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AN ASSESSMENT OF INFLUENCE OF SELECTED CHARACTERISTICS OF FEED ON THE RESULTS OF BALL MILL GRINDING PROCESS COURSE FOR POLISH COPPER ORES

OCENA WPŁYWU WYBRANYCH CHARAKTERYSTYK NADAWY NA WYNIKI PROCESU MIELENIA W MŁYNIE KULOWYM DLA POLSKICH RUD MIEDZI

The article concerns issues related to the copper ore ball mill grinding process, operating at different technological parameters. The aim of the study was to investigate the influence of various operating parameters and feed characteristics on selected technological effects (comminution degree, yields of the finest particle size classes, ready for downstream flotation operations).

The research program included grinding tests of two lithological types of Polish copper ore (dolomite and sandstone) and their mixtures in the proportions: 70% dolomite +30% sandstone and 30% dolomite +70% sandstone. Material was treated under wet and dry grinding in Bond's ball mill. Three different grinding time were applied together with three levels of mill's rotational speed. The feed material with three different particle size compositions was used in the rests.

The results show that increases in yields of fine particle size fractions for each sample are dependent on the particle size composition of feed, grinding time and rotational speed of mill. Together with increasing of grinding time, fine particle size fraction contents increase too, especially for the coarse feed without fine particles. In general, higher comminution degrees were obtained for ore mixtures, the most favorable results for a mixture of 30% sandstone +70% dolomite, where S_{50} equaled 358 and S_{90} = 178. Correlation analysis showed that in fact all technological parameters under investigation were significantly related to the obtained comminution effectiveness.

Keyword: comminution, copper ore, ball mill operation

Artykuł dotyczy zagadnień związanych z badaniem procesu mielenia rud miedzi w młynach kulowych, pracujących przy różnych parametrach technologicznych. Celem pracy było zbadanie wpływu poszczególnych parametrów pracy młyna oraz charakterystyk nadawy na uzyskiwane wybrane efekty

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technologiczne (stopień rozdrobnienia, wychody klas najdrobniejszych zdolnych do flotacji). Program badawczy obejmował przemiały dwóch typów litologicznych nadawy (dolomit i piaskowiec) oraz ich mieszanek w proporcjach 70% dolomitu +30% piaskowca oraz 30% dolomitu +70% piaskowca, mielonych na sucho i mokro w laboratoryjnym młynku kulowym Bonda. Przemiały były prowadzone dla trzech różnych czasów mielenia oraz trzech prędkości obrotowych młyna, dla nadawy o trzech różnych zakresach uziarnienia.

Wyniki badań wskazują, że przyrosty wychodów drobnych klas ziarnowych poszczególnych próbek są uzależnione od składu ziarnowego nadawy, czasu mielenia i prędkości obrotowej młyna. Wraz ze wzrostem czasu mielenia wzrastają udziały klas ziarnowych zwłaszcza w nadawie (gruboziarnistej) pozbawionej drobnych ziaren. Generalnie wyższe wartości stopni rozdrobnienia uzyskano dla mieszanek rudy 30% piaskowca +70% dolomitu (S50 = 358 i S90 = 178).

Wykonana analiza korelacji wskazuje na wysoki wpływ wszystkich analizowanych parametrów technologicznych procesu na uzyskiwaną efektywność rozdrobnienia rudy.

Słowa klucze: rozdrabnianie, rudy miedzi, mielenie w młynach kulowych

1. Introduction

Grinding is the primary operation in many types of raw material processing circuits, both in ore treatment, and in aggregates production. It's main role in ore processing industry is to reduce the size of material particles and to liberate the grains of useful mineral from the gangue rock. It is especially significant for those ores that are being upgraded by means of downstream flotation processes. Processes of ore preparation for flotation include operations of multi-stage grinding and classification, which usually operate in closed circuits in tumble ball or rod mills, as well as in SAG and AG ones. In example, for Polish conditions of copper ore processing, technological circuits of mechanical processing include grinding operations in in ball and rod mills. Average particle size of grinding products, being at the same time the feed for flotation processes, should be within the range 0.02 to 0.07 mm, which provides achievement of suitably high values of copper recoveries (Potulska, 2008).

In general, the efficiency of the ball mill operation is determined by a large number of variables, which impact on the results is diverse. These variables can be divided into several groups, related to the type of material, construction parameters of the grinding device, and the method of process course. On the other hand, the energy consumption is regarded as one of key indicators of grinding progress assessment. Grinding operations are very energy-intensive and the amount of energy required for the proper comminution of ore mainly depends on: lithological and petrographic characteristics and contents of various of lithological types in the feed material (shales, dolomites and sandstones); physical and mechanical properties of material (particle size, density, ore-water ratio); types of machinery and equipment applied in the process; and finally the conditions of technological processes course (grinding time, the number of crushing stages, amount and types of grinding media, frequency of mill's rotation, etc.) (Naziemiec et al., 2017; Kasińska-Pilut, 2008, 2014; Gawenda, 2013; Foszcz & Gawenda, 2012; Tumidajski et al., 2010; Trybalski & Krawczykowski, 2005).

Results of numerous research (Wills & Napier-Munn, 2006; Lowrison, 1974; Potulska, 2008) confirm that achievement of an adequate particle size distribution in grinding operations, together with the high level of useful minerals liberation entirely determines effectiveness of downstream flotation processes course and high values of metal recoveries. Significant role within this issue plays the time of residence of the material in the mill's chamber. Too long grinding may lead to the ore overgrinding, which is an unfavorable phenomenon, due to increasing the content of very fine particles, with low floatability properties (Łuszczkiewicz & Wieniewski, 2006). In order to limit this unfavorable phenomenon, flotation processes in the grinding circuit can be applied. The purpose of such solution is to collect the completely liberated particles of useful components and to direct them to the final concentrate. This solution positively influences on increasing an effectiveness of flotation operations and improves an overall efficiency of technological beneficiation process.

Considering the above aspects, the main purpose of the paper is to estimate the influence of selected operating parameters of the grinding process on its effectiveness, measured through yields and size of fine particles in grinding products (i.e. an average particle size, 80% and maximum particle size).

2. Materials and methods

All tests were conducted in a laboratory Bond's ball mill, with dimensions 305×305 mm (Fig. 1 a and b). The mill has operated under the conditions accepted for determination the value of Bond's work index: the weight of balls was 20.1 kg, number of balls: 285, ball diameter ranged from 15 to 38 mm.


a)


b)

Fig. 1. Grinding device applied for tests: a) Bond's ball mill, b) grinding media and ore inside the mill (*photo:* T. Gawenda)

TABLE 1

Chemical and mineralogical characteristics of the feed material

Chemical component	**Percentage/[g/Mg] content**	
	Dolomite	**Sandstone**
1	**2**	**3**
Cu	1,31	1,71
C organic	0,54	0,2
Pb	0,265	0,029
Na_2O	0,27	0,41
CaO	24,08	8,24

1	2	3
Al_2O_3	5,25	3,87
Fe_2O_3	0,785	0,53
K_2O	1,115	1,187
MgO	11,36	1,79
S	0,73	0,74
Zn	0,06	0,015
Ag [g/Mg]	122	29
Ni [g/Mg]	169	36
Co [g/Mg]	114,5	21
Mo [g/Mg]	142,5	7
V [g/Mg]	662	48

Two lithologic types of copper ore: sandstone and dolomite, were used in tests. Shale, the third lithologic component of this ore was not tested, due to its lowest content in the run-of-mine (approx. 10%). Additionally, industrial practice along with literature review (Piestrzyński (ed.), 2008; Konopacka & Zagożdżon, 2014) show that it does not constitute significant problems in grinding operations and do not interfere the process of joint comminution of the three lithologic types. Chemical and mineralogical characteristics of the two lithological types under investigation, was presented in Table 1.

For the reason that Bond's index value W_i is very useful in assessment of energy consumption and grindability properties for the comminuted material, as well as in evaluation of its physical and mechanical properties, these indices were also determined (Table 2) according to the formula (Bond, 1952):

$$W_i = 1.1 \frac{44.5}{P_i^{0.23} G^{0.82} \left(\frac{10}{P^{0.5}} - \frac{10}{F^{0.5}} \right)}, \left[\frac{\text{kWh}}{\text{Mg}} \right] \tag{1}$$

where:

- W_i — Bond index value,
- P_i — sieve size used in test [microns],
- G — ball mill grindability [g/rev],
- P — product 80% passing size [microns],
- F — feed 80% passing size [microns].

TABLE 2

Values of Bond's working indices for sandstone and dolomite

Lithological type of ore	**Bond's working index W_i [kWh/Mg]**
Sandstone	17,0
Dolomite	9,8

On the basis of these results it can be especially possible to calculate the amount of energy W, required for grinding the feed in a ball (rod) mill to the desired particle size. It is also possible to assess the grinding process of either the ore, or the particular lithological ore types, in a laboratory drum mill. Evaluation of that grinding effectiveness depends on the operating variables of the mill. Therefore the value of Bond's index (W_i) shows, how much energy (W) is required for comminution of the feed material with particle size D, to the product with particle size d:

$$W = W_i \left(\frac{10}{P^{0.5}} - \frac{10}{F^{0.5}} \right), \left[\frac{\text{kWh}}{\text{Mg}} \right] \quad (2)$$

where:

W — energy required [kWh/short tonne],
W_i, P, F — denotations given in formula (1).

Investigative programme included testing of following parameters: lithologic characteristics of material, particle size composition, different grinding times and various rotational speed of the mill.

a) Lithological type of feed. Two types were grinding separately, but there were also composed two mixtures in proportions: 70% of dolomite and 30% of sandstone (mixture I), and 30% of dolomite and 70% of sandstone (mixture II). The accepted proportions in mixtures reflect the plant operating conditions in grinding of dolomitic and sandstone ores in two technological circuits. As a result of the above, four types of material were tested under this point: dolomite (D), sandstone (S), 70% dolomite (D) +30% sandstone (S), 30% dolomite (D) +70% sandstone (S);
b) Particle size composition of feed. Three different types of samples were prepared accordingly. The idea was to test the influence of finest particles in each type of material on grinding effectiveness, the problem is significant especially for the mixtures of sandstone and dolomite:
   - Sample I (particle size 2-10 mm without finest particles),
   - Sample II particle size 0-10 mm with uniform composition of particle size fractions),
   - Sample III (particle size 0-10 mm with increased content of fine particles below 2 mm);
c) Rotational speed of mill. The results show (Lowrison, 1974), that the ball mills in ore processing circuits operate within the range of 75-85% of critical revolutions (Box, 1976). The experimental programme included testing an extended range of the mill's critical speed from 70 to 90%: speed I (90%), speed II (80%) and speed III (90%).

Grinding time. Three different durations of grinding were accepted, based on experience of the authors: 5 minutes, 15 minutes and 25 minutes

The grinding process has been assessed from three scopes:

- particle sizes of feed and products,
- yields of fine particle size fractions below 250, 100, 71 and 45 μm,
- average and maximum comminution degrees,
- values of Bond's working indices.

Granulometric sieve analyses and laser diffraction method were used to particle size of respective grinding products. The laser diffraction method was applied for the reason that results of sieve analysis for sieves with d_T lower than 0.25 mm were not repeatable, especially for changeable moisture content of material. Table 3 shows scheme of investigative programme.

TABLE 3

Values of feed characteristics and operational parameters, used in experimental programme

Lithological type of feed	Rotational speed, [1/min / percent of crit. speed]			Grinding time [minutes]			Particle size composition of feed [mm]		
	70/90	63/80	55/70	5	15	25	2-10 (I)	0-10 (II)	0-10 (III)
Dolomite(D)	x	x	x	x	x	x	x	x	x
Sandstone (S)	x	x			x		x	x	x
D 70% + S 30%	x	x			x		x	x	x
D 30% + S 70%	x	x			x		x	x	x

3. Results and discussion

Forty five single grinding tests were carried out in total within the investigative programme. The results were presented in Tables 4-7. Each grinding product was then subjected to size analysis, in order to determine yield values for the three finest size fractions: below 100, 71 and 45 microns. Along with the yields there were calculated respective comminution degrees: S_{50}, S_{80} and S_{90} (fifty, eighty and ninety per cent comminution degrees), according to formula:

$$S_x = \frac{D_x}{d_x} \tag{3}$$

where:

- S_x — particular comminution degree (i.e. S_{50} – average/fifty per cent comminution degree)
- D_x — characteristic particle for feed material (i.e. D_{50} – fifty per cent passing size of feed),
- d_x — characteristic particle for feed material (i.e. d_{50} – fifty per cent passing size of product).

TABLE 4

The obtained results for sandstone feed (S)

Rotational speed	Grinding time	Particle size	Yield of individual size fraction, [%]			Characteristic particle (d_x) and comminution degree (S_x)					
			<0.100	<0.071	<0.045	D50	d50	S50	D90	d90	S90
70/90	15	I	92.2	82.9	69.3	4.30	0.022	196.3	7.3	0.087	84.1
70/90	15	II	89.2	81.0	67.6	3.65	0.021	173.0	7.2	0.084	85.7
70/90	15	III	83.2	76.3	64.2	1.70	0.021	80.6	6.1	0.084	72.4
63/80	15	I	91.7	81.6	66.9	4.30	0.024	179.2	7.3	0.092	79.3
63/80	15	II	88.9	79.9	65.7	3.65	0.024	155.3	7.2	0.087	82.9
63/80	15	III	80.1	71.5	59.1	1.70	0.024	71.1	6.1	0.098	62.4

TABLE 5

The obtained results for dolomite feed (D)

Rotational speed	Grinding time	Particle size	Yield of individual size fraction, [%]				Characteristic particle (d_x) and comminution degree (S_x)					
			<0.25	<0.100	<0.071	<0.045	D50	d50	S50	D90	d90	S90
70/90	5	I	48.7	44.9	42.5	38.3	4.30	0.26	16.5	7.3	6.30	1.2
70/90	15	I	85.6	83.4	81.2	75.9	4.30	0.13	33.1	7.3	4.00	1.8
70/90	25	I	93.3	93.3	92.7	88.9	4.30	0.11	39.1	7.3	0.23	31.7
70/90	5	II	52.6	49.6	47.1	42.2	3.90	0.18	21.7	7.3	6.40	1.1
70/90	15	II	82.5	82.1	80.5	75.7	3.90	0.12	32.5	7.3	0.50	14.6
70/90	25	II	88.8	88.8	88.5	85.3	3.90	0.11	35.5	7.3	0.23	31.7
70/90	5	III	61.8	57.0	53.9	48.6	1.70	0.14	12.1	6.1	4.65	1.3
70/90	15	III	76.3	76.2	75.0	70.2	1.70	0.12	14.2	6.1	0.24	25.4
70/90	25	III	81.3	81.3	81.1	78.7	1.70	0.11	15.5	6.1	0.21	29.0
63/80	5	I	44.8	41.0	38.8	35.0	4.20	0.95	4.4	7.30	6.30	1.2
63/80	15	I	80.0	79.3	77.5	72.3	4.20	0.14	30.0	7.30	5.00	1.5
63/80	25	I	90.4	90.2	89.2	85.3	4.20	0.11	38.2	7.30	0.25	29.2
63/80	5	II	50.1	46.5	44.1	39.7	3.65	0.20	18.3	7.20	6.30	1.1
63/80	15	II	78.1	78.0	76.8	72.5	3.65	0.11	33.2	7.20	4.80	1.5
63/80	25	II	84.6	84.6	84.0	80.6	3.65	0.11	33.2	7.20	0.25	28.8
63/80	5	III	57.8	52.5	49.6	44.7	1.70	0.11	15.5	6.10	5.45	1.1
63/80	15	III	77.0	77.0	75.8	71.8	1.70	0.11	15.5	6.10	0.25	24.4
63/80	25	III	78.1	78.1	78.1	76.1	1.70	0.11	15.5	6.10	0.25	24.4
55/70	5	I	35.3	32.4	30.8	27.8	4.2	2.60	1.6	7.30	6.45	1.1
55/70	15	I	70.1	69.0	67.2	62.7	4.2	0.16	26.3	7.30	5.90	1.2
55/70	25	I	81.6	81.6	81.3	78.3	4.2	0.13	32.3	7.30	5.00	1.5
55/70	5	II	43.4	39.9	37.6	33.8	3.7	0.25	14.8	7.25	6.60	1.1
55/70	15	II	70.9	68.6	68.8	64.5	3.7	0.14	26.4	7.25	5.50	1.3
55/70	25	II	79.3	79.2	78.9	76.2	3.7	0.12	30.8	7.25	4.40	1.6
55/70	5	III	53.3	47.1	44.2	39.5	1.70	0.16	10.6	6.10	5.50	1.1
55/70	15	III	73.5	73.5	73.1	69.1	1.70	0.11	15.5	6.10	0.50	12.2
55/70	25	III	75.9	75.9	75.8	73.2	1.70	0.11	15.5	6.10	0.25	24.4

TABLE 6

The obtained results for Mixture I (70% dolomite and 30% sandstone)

Rotational speed	Grinding time	Particle size	Yield of individual size fraction, [%]			Characteristic particle (d_x) and comminution degree (S_x)					
			<0.100	<0.071	<0.045	D50	d50	S50	D90	d90	S90
70/90	15	I	100.0	97.9	91.4	4.30	0.012	358.3	7.3	0.042	174.2
70/90	15	II	95.7	94.7	88.9	3.65	0.012	309.3	7.2	0.041	177.8
70/90	15	III	89.5	89.8	84.7	1.70	0.012	145.3	6.1	0.038	160.5
63/80	15	I	99.9	97.7	91.2	4.30	0.013	341.3	7.3	0.042	173.0
63/80	15	II	95.7	94.4	88.4	3.65	0.013	292.0	7.2	0.042	171.8
63/80	15	III	89.3	89.0	83.4	1.70	0.013	136.0	6.1	0.042	145.2

TABLE 7

The obtained results for Mixture II (30% dolomite and 70% sandstone)

Rotational speed	Grinding time	Particle size	Yield of individual size fraction, [%]			Characteristic particle (d_x) and comminution degree (S_x)					
			<0.100	<0.071	<0.045	D50	d50	S50	D90	d90	S90
70/90	15	I	96.8	91.4	80.9	4.30	0.016	267.1	7.3	0.067	109.3
70/90	15	II	92.3	87.6	77.6	3.65	0.016	226.7	7.2	0.067	107.5
70/90	15	III	87.3	84.2	75.3	1.70	0.015	114.1	6.1	0.060	101.3
63/80	15	I	95.3	88.6	76.8	4.30	0.019	232.4	7.3	0.075	97.2
63/80	15	II	90.9	85.5	75.0	3.65	0.018	206.2	7.2	0.074	97.3
63/80	15	III	84.9	80.7	71.0	1.70	0.017	98.8	6.1	0.073	83.6

For each type of the material under investigations, a ball mill Bond's work indices (W_i) along with the ball mill grindabilities per one revolution of mill (G), were determined. Results were presented in Table 8. The grinding susceptibility denotes the weight of particles (in grams) of the material finer than 0.1 mm per one revolution of the mill. The greater the value, the material is of a higher grinding susceptibility, which can be related with the other strength parameters, like the compactness or crushing resistance. As it was mentioned in Section 2 of this article, the Bond's index W_i determines the energy requirements for comminution of 1 Mg of feed material. Knowing the value of Bond index and the characteristic particle of feed (i.e. D_{80}) and the size of the grinding product that we want to obtain (i.e. d_{80}), we can calculate the amount of energy required to spend for comminution of that type of feed in a plant scale, utilizing formula (2) (Tumidajski et al., 2010; Gawenda & Saramak, 2018). The calculated energy consumption can be also analyzed in relation to the achieved values of comminution degrees (Gawenda, 2013, 2015).

TABLE 8

Values of Bond work indices W_i for various lithological types of copper ores and their mixtures, determined with using formula (1)

Lithological type of copper ore	*G* [g/rev]	W_i [kWh/Mg]
Dolomite	2.15	9.40
Sandstone	0.92	18.8
Dolomite (70%) + Sandstone (30%)	1.71	11.3
Sandstone (70 %) + Dolomite (30%)	1.08	16.5

The results presented in Tables 4 to 7 show that the lithological type of feed is associated with the obtained grinding efficiency. In general, the more favorable (higher) comminution degree indices and higher yields of finest particle size fraction were obtained for dolomite and sandstone mixtures. It should be also noted that the efficiency in increases of particle size fractions below 100, 71 and 45 microns were diverse for sandstone and mixtures of sandstone and dolomite. The greatest increases, up to 100%, were reported for mixture II (70% of dolomite and 30% of sandstone), which also means that these lithological types were comminuted the most intensively, due to the high grinding susceptibility of dolomite (Table 8). The sandstone occurs in the copper ore in coarser forms and in general is susceptible to comminution. However, in the final stage of grinding process, when the fineness below 100 μm (71 μm) is required, the sandstone shows the lower grinding susceptibility, which may be related to the size of the crystallized particles of quartzite, which is very hard and abrasive material. Therefore, the values of energy consumption according to Bond indices show high levels of energy consumption, (i.e. 18.8 kWh/Mg for sandstone and 16.5 kWh/Mg for mixture II) and low susceptibility to grinding G (low increase of product finer than 100 μm, measured per 1 revolution of the mill).

Table 9 shows the values of linear correlation (r-Pearson coefficients) between the grinding effectiveness measured through an average (S_{50}) and 90-percent (S_{90}) comminution degree indices and the analyzed operational parameters of mill. The values marked in red are statistically significant at 95% confidence level.

TABLE 9

Values of correlation coefficients between comminution degree and operating parameters of the mill

Operating parameter	S_{50}	S_{90}
Type of feed	0.61	0.60
Mill's revolutions	0.31	0.36
Grinding time	0.62	0.71
Particle size	0.40	-0.27

Analyzing the results presented in Table 9 it can be noticed that in fact all parameters demonstrates significant relationship with the obtained values of comminution degrees. The most significant relationships show the grinding time and lithological type of feed. This is consistent with the observed industrial practice, because the sandstone, to some extent, is being comminuted more easily than dolomite. The results also indicate a relationship between the rotational speed of mill and the grinding effectiveness.

An impact of the yield of finest particle size fractions in individual grinding products and their possible relationship with operational parameters of the ball mill, were also under analysis. The yields in particle size fractions below 71 and 45 microns were taken into consideration and the results are presented in Table 10.

TABLE 10

Values of correlation coefficients between yields of finest particle size fractions
and operating parameters of the mill

Operating parameter	**Yield of particle size fraction:**	
	below 0.071 mm	**below 0.045 mm**
Type of feed	0.37	0.18
Mill's revolutions	0.33	0.29
Grinding time	0.90	0.92
Particle size	0.07	0.05

The values, presented in Table 10, indicates that there is a correlation between the yield of particle size class finer than 71 μm and the three of four tested parameters, but only the grinding time has a significant impact on the yield of product finer than 45 μm. The highest value of correlation coefficient was observed for the grinding time, while it appeared insignificant for the particle size composition of feed. The rotational speed of mill and type of feed, influence on the yield of the fine size class below 71 microns, similarly like the comminution degree value (significant correlation coefficients were marked in red in Table 8). Correlation between the yield of particle size fraction finer than 45 microns and the rotational speed of mill is on the border of statistical significance. This is due to the fact that for this type of material disintegration of finest particles is less effective in dry grinding operations (Lowrison, 1974; Pudło, 1976; Foszcz et al., 2010).

Analyzing the data in Tables 3 and 4 it can be seen that increases of yields in size fractions for individual samples are dependent on the particle size composition of the feed and the grinding time. Together with an increase of the grinding time, yields of particle size fractions increases too, for example, for coarse sample 2-10 mm (sample III) the highest reported values exceeded 93% of yield below 0.1 mm for the grinding time 25 minutes, but most intense grinding was observed for the first 15 minutes of grinding, achieving the growth of 83%. This means that the next 10 minutes of grinding result in a lower increase of the finest size fractions in product, which can be considered as ineffective from the point of view of the process energy consumption. The obtained values of comminution degree S_{50} and S_{90} for this sample were the highest and equaled approximately 39 and 32. With an increase of grinding time, comminution degree and the yield of products increase, too. Exemplary results obtained for dolomite were presented in Fig. 2 and 3.

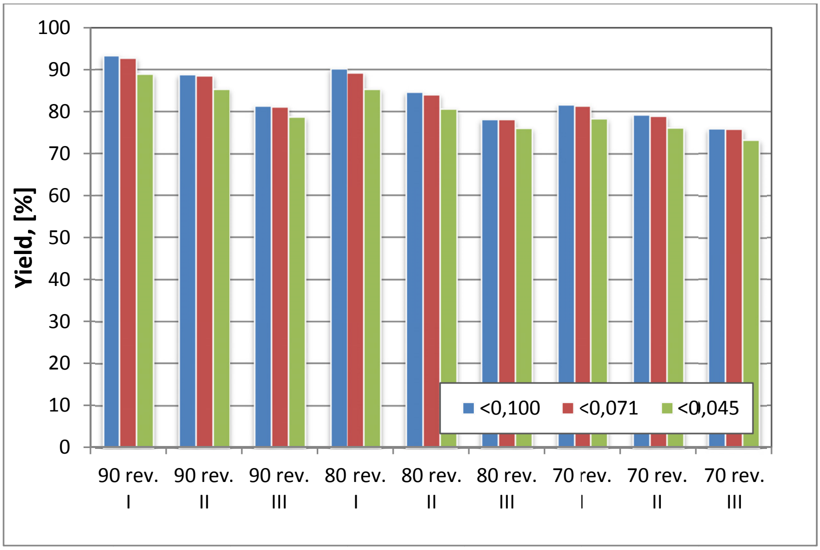

Fig. 2. Grinding results in relationship to particle size composition of feed (particle size I, II, III) and number of mill's revolutions (90, 80, 70) obtained for dolomite

It is also worth noticing that the obtained values of comminution degree indices may be grouped in three categories:

– ores with the lowest content of sandstone (30%), which can be characterized by highest values of comminution degree (S_{50} = 358 and S_{90} = 178);
– mixture I (with 70% sandstone and 30% dolomite), which was characterized by lower values of comminution degrees

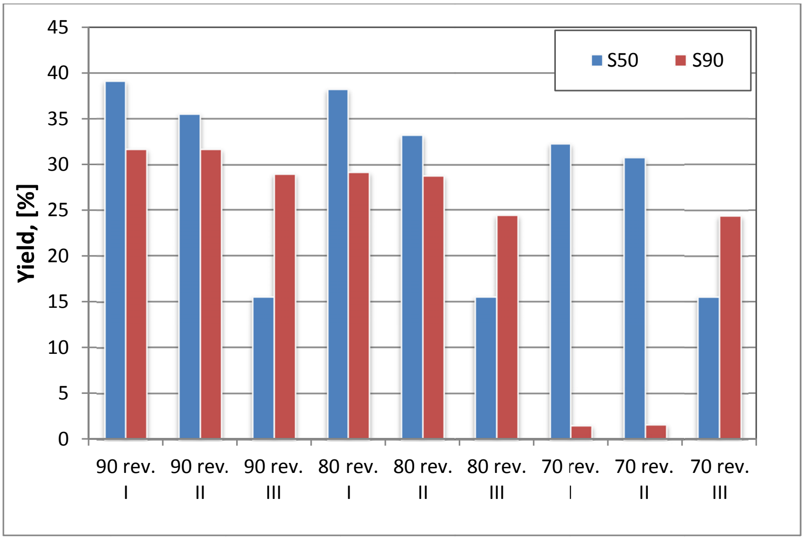

Fig. 3. Comminution degree values in relationship to particle size composition of feed (particle size I, II, III) and number of mill's revolutions (90, 80, 70) obtained for dolomite

– sandstone ore, which showed the lowest comminution degree values (S_{50} = 196 and S_{90} = 86). However, these values can be anyway regarded as still very high ones, (up to 10 times higher) than the results obtained for the dry regrinding of dolomite during the same time.

Such differentiation in results was induced through increased grinding susceptibility of dolomite with higher water content, due to decreasing of intermolecular cohesion forces, what resulted in increased viscosity of the pulp and more intense impact of grinding media. In wet grinding process the pulp is glued around grinding balls that strike each other increasing grinding intensity, while in dry grinding, the ore particles move freely and grinding usually takes place at the interface of the balls and the mill liner, and partially between the balls. In the case of wet grinding it was observed the lack of particles coarser than 0.2 mm, while for dry process, the coarse particles, coarser than 5 mm, existed in the product even after 15 minutes of grinding. However, it needs to be pointed out that this is not a general rule, and wet grinding might not be more effective for all types of material. This could be improved when various grinding methods could be tested for given material, but it was not a main scope of the paper.

The wet grinding tests also enabled us to observe a tendency for easier grinding for samples without fine particles in the feed (Sample I). All these samples were characterized by higher comminution degree values, comparing to the other samples (Table 4).

4. Summary

The aim of the study presented in the paper was to determine the influence of the particle size of the feed at different times of grinding and different rotational speed of mill on the efficiency of the grinding process in a ball mill. The feed constituted two separate lithological types of copper ore – dolomite and sandstone and two samples in the form of mixtures (70% dolomite 70% with 30% sandstone, and 30% dolomite with 70% sandstone) in three types of particle size composition. Sandstone samples were characterized by high levels of energy consumption: 18.8 kWh/Mg for sandstone and 16.5 kWh/Mg for the sandstone-based (70%S + 30%D) mixture. The lowest rate of energy consumption was obtained for dolomite (9.40 kWh/Mg) and then for dolomite-based (30%S + 70%D) sample (11.3 kWh/Mg).

Obtained results of investigations show that increases of yields in particles size fractions for individual samples were mostly dependent on the grinding time, then the particle size composition of the feed. With an increase of the grinding time, yields of particle size fractions increase too, but these increases are not linear in time. There were observed higher increases of fines during first stage of grinding process, further grinding resulted in relatively lower increases of fine size fractions. These relationships are convergent with similar investigations within the issue, presented in literature, too.

Analysis of wet grinding shows that efficiency of increases of particles below 100, 71 and 45 microns, is clearly differentiated for sandstone and mixtures of sandstone and dolomite. The highest increases, up to 100%, were reported for the mixture I (70% dolomite an 30% sandstone), due to the high susceptibility to grinding of dolomite.

In the wet grinding process the highest values of comminution degrees were achieved (S_{50} = 358 and S_{90} = 178) for the mixture I. For the mixture II, the lowest values of comminution degrees were obtained. These values equaled respectively S_{50} = 196 and S_{90} = 86. However, these values can be still treated as better, than the results obtained for the dry regrind of dolomite during the same time.

The results of investigations presented in the paper clearly show, that it is possible to control the selected operating parameters in grinding process as well as some characteristics of the feed, in order to obtain the required effectiveness of technological grinding process course. As a result of the above, there can be designed a suitable models of work (Napier-Munn et. al., 1996, Saramak 2012), that may optimize the process from the scope of the requested technological criterion (i.e. comminution degree value, yield of individual particle size fraction etc.) These issues are planned to be the subject of further research in this area.

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