Analysis of the working chamber size influence on the effectiveness of grinding in electromagnetic mill

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Abstract. The paper presents study on the working chamber size influence on the technological and economic effectiveness of mineral material grinding in electromagnetic mill. Performance at desired throughput and technological effectiveness is the key issue for the processing apparatus application in the specific technological circuits. The problem of process effectiveness assessment for the specific mill’s construction is important for the grinding circuit design and the process operating points’ selection. It also allows for the proper control system design and the process optimization according to the specific criteria function. The research with electromagnetic mill was performed in order to assess the influence of the physical parameters of the mill’s working chamber on the grinding process effectiveness. Quality factor was based on the chosen grain size fraction increase in the final product. Experiments were performed on electromagnetic mills with the working chamber diameter 200 mm and 320 mm respectively.

1. Introduction

Technological operations of mineral processing determine the efficiency of mining companies’ production lines. The processing operations play an important role in shaping the properties of the processed material which finally becomes a commercial product. Mineral materials, depending on their final technological use, must be characterized by properties and parameters that meet the expectations of the recipient. In that regard, the most important material properties are: grain size, shape of grains, surface features, impurities content, oversize and undersize share, etc. From the final industrial application point of view, the geometrical properties of grains like shape, volume, surface area are of key importance [1]. These properties are shaped for a given raw material as a result of appropriate processing operations within the particular technological system.

The growing demand for raw materials from primary and secondary deposits, in particular those classified as strategic or critical, requires the appropriate selection of technological processes in terms of increasing their efficiency and effectiveness. Innovative solutions in the field of construction and processing technologies lead to development of modern solutions allowing to produce the products of
desired quality taking into account a number of aspects, including economical or environmental ones. These solutions are particularly important due to the post-production waste management.

The scattering and depletion of natural resources in terms of the content of raw materials desirable for the economy, with the rapidly growing demand forced by the development of technology and consumer demand, forces the search for modern solutions in the technology and technology of processing raw materials and waste. Solutions in this area focus on adapting process engineering operations to the complex characteristics of mineral raw materials, i.e., their physical, physicochemical and chemical properties. The raw material situation and technological needs as well as economic considerations inspire the continuous development of machinery and technological equipment construction. This development has a strong economic basis due to the energy consumption of processing processes. Directions of development, in addition to increasing the efficiency of machines, are based also on appropriate adaptation of technologies and devices to the properties of raw materials, which enables reduction of costs in relation to the volume of its processing. For the effective conduct of the process of transformation, it is necessary to know the characteristics and factors affecting the course of a given process. Full identification of processes along with the geometallurgical model of the deposit enables appropriate control and optimization of the technological process at every stage from extraction to metallurgical processes for metal ores enabling the introduction of a production management system in industrial conditions. Such activities are necessary for the full exploitation of exploited deposits by mining enterprises, as they will help to minimize the unavoidable losses of a useful component in waste.

One of the most energy-intensive processes is the process of grinding in particular when it concerns the needs in terms of obtaining fine graining of the product by grinding. Depending on the raw material, the purpose of the grinding operation is different. In the case of ores and raw materials requiring enrichment processes, grinding is aimed at the liberation of ore minerals. The course of the enrichment process depends on the degree of release of useful minerals. They are carried out so as to achieve an appropriate degree of liberation, and the granulation is determined by the dimensions of the mineral grains, the more precisely the useful minerals are liberated, the easier it is to enrich the given feed. The process of mineral liberation in grinding operations depends, among other things, on the properties of rocks and the minerals forming those rocks, and on the nature of the grinding process. Preparation of the feed for enrichment is a complex system of comminution (crushing, grinding) and classification with dizziness. The basic operation is grinding which, depending on the conditions and the adopted technological assumptions, can take place in drum mills (e.g. rod, ball or cylpebs), semi-autogenous (SAG) and autogenous (AG) [2-4]. At the subsequent stages of milling, vertical, vibrating and other rotor mills are used. However, bringing the material (feed, ore, rock raw material) to the grain size below 0.1 mm is very energy intensive. The amount of energy required for proper fragmentation depends mainly on the mechanical properties of the mineral raw material, but also on the type of mills used and the technological rules. It is assumed that, for example, drum gravity mills absorb up to 50% of the energy costs of the processing plant. An electromagnetic mill, due to its capabilities in the field of grinding raw materials is a device with a high potential for effective grinding of raw materials at low energy costs. An important element of the introduction of an electromagnetic mill to the technological system is to determine the parameters of the feed determining the efficiency of its operation. This means that it is necessary to determine the efficiency of the work of mills on the first stage working in the systems of preparing the raw material for enrichment or for further technological operations [3,4].

The enrichment of non-ferrous ores in the flotation process is not an easy matter. It requires certain conditions that guarantee obtaining high-quality flotation concentrates. One of the basic factors that are of key importance for the effectiveness of this process is the grain characteristics of the feed. The appropriate graining of the feedstock is achieved thanks to the use of mills in classification and fragmentation nodes. However, conventional grinding equipment (ball mills, rod mills, cylpebs mills) are characterized by high energy consumption. The reduction of process costs can be achieved by introducing into the technological systems electromagnetic mills, characterized by the reduction of
energy consumption to a large extent, which is their undeniable advantage. The key element, however, is the surface condition of the mineral grain and its release from the gangue. Verification of this state takes place during the beneficiation process, e.g. flotation and evaluation of the ore beneficiation characteristics.

2. **Features and advantages of electromagnetic mill**

The results of laboratory tests on Polish copper ore showed that the electromagnetic mill allows obtaining the expected grain size of the feed directed to the flotation enrichment nodes in processing plants. An important problem associated with the main process of separation of minerals from gangue is the size of the ore grains. This factor forces the feed to the appropriate grain size, most often the grain size is below 0.1 mm, although in some cases this limit decreases even to 10 μm. Tests of grinding media dedicated to electromagnetic mills showed that the best results were achieved for 10x1 mm stainless steel grinding media. Obtaining copper ore with a granulation of 0-45 μm was possible after almost 25 seconds of the grinding process. During the extension of the grinding time of the material to 30 seconds in an electromagnetic mill, it was possible to obtain a relative increase in the 0-0.02 mm class at a level of approximately 80%. It can be concluded that the use of smaller size grinding media provided faster growth of the studied grain grades in milling products [5,6,7,9].

Obtaining the right graining determines the technological efficiency of a given system and devices included in its composition. This makes it necessary to select the right machines and their system in order to obtain the appropriate technological effect while maintaining the cost minimization criterion. The key is to ensure high efficiency for high cost operations, i.e. grinding. The selection of the mill and its technical parameters determines the degree of fragmentation to be obtained and the efficiency is strictly dependent on the type of feed. When considering a particular material, the final grinding efficiency is also affected by the moisture content of the feed and its initial particle size distribution. For this reason, direct comparison of different types of mills is difficult and their performance is difficult to rescale. It is worth to pay attention to such parameters as the efficiency and energy consumption of different types of grinding installations, since knowledge of those parameters is necessary to pre-assess the usefulness of a mill for specific applications.

The ball mill belongs to the group of gravitational mills, in which balls of various diameters are used as the grinding media. Grinding media are made of high density materials and low abrasiveness, the most commonly used grinding media are steel and ceramic grinding media. Ball mills are currently the basic devices used in technological processing systems of ores, hence they can be a reference element in the case of assessment of new technical solutions in the field of grinding. The main disadvantages of the mill include its low energy efficiency, which results in ongoing work on the development of new solutions [5,10]. One of the examples of such works may be an electromagnetic mill developed as part of the PBS project financed by NCBiR - SYSMEL [6,11]. Quality of the mineral processing products depends highly also on the quality of the process control [12]. For this reason, research on measurement and control systems for electromagnetic mill were also important part of the SYSMEL project. Models for the soft-sensing measurements and control purposes were identified [13,14] and dedicated control structures and algorithms were proposed [15,16].

The electromagnetic mill is a device in which the mill's ferromagnetic grinding media are moved by the purposely generated rotating electromagnetic field as a carrier of energy. The mill is made up of the exciter of the rotating magnetic field and the tube placed in its axis, constituting the working chamber [6,11]. The work chamber is filled in about 20% with ferromagnetic grinding media. The effectiveness of the grinding process depends on the proper selection of the parameters of both the work coil and the working chamber [17,18,19]. The solution allowing for significant intensification of many technological processes is leading them in the works space in which the small ferromagnetic rods (grinding media with a properly selected ratio of length to diameter) move due to the action of the rotational electromagnetic field [18]. Devices with electromagnetic rotation of a very large number of grinding media, allow to intensify a number of technological processes due to the simultaneous and comprehensive impact on the load treated in them, many physical variables of force fields, including:
electric, magnetic, acoustic (also in the field of ultrasounds), thermal, high pressure and friction [20]. The electromagnetic mill has been a little-known grinding device used in laboratories rather than in industry. This limitation of applications resulted from the very low efficiency and low efficiency of this type of mills. The low technical and operational parameters were influenced by improper design assumptions leading to very large losses in the rotating magnetic field coil. The change in the design assumptions allowed for the construction of a prototype electromagnetic mill at the Częstochowa University of Technology [18]. The research on the milling process in this mill has shown its high efficiency as manifested by short several-second grinding time for one portion of material and low particle size distribution including colloidal one. The industrial use of this type of equipment will be determined by the possibility of building a high efficiency mill (several dozen Mg per hour) [18, 19]. The possibilities of such a highly efficient mill depend primarily on the properly designed magnetic exciter of the rotating field. The mill works efficiently in terms of both high and low humidity of the feed. Material with humidity in the range of 15%-30%, especially if it has a high viscosity, reduces the grinding efficiency by about 30%.

The basic condition for the use of an industrial electromagnetic mill is the possibility of its continuous operation. Grinding media should match grain size of granular material. In the case of a large variation in grain size, a mix of grinding media of various sizes is used [21]. The possible size changes of the grinding media match the physical properties of the ground substance and the final graining of the milling product. The electromagnetic mill technology is particularly useful in the case of ultra fine milling, with grain sizes beyond the reach of conventional solutions, or when obtaining such a small particle size distribution would require disproportionate energy expenditure [7]. The competition may be the IsaMill mill developed by Xstrata Technology. It is a mill used for very fine grinding of ores for the graining of products with a size of several or several micrometers. The mill is characterized by a relatively low energy consumption compared to ball mills, even 10 times smaller when crushed to a size below 10 micrometers (figure 1).

![ IsaMill™ Energy Use](image)

**Figure 1.** Energy consumption for ball mill and IsaMill [22].
Consideration of the energy consumption of the grinding process in various mills and technological systems allows to determine the general demand for grinding energy depending on the grain size of the feed as well as the desired products. According to figures 1, 2 and 3, the finer the product we want to achieve, the more energy should be put into its fragmentation, the optimal grinding can be obtained by increasing the grinding time, selecting proper grinding media physical parameters, reducing particle size (introducing the previous crushing or grinding device) or introducing additional milling stage or changing the type of mill (figure 3).

![Figure 2. Relation between energy consumption and product grains size [23].](image1)

![Figure 3. Energy consumption comparison for different grinding devices [24].](image2)

Comparative laboratory tests show that in the case of an electromagnetic mill, its efficiency is about 28% higher in relation to a ball mill, but in the range of a fine feed of less than 1 or 2 mm. This means that under industrial conditions an electromagnetic mill could bring tangible benefits in the case of raw material grading at the final stages of comminution. The advantage of this mill is also the short grinding time of the material associated with the short residence time of the material in the mill,
which, using a recycle classification system, will selectively separate the product capable of flotation, protecting the metal components from being milled [8, 9].

An important element is to determine the efficiency of grinding depending on the load of the electromagnetic mill with ground raw material and the possibilities of increasing the capacity of the working chamber of the electromagnetic mill.

3. Analysis of grinding process in electromagnetic mills with different working chambers

Research in the evaluation of grinding efficiency depending on the mill load was carried out in an electromagnetic mill with a diameter of 200 mm (D200). In terms of increasing the working chamber, grinding tests were carried out in a mill with a diameter of 320 mm (D320) along with reference tests in a mill with a diameter of 200 mm. The material for testing was copper ore from KGHM PM S.A.

3.1. Influence of the material load on D200 mill effectiveness

In order to determine the possibilities of loading the mill with ground material, tests were carried out on a mill with a diameter of 200 mm with different loading of the quantity of ground material - 1 kg, 2 kg, 2.5 kg and 3 kg with solid filling with grinding media weighing 1.5 kg and size used grinding media with a diameter of 1 mm and a length of 10 mm.

The obtained test results were analyzed for specific grain size increments in the grinding product after 15, 25 and 35 seconds for grinding 1 kg and 2 kg feed and 15 and 25 seconds for grinding material weighing 2.5 and 3 kg. Increments of grain class were analyzed: 0.045 mm; 0.071 mm; 0.1 mm; 0.2 mm.

Analysis of the grain class growths after time made it possible to determine the milling speed of the electromagnetic mill, which allowed to determine the time and load of the mill with the material after which for the given grain class there is an end to the possibility of further growth of this class due to the decline of the mill's efficiency. In figure 4, the increments of analyzed particle size distributions for the mill are summarized for each of the samples. The analysis was based on relative increments as the value of the difference in the content of a given grinding product class in relation to the potential maximum value of this class increase resulting from the difference: 100% - the contents of this class expressed as a percentage in the feed:

\[
\text{class relative increase} = 100 \times \frac{\Phi_{\text{class in product}} - \Phi_{\text{class in feed}}}{100 - \Phi_{\text{class in feed}}} \%
\] (1)

The relative increase analysis makes it possible to assess the end of the mill's potential in terms of further growth of the analysed particle size fraction. Comparison of the work of a mill filled with specific grinding media through relative growth makes it easier to evaluate the efficiency of grinding - achieving 100% of the increment of the analysed grain class means high efficiency of the mill in the grinding of a given grain class. An important element of the analysis is also the time in which the high increment values appear and the state of saturation (lack of increment) occurs, which in case of increments with values lower than 100%, sets the limit of the mill capacity in terms of further material fragmentation.
Figure 4. Grain size class increase for different processing time and material load in EM.

Figure 5. Grinding effectiveness in function of mill load for different processing time: a – 15 seconds, b – 25 seconds.

3.2. Grinding effectiveness in mills D200 and D320
In order to assess the efficiency of the electromagnetic mill with increasing dimensions of its working chamber, a sample of copper ore with particle size 0-1 mm was tested, with a higher content of particles above 0.5 mm (feed 1), and with a lower content in the mill feed grade above 0.5 mm (feed 2).
For this purpose, copper ore was prepared in the grinding and classification process and grinding in a rod mill and then the raw material prepared in this way was divided into a sample with 1 kilogram weight for grinding in a mill D200 and 6.5 kg for grinding in a mill D320. The mass of the samples resulted from the calculation of the load on the mill D200 and D320 with such masses of material that gave the same level of filling the chamber with the material. Grinding tests were carried out at 10, 15, 20 seconds - the choice of time resulted from previous work optimization experiments carried out on the D200 mill. The results of sieve analysis of the feed and the grinding product is presented on figures 6-9. For easier analysis the results were grouped according to the feed type and the mill size. Feed 1 and 2 differs by a larger and smaller share of the class above 0.5 mm.

![Cumulated graining curves for feed 1 grinding process in D200 mill.](image1)

**Figure 6.** Cumulated graining curves for feed 1 grinding process in D200 mill.

![Cumulated graining curves for feed 2 grinding process in D200 mill.](image2)

**Figure 7.** Cumulated graining curves for feed 2 grinding process in D200 mill.
Figure 8. Cumulated graining curves for feed 1 grinding process in D320 mill.

Figure 9. Cumulated graining curves for feed 2 grinding process in D320 mill.

The grinding efficiency was measured by the relative increase of selected grain classes. The analyzed grain classes are 0-0.071 mm, 0-0.1 mm and 0-0.2 mm. The results of the growth along with the grinding time of the analyzed grain classes for grinding ore in mill D320 are shown in figures 10 and 11 for the mill D200 in figures 12 and 13 and collectively for both mills for the 0-0.2 mm class in figure 14.
Figure 10. Kinetics of the analyzed grain size class increase in grinding product for mill D320 and feed 1.

Figure 11. Kinetics of the analyzed grain size class increase in grinding product for mill D320 and feed 2.

Figure 12. Kinetics of the analyzed grain size class increase in grinding product for mill D200 and feed 1.
The results clearly indicate that the mill with a smaller diameter D200 in the tested mass load range in a volume unit (the same for both mills) worked more efficiently. The relative increase of the analyzed grain classes in relation to the larger D320 mill was several percent (about 15%) higher for a coarse feed and a few percent for a feed with a smaller class content of more than 0.5 mm. This may indicate that the larger mill, due to the obtained kinetic energy, requires finer feed for grinding.

Analyzing the unit energy consumption with respect to the possibility of individual loading of both mills, we obtain values representing the material grinding time, respectively (table 1). The mill with a larger diameter has a lower energy consumption per ton of raw material by about 8% in relation to the smaller mill.

However, if one looks closer to particular grain size classes, the difference is opposite in some cases. The same energy index calculated for the production of 1 ton of the finest 0.071 mm grain size class is higher for the bigger mill (table 2). Authors must stress that such results were obtained in the
batch experiments. Such approach, on the one hand, allows for the precise repetition of the experiments’ conditions. On the other hand, when such short processing times are considered, different start-up dynamics of D200 and D320 mills influence the results. One can notice that effect, while comparing results for feed 1 – the difference is about 35% for 10 seconds of processing time and only about 10% for 15 and 20 seconds. Above results requires further analysis of mill scaling effect in continuous processing experimentation, that will neglect start-up effect.

Table 1. Comparison of unit energy consumption for D200 and D320 in relations to the grinding time.

| Processing time (s) | D200 load (Mg/h) | D320 load (Mg/h) | D200 unit power consumption (kWh) | D200 unit energy consumption (kWh/Mg) | D320 unit power consumption (kWh) | D320 unit energy consumption (kWh/Mg) |
|---------------------|------------------|------------------|-----------------------------------|--------------------------------------|-----------------------------------|--------------------------------------|
| 10                  | 0.36             | 2.34             | 22                                | 61.1                                 | 56.4                              |
| 15                  | 0.24             | 1.56             | 22                                | 91.7                                 | 84.6                              |
| 20                  | 0.18             | 1.17             | 22                                | 122.2                                | 112.8                             |

Table 2. Comparison of unit energy consumption for D200 and D320 for 0,071 mm grain size class.

| Processing time (s) | D200 load (Mg/h) | D320 load (Mg/h) | Feed 1 D200 unit energy consumption (kWh/Mg) | Feed 1 D320 unit energy consumption (kWh/Mg) | Feed 2 D200 unit energy consumption (kWh/Mg) | Feed 2 D320 unit energy consumption (kWh/Mg) |
|---------------------|------------------|------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| 10                  | 0.36             | 2.34             | 258.9                                         | 352.4                                         | 326.2                                         | 339.3                                         |
| 15                  | 0.24             | 1.56             | 376.5                                         | 413.9                                         | 470.0                                         | 449.2                                         |
| 20                  | 0.18             | 1.17             | 469.3                                         | 527.8                                         | 500.5                                         | 590.7                                         |

4. Conclusions
Studies on the efficiency of grinding process in electromagnetic mills with different diameters of 200 and 320 mm were carried out in the Eltraf laboratory in Lubliniec. Analysis of the impact of mill load with mass of ground material indicates that the mill with a diameter of 200 mm works most efficiently with a load of 1 kg of material (relative growth of the studied grain classes in the grinding product after 15 seconds was from 70 to 85% and after 35 seconds from about 85 up to 95% - fig. 5). Increasing the mass of ground material to 2 kg (or two times) causes a rapid drop by nearly half of the relative growth value of a given grain class for the grinding time of 15 seconds and about 30% for a grinding time of 35 seconds. Further increase of the material mass already causes a slight decrease in efficiency, which means that it is very beneficial to introduce the work of this mill in a closed system with the dizziness of unmilled material. Such operation may result in an increase in the efficiency of the mill, however, it requires appropriate mill control systems to ensure adequate efficiency of the entire grinding system.

Analysis of the obtained results allows to conclude that increasing the size of the mill has a positive effect on the mill's efficiency increase of about 6.5 times and a reduction of energy consumption by about 8% with a slight decrease in grinding efficiency measured by the increase of fine grain sizes in the milling product. Further research should focus on the verification of the maximum feed grain directed to the D320 mill due to the kinetic energy of grinding media and thus the ability to grind larger size granules.
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