Analysis of process of grinding efficiency in ball and rod mills with various feed parameters

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Abstract. The article presents the results of laboratory-scale research on the determination of the impact of ball mill parameters and the feed directed to grinding on its effectiveness and comparing it with the efficiency of grinding in a rod mill. The research was carried out for grinding copper ore processed in O/ZWR KGHM PM S.A. The aim of the research was to evaluate the efficiency of grinding in a drum mill dependably on the grinding media used (balls, rods) for various feed parameters - i.e. particle size distribution, mix of lithological type generating different susceptibility to grinding. Determination of the influence of the grinding media type on the efficiency of material grinding is of great practical importance in the designing of optimal grinding circuit. Furthermore, thanks to the acquired knowledge in this area it allows to improve the technological and economic indicators of the copper ore enrichment process.

The paper presents guidelines and recommendations for conducting the grinding process of mineral raw material (copper ore) enabling the achievement of optimal technological indicators. An important practical part of the recommendation is determination of the conditions for using a given type of grinding media, such as rods or balls.

1. Introduction
Grinding is a very important process of mineral processing of raw materials constituting an significant part of the technological system of comminution in which the process of preparation of the feed for further operations occurs. Dependably on many factors and requirements related to the enrichment process, various technical and technological solutions can be used. The important factors determining the choice of specific solution for enrichment process are such properties of the feed as mineral composition, particle size distribution, lithological type of material, moisture, content of substances hindering the screening and crushing process as well as processing costs. An example of changes in existing technological systems resulting in lower costs is the Mount Isa processing plant [1]. The Mount Isa processing plant started working with a grinding system based on two-stage crushing in jaw crushers and grinding in rod mills. The second regrinding stage consisted of two ball mills with a diameter of 5 m in a closed circuit with a 505 mm hydrocyclone. The expected capacity was 800 Mg/h, assuming that the 80-percent of particle size of the hydrocyclone overflow will be approximately of diameter 140 μm. In 1991, two self-grinding mills were installed to replace two crushing stages - rod mills and ball mills for the first regrinding. The original self-grinding mills were
unable to achieve 800 Mg/h, so they were adapted to the SAG (semi autogenous) operation by adding a grinding medium. The energy consumption of the AG / SAG mill system was 30% higher than the old crushing and first grinding system. At a capacity of 800 Mg/h, 80% of the passing particle size as a product of the AG/SAG system was about 120 μm in size, i.e. 20 μm smaller comparing with the old system. Mineralogical studies of the comminuted products indicated that the current energy consumption of the second stage of size reduction was higher than required for proper liberation of chalcopyrite, therefore, one or two mills from this system could be removed without affecting the productivity of the plant. According to this the costs reduction by more than $2 million a year was expected. However, it required proper tests of the efficiency of the work of ball mills. Simulations of the grinding circuit were carried out for various system configurations. The analyzed mill parameters were the size of the balls, mill filling and density of the feed to the mill. Also the diameters of the hydrocyclones, the angle and the overflow nozzles were selected at the same time. The technological circuit based on a two-stage classification with regrinding of the underflow of the second hydrocyclone, despite the replacement of the original diameter of hydrocyclones from 505 mm up to 660 mm, did not meet expectations due to the unfavorable effect of coarse grains from overflows of hydrocyclones. To reduce this unfavorable phenomenon, changes were made to the system configuration and two underflows of hydrocyclones were directed through the ball mill. Balls of size 65 mm were replaced with 80 mm balls to reduce the amount of coarser particles in circulation. Larger balls reduced the number of particles coarser than 1 mm by about 5%. In case the feed to ball mill was equal to 1200 Mg/h, it resulted in a reduction of 60 Mg/h of the weight of coarse particles in circulation. It also enabled the processing of a larger feed size without the risk of balls being thrown from the mill. No negative impact on the use of a larger size of balls to the production of particles smaller than 150 μm was noticed.

The circuit with one mill reached an average yield of 670 Mg/h over a 12 month period, with recovery of 93.2% Cu and a concentrate content of 27.2%. The results were better than expected and saved more than $2 million. It proved that the modification of the grinding circuit in 2nd stage to reduce energy consumption significantly lowers operating costs.

The authors Wei D., Craig I.K. [2] provided information on trends in the application of technical solutions in individual mines. A questionnaire asking for basic information related to the enrichment process for processing plants such as gold (27% - respondents), platinum (22% - respondents), silver (19% - respondents), copper (16% - respondents), cobalt, diamonds, lead, nickel, antimony, pyrite, magnetite, Fe, TiO₂, Cr₂O₃ and CrFe was sent. The work shows that the most commonly used mills in the world include ball mills, which are being used in around half of the processing plants in the world. SAG/AG mills are used less frequently (38%), while rod mills are used the least frequently. Half of the respondents indicated that the number of milling circuits varies from 1 to 3. There is often only one milling circuit (35%). Only a few plants have more than 5 circuits (10%). The most common configuration of the circuit is a single-stage and closed circuit (37%).

The second most commonly used configuration is a two-stage, first open and then closed grinding circuit (30%), in some plants multistage circuits exist. When asked what was applied to the classification if the circuit was closed, mainly cyclones with the division into branches (37%) were indicated, individual cyclones were used less frequently (27%). Spirals or incline classifiers, as well as combinations of sieves and cyclones, are less commonly used. In the major number of plants (92%) balls are used as grinding media, the ore itself is used less frequently (31%). The percentage profile of individual mill fillings depends directly on its type.

The latest technological solutions for grinding are based on high pressure grinding rolls (HPGR), which redefine the needs for determining particle size for the grinding process due to the additional effects of destruction inside particles and changes in their enrichment properties because of better opening of the mineral surface [3]. The use of HPGR in technological circuits creates the possibility of reducing the particle from the crushing process while ensuring high productivity and low costs. Interesting solutions in this field include two technological circuits for raw mineral materials processing presented in Fig. 1 (copper processing plant in Kazakhstan) and 2 (gold processing plant in
Irkutsk, Russia), which are in line with the global trend related to the use of HPGR. In the plant located in Kazakhstan, two high-pressure grinding rolls for milling and only one ball mill grinding stage were used. The maximum particle size for roll presses in this plant is equal to 38 mm and it is the result of the fragmentation of the material in a cone crusher. The product crushed in the first roll press is classified in two stages on a 5mm screen and hydrocyclones. The upper product of the screen is directed to the second roller press, including the underflow of hydrocyclone from 1st stage. The overflow of hydrocyclone goes to the 2nd stage classification, which overflow is a final product, and the underflow is directed to a ball mill co-working in a closed circuit with the second stage of classification in hydrocyclones. For the classification of the second stage conducted in hydrocyclones, the product is also directed after crushing in the second press after prior classification on the screen.

Kazakhstan: Roller Press RPS 13-170/140
Design and process data

| Company/Location: Kasachmys/Kazakhstan |
|------------------|------------------|
| Roll diameter: | 1.700 mm |
| Roll width: | 1.400 mm |
| Feed material: | Copper ore |
| Feed moisture: | max. 3 % |
| Top feed size: | 38 mm |
| Final grain size: | max. 3,0 % |
| Throughput rate: | 945 Mg/h |
| Spec. energy consumption: | <2,0 kWh/Mg |
| Spec. press force: | 5N/mm² (max) |
| Motor size: | 2x1,150 kW |
| Lifetime of studded tyres: | 8,500 operating hours |

![Figure 1. The technological scheme of the copper processing plant in Kazakhstan (advertising materials KHD Humboldt Wedag) [4].](image)

The gold processing plant in Irkutsk, Russia, was designed to obtain a product below 1 mm in a three-stage crushing system (1st stage in jaw crusher, 2nd stage in impact crusher and 3rd stage in roll press). The roll press feed particle size is equal to 25 mm. This solution with double classification as
well with product circulation after the roller press on the first screen ensures its proper load and allows achieving the expected particle size while minimizing energy costs.

Russia: Roller Press 5-100/90 For grinding of gold ore
Design and process data

| Company/Location: | Suchoj Log/Irkutsk Russia |
|-------------------|---------------------------|
| Roll diameter:    | 1,000 mm                  |
| Roll width:       | 900 mm                    |
| Feed material:    | gold ore                  |
| Feed moisture:    | max. 6.5 %                |
| Top feed size:    | 25 mm                     |
| Final grain size: | 40 % < 1.0mm; 70 % < 5.0 mm |
| Throughput rate:  | 320 Mg/h                  |
| Spec. energy consumption: | <1.80 kWh/Mg   |
| Spec. press force:| 5 N/mm² (max)             |
| Motor size:       | 2x400 kW                  |
| Lifetime of studded tyres: | 8,800 operating hours |

**Figure 2.** The technological scheme of the gold processing plant in Irkutsk, Russia (advertising materials KHD Humboldt Wedag) [4].
Summarizing, it should be emphasized that the mill's processing results are effect of its milling capacity, processing capacity of the technological circuit and susceptibility to grinding of raw material as well as the particle size distribution of the feed. Changing these parameters reduces or increases the capacity of the mill. Properly selected parameters, taking into account their mutual impact on the efficiency of work of grinding equipment are crucial in determining the working conditions and can lead to an improvement of the process of crushing (grinding) and lowering costs [5-9].

For each ore, there is an optimal size distribution of the feed to the grinding circuit. It is conditioned by the technological properties of the ore. The optimum particle size depends on the nature of the crushing and grinding costs dependably on the maximum particle size in the crushing product and it is often "fuzzy". Technological limitations (i.e. ore moisture) do not allow working in an area considered as optimal. Looking at the technological circuits operating in O/ZWR KGHM PM S.A. one should remember about the specific character of ore and the period when the plant was built, i.e. the 70's of the last century. Rod mills found application for relatively coarse grinding and were installed in the first grinding stage. The use of rod mills can be treated as the second degree of size reduction, the grinding product obtained contains about 30% of the size -0.075 mm. The rod mill discharge, as compared to the ball mill grinding product, is characterized by less concave (indented) character of the particle size of the product. The rods inside the drum during grinding retain a distance between each other thanks to pieces of ore and serve as screening grids. Small particles are transferred through the gaps between the rods and they quickly leave the mill. In contrast, coarser particles are retained between the rods and a relatively slower process of their grinding takes place. This avoids over-grinding of ore particles that are fragile in nature and are more susceptible to comminution. In rod mills, grinding as a result of the abrasion process is less intense than in ball mills. Therefore, a significant part of middle fractions is observed in the grinding product of rod mills. The content of coarse (not grinded) particles of the feed as well as the very fine particles is small.

Ball mills due to the different nature of the grinding process are used for fine grinding. Impact and abrasion cause the formation of a large amount of fine particles. The particle size distribution curve of the product can be obtained here. The grinding material stays in the mill for a relatively long time, which often causes the over-grinding of ore particles, which are usually characterized by greater brittleness than particles of gangue [10, 11]. Comparative analyses for strength distribution for three lithological type of copper ore was investigated by authors [12-14]. The use of rod mills was justified by the need of crushing the coarse particles of dolomite and shale. At the same time, the concerns about possible over-grinding of ore minerals previously released from sandstone ore were eliminated.

The effectiveness of the mill's operation is determined by the parameters of its operation, i.e. rotational speed, load, filling with grinding media, size distribution of grinding media as well as the parameters of the grinded feed. The most important feed parameters are the particle size distribution, including maximum particle size subjected to grinding and susceptibility to grinding.

The key technological issue related to grinding is the proper selection of both the type of mill/grinding media and their size enabling the proper efficiency of the entire grinding stage and classification circuit as well as the regrinding of the feed properties subjected to this process [3, 6]. For rod mills, the breaking of the feed particle occurs as a result of falling and rolling cylindrical rods as a grinding medium in which the feed particle can reach 50 mm size, the particle size of the product is <1 mm. The crushing occurs due to the large mass and surface of the grinding media. For ball mills, grinding media are balls of various diameters, the feed load is finely grained in relation to the feed of rod mills and its size is <15 mm. The product achieves a much finer particle size <0.2 mm. The process takes place by grinding and abrading the material with a large surface of grinding media and the number of contacts [10, 11].
The basic parameters determining the mechanics of the work of drum mills are:

- the relative frequency of rotation of the mill roll $\psi$, equal to the ratio of the actual frequency of rotation $n$ to the conditional critical frequency of rotation $n_{kr}$:

$$\psi = \frac{n}{n_{kr}}$$  \hspace{1cm} (1)

The conditional critical velocity is determined by the formula:

$$n_{kr} = \frac{30\sqrt{2g}}{\pi \sqrt{D}} \approx 42.3$$ \hspace{1cm} (2)

where: $g$ – standard acceleration due to gravity, m/s$^2$; $D$ – the inside diameter of the drum; m.

- relative filling of the mill with grinding media $\phi$, equal to the ratio of the grinding media $V_m$ to the internal volume of the mill roll $V$:

$$\phi = \frac{V_m}{V} = \frac{4G_m}{\gamma_m \pi D^2 L}$$ \hspace{1cm} (3)

where; $G_m$ - mass of grinding media; Mg; $\gamma_m$ - bulk density of grinding media depends on the composition.

The above parameters must be taken into account when selecting the operating conditions of the drum mill. It should also be marked that rod mills generally work at lower speeds than ball mills, ranging from 50 to 65% of critical rotation.

2. Materials and methods

The aim of the research was to determine the influence of the grinding media type on copper ore grinding efficiency, determine the conditions for the change of grinding media used in industrial conditions from rods to balls with the evaluation of the benefits resulting from them. Research may enable improvement of technological and economic indicators of the copper ore enrichment process.

Laboratory experiments were carried out for a mill filled with rods as basis and balls as the preferred solution to increase the efficiency of ore grinding. Varying feed parameters (mix of lithological type, grain size distribution) and grinding media sizes were used. In addition, for the mill filled with balls, its rotational speed has been changed.

The plan of experiments as well as the conditions and scope of their implementation are presented in Table 1. Three additional experiments were carried out for mix lithological type with O/ZWR KGHM a sample 1 in the fraction 0-8 mm with a lower proportion of sandstone (60P + 25D + 15L), with an increased speed of the mill (from 58 to 70 rpm) and three grinding times (10, 20 and 40 min). In total, 51 milling tests had been done.
Table 1. Plan and conditions of experience.

| Feed particle size | Lithological composition | District | Grinding time |
|--------------------|--------------------------|---------|--------------|
|                    |                          |         | t = 10 min   | t = 20 min   | t = 40 min   |
|                    |                          |         | Rods | Small balls | Large balls | Rods | Small balls | Large balls | Rods | Small balls | Large balls |
| 0-8mm              | mix (lithological type) | O/ZWR  | x    | x            | x            | x    | x            | x            |
|                    | (80%P+5%D+15%L)         | KGHM   |      |              |              |      |              |              |
|                    | mix (lithological type) | O/ZWR  | x    | x            | x            | x    | x            | x            |
|                    | (60%P+25%D+15%L)        | KGHM   |      |              |              |      |              |              |
|                    | sample 1                |         |      |              |              |      |              |              |
|                    | natural mix (industry)  | O/ZWR  | x    | x            | x            | x    | x            | x            |
|                    |                          | KGHM   |      |              |              |      |              |              |
|                    |                          | sample 1|      |              |              |      |              |              |
| 0-16mm             | natural mix (industry)  | O/ZWR  | x    | x            | x            | x    | x            | x            |
|                    |                          | KGHM   |      |              |              |      |              |              |
|                    |                          | sample 1|      |              |              |      |              |              |
|                    |                          | O/ZWR  | x    | x            | x            | x    | x            | x            |
|                    |                          | KGHM   |      |              |              |      |              |              |
|                    |                          | sample 2|      |              |              |      |              |              |

where: P – sandstone ore, D – dolomite ore, L – shale ore

The milling tests were carried out on 6 mixes of ore types (four from O/ZWR KGHM O/ZWR KGHM a sample 1 and two from O / ZWR KGHM O/ZWR KGHM a sample 2) prepared according to the scheme (Figure 3). The lithological composition of the mix is presented in Table 2.

Figure 3. Scheme of sample preparation for tests.
Table 2. Percentages of individual lithological types in mix prepared for milling tests.

| Place of sample | O/ZWR a sample 1 | O/ZWR a sample 1 | O/ZWR a sample 1 | O/ZWR a sample 2 |
|-----------------|------------------|------------------|------------------|------------------|
| Mix of ore      | 80P+5D+15L mix   | 60P+25D+15L mix  | natural mix (industry) | natural mix (industry) |
| Sandstone       | % 80.0           | % 60.0           | % 64.5           | % 62.9           |
| Shale           | % 15.0           | % 15.0           | % 12.0           | % 8.6            |
| Carbonates      | % 5.0            | % 25.0           | % 23.6           | % 28.5           |
| Sum             | % 100.0          | % 100.0          | % 100.0          | % 100.0          |

The tests were carried out in a laboratory batch drum mill. The mill parameters were as follows:

- diameter of the mill \( \phi = 305 \text{ mm} \)
- length of the mill \( l = 440 \text{ mm} \)
- number of rotations \( n = 58 \text{ rpm, 70 rpm (respectively: 75.7\% and 91.4\% critical rotation)} \)
- mass of grinding media – 14 kg

Three types of steel grinding media were used in the experiments: rods and balls of smaller and larger size. Detailed size distribution of grinding media is presented in Table 3.

Table 3. Size distribution of grinding media.

| d mm | Q [g] | Q [g] | Q [g] | \( \gamma [%] \) | \( \gamma [%] \) | \( \gamma [%] \) |
|------|-------|-------|-------|-----------------|-----------------|-----------------|
| 15   | 5903  | 4800  | 1008  | 42.2            | 34.3            | 7.2             |
| 20   | 8090  | 1842  | 1984  | 57.8            | 13.2            | 14.2            |
| 30   | –     | 7365  | 3900  | 0.0             | 52.6            | 27.8            |
| 35   | –     | –     | 3009  | 0.0             | 0.0             | 21.5            |
| 42   | –     | –     | 4110  | 0.0             | 0.0             | 29.3            |
| Sum  | 13993 | 14007 | 14011 | 100             | 100             | 100             |

3. Analysis of results

The results of the 51 experiments were presented in the form of graphs of the curves of particle size distribution of the grinding product for particular conditions of the process and particular feeds. Exemplary curves for selected grinding conditions are shown in Figure 4.
Figure 4 Curves of the particle size distribution of the grinding product in a rod mill (MP) and a ball mill (MK) for feed from O/ZWR KGHM a sample 1 with a grain size of 0-8 mm and a lithological composition of 60% of sandstone, 25% of dolomite, 15% of shale.

The results in the form of particle size distribution curves enable a preliminary comparative analysis of the grinding efficiency depending on the grinding media used, as well as the rotational speed of the mill. The analysis shows that in the range of fine particle size <0.1 mm, the grinding efficiency with the use of balls is higher compared to the rod mill for the smaller feed size 0-8 mm. The increase in particle size of the feed to 0-16 mm resulted in a decrease in the milling efficiency of the ball mill, but still in the range of fine particles it is higher in relation to the rod mill. Increasing the size of the balls improves the ball mill's grinding efficiency, the grinding efficiency increases also for higher rotational speeds of the mill filled with balls.

The increments of particle size fraction such as: <0.04 mm; <0.071 mm; <0.1 mm; <0.2 mm in the grinding product after 10, 20 and 40 minutes were also analyzed. It indicates that the grinding efficiency measured by the particle size fraction growth depending on the grinding media used is strongly dependent on the particle size of the analyzed fraction and feed size, especially for fine particles below 0.2 mm and finely grained 0-8 mm feed. This efficiency is higher for a mill filled with balls. For example, the milling efficiency measured by the grain size increase <0.1 mm for feed with a particle size of 0-8 mm and a lithological composition of 80% sandstone, 5% dolomite and 15% slate depending on the grinding time is shown in table 4.
4. Conclusions

Based on the results of tests carried out in laboratory conditions, a higher efficiency of the ball mill comparing to the rod mill, in conditions of increment of small size fractions was found. The value of grinding efficiency in a ball mill depends on the particle size of the feed. For the small-grained feed, the grinding efficiency of the ball mill is increased by approx. 20-30%.

The effect of the grinding environment tested (ball and rod) on the grinding efficiency depends on the change in the lithological composition, i.e. sandstone and dolomite content indicates that the mill filled with balls after a longer grinding time better cope with the grinding of ore with increased sandstone content, in particular for increments fraction <0.071 mm and <0.1 mm. For shorter grinding time, as well as for the increment of the small size fractions, the effect of the various lithological composition on the change in efficiency is comparable.

The results of the tests and the analyzes carried out indicate, that for the small-grained feed, ball mills should be used. This is due to the higher efficiency of grinding ore measured by the increasing of small size fractions, and for longer milling time, the higher efficiency of grinding ore with an increased content of the sandstone fraction of the mill, filled with matched balls.

Applying grinding environment changes, and, in particular, the determination and optimization of parameters such as the grinding balls size, should be preceded by tests in industrial conditions confirming specific technological effects.

The results of the tests indicate higher milling efficiency in the ball mill in relation to the rod mill in conditions of increasing of small size fractions with comparable ranges of not grinded coarse particles for a 0-8 mm particle feed suggest changing of the rod grinding environment for ball mills in industrial conditions. The expected benefits, from changing the type of grinding media are: an increase of approx. 20-30% in relation to the current classifier overflow stream, and thus a smaller stream of grinding material in the second-stage ball mill, increased operating time of the ball mill, more convenient process of loading and unloading of grinding environment, no effect of rods jamming, lower efficiency of the mill filled with balls due to its lower sensitivity to impurities accumulated in the spaces between the rods, high grinding speed measured by the increasing of small size fractions over time, with relatively small disadvantages of this solution (balls application), i.e. smaller maximum permitted particles for grinding feed, higher rotational speeds, possibility of over-grinding coarsely grained minerals.

Conclusions from the analysis indicate, that the ball-filled mill is more resistant to changes in the lithological composition, which means that the particle size distribution of the feed is the key to changing the grinding environment. However, the condition of applying a ball mill is to meet specific process conditions, especially in terms of grain size and size of grinding environment. The maximum particle in the feed should not exceed 20 mm in the industrial conditions. In the field of industrial practice, it is recommended to evaluate the possibility of particle reduction, due to the positive effect of the grinding kinetics increase and obtaining much higher increment of small size particles.

The research results confirm the need to select optimal technical and technological solutions for the properties of the raw material in theoretical and experimental way in order to determine the process parameters and details of the technological circuit.
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