investigated. For each single test a dust emission level was recorded with using the particle dust analyzer **Casella.** Prior to measurements it was determined a dust emission in the laboratory, when no equipment was operating (so-called background level). The results are presented in Figure 11. It can be seen that average level of dust emission is around 0.1-0.2 mg/m^3. Values of dust emission for each single test, together with standard deviations, are presented in Table 3.

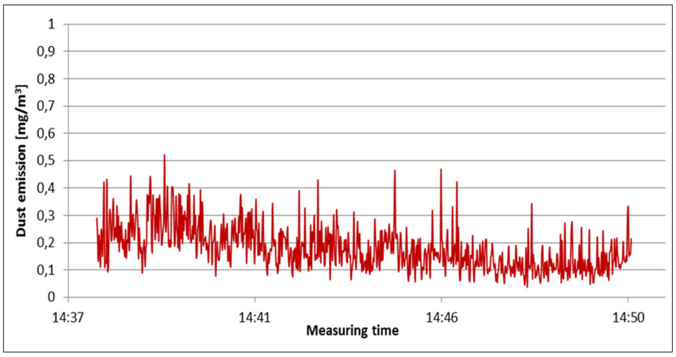

Fig. 11. Dust emission for the background in laboratory conditions

TABLE 3

Average values and standard deviations of dust emissions for HPGR tests

HPGR pressing force, [kN]	Average dust emission [mg/m^3]	Standard deviation
4	3.93	0.922
6	4.74	0.884
8	5.28	1.482
10	5.21	1.249

Results show that it is difficult to say clearly whether the operating pressure influences significantly on the dust emission. Values for pressing force 8 and 10 kN are very similar, additionally the standard deviations for all measurements were high, what may indicate that differences between individual dust emissions can be insignificant (especially for higher values of HPGR pressing force). However, further investigations within this matter are necessary to determine some more clear relationships or models.

3.5. General assessment of results

Figure 12 summarizes overall beneficiation effectiveness for exemplary technological circuit, consisted of two crucial parts: size reduction operations (HPGR and ball mill) and separation ones (flotation). Based on literature review and results of investigations presented in the paper, the course of that relationship is close to the one, presented in Fig. 12, where: F_{sp} – specific pressure in HPGR, [N/mm^2].

The shape of total effect (black solid line, thick), measured by useful mineral recovery, is convergent with the shape of relationship presented in Fig. 1, what confirms the validity of the assumptions presented in first section of the paper. This course was determined as a cumulative effect of HPGR and beneficiation operations effectiveness, described below.

The effect of HPGR, understood as comminution effectiveness (red solid line, thin), increases, but after passing a certain value of operating pressure, comminution degree gains are lower. This was confirmed in Figs. 7,8, and indirectly in Fig. 9. This is also convergent with idea of comminution process course – increase of breakage factor results in more intense material

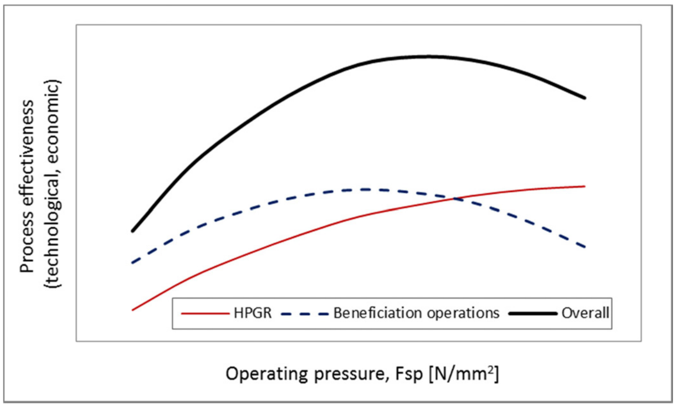

Fig. 12. Possible technological and economic effects from the scope of HPGR-mill circuit

disintegration, but after a certain point these increases are lower and lower. Therefore dynamics of the process decreases. The different situation can be observed for flotation process. Too intensive disintegration results in decreasing an effectiveness of beneficiation, mainly (but not only) due to material overgrinding. Therefore the course of the blue dashed line, reflecting the relationship of beneficiation process to the value of HPGR operating pressure, shows decreasing in effectiveness of these operations, together with excessive increasing of operating pressure value. This course was confirmed in Fig. 10, where results of flotation effectiveness are lower for the highest values of HPGR operating pressure.

4. Conclusions

The results of investigations presented in the paper show that the HPGR operating pressure significantly influences the effectiveness of downstream grinding and beneficiation operations. Apart from that, the operating pressure value influences effectiveness of downstream beneficiation operations (flotation) while intensity of dust emission can be considered as not related significantly to the value of pressure. At the same time it also shows that potential benefits of the roller press application into technological circuit of mineral processing should be considered from the scope of a multi stage comminution circuit as a whole, than from the point of view only a single HPGR device operation. Illustration of this relationship (operational pressure – overall effect) was presented in Fig. 12, which reflects to both technological (characterized through comminution ratio) and economic (considered as the energy consumption) effects of HPGR-based comminution circuit.

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