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# A New Grinding Technology Using an Electromagnetic Mill – Testing the Efficiency of the Process

*S. Styła*

*Institute of Electrical Engineering and Electrotechnology, Lublin University of Technology, 20-618 Lublin, ul. Nadbystrzycka 38a; e-mail: s.styla@pollub.pl*

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**Summary.** The article presents a prototype device for grinding and mixing materials called electromagnetic mill. It further shows the experimental research covering the selection of the optimal design parameters of the internal circuit inductor with the working chamber and the grinding elements with regard to the maximum effectiveness of grinding. The research also addresses how the efficiency of the process is influenced by the amount of grinding elements and the volume of the shredded material arranged in the working chamber of the mill, as well as the shape and dimensions of those elements.

**Key words:** electromagnetic mill, magnetic field inductor, grinding materials, grinding.

## INTRODUCTION

The mechanics of material grinding processes is complex and despite a long time of using various technological devices for grinding, the knowledge about them is mainly based on empirical research. The available bibliographic studies offer few mathematical descriptions based on scientific theories. This is due to the difficulty of exact description of the phenomena taking place in the shredded grain [13, 31]. Therefore, knowledge of the design of the technological systems of a milling plant and the loads which occur in them is based primarily on experimental studies.

Currently operated mills can be divided into five groups [8]: grinding, ring-runway, streaming, disk- and fan-type. The most widely used have been grinding mills in which the rotating drum sets in motion the steel balls or cylpebs. Under the influence of gravity these elements strike the ground material causing its disintegration into smaller grains, thus such machines are often called gravity mills. This method allows to obtain very fine granularity of the product (or the grinding result) compared to the particle size of the feed (the raw material prior to grinding).

Due to rising electricity prices people are increasingly turning to energy efficient solutions. In simple terms, this effect can be achieved by reducing the milling time. However, such a procedure used in the existing mill structures deteriorates the quality of the product of grinding and cannot be accepted by technologists. Hence the constant search by designers from different industries, trying to develop new, high-performance mills and methods to obtain ultra fine grain size of the product [5, 9, 10, 12, 29]. The development also relates to methods of controlling milling processes [6, 24].

According to literature references [3, 16, 25, 26, 27] it is possible to use an electromagnetic field produced in a properly designed inductor for grinding (milling) and mixing loose materials, liquid and gas. The working elements are ferromagnetics called grinding media, which are placed inside the inductor in the specially prepared working chamber of non-magnetic material. Under the influence of the rotating field, directed perpendicularly to the axis of the inductor, the grinding media keep moving causing collisions with the ground material.

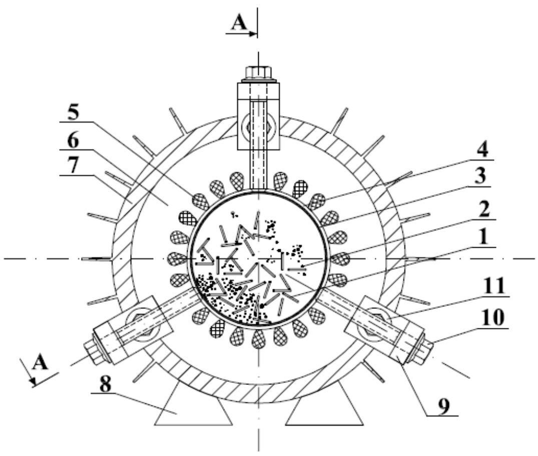
In assessing the properties of the electromagnetic field [1, 2, 7, 23] and analysing the construction of AC machine stators [4, 14, 15, 22] it can be stated that the electromagnetic mill operates on the principle similar to three-phase AC motors, and therefore the stators of such machines can be used for its construction.

## ELECTROMAGNETIC MILL

An electromagnetic mill is a device whose essential feature is the intensification of many technological processes through the simultaneous effect on the ground material of many force fields. Therefore, in comparison with commonly-used devices, the operation of the electromagnetic mill is many times faster, even several thousand times, depending on the application. It also allows to obtain a number of effects of the treatment of materials impossible to achieve by other methods and with conventional equipment.

Figure 1 shows the model of the electromagnetic mill constructed at the Technical University of Lublin which is the subject of this research. According to current knowledge of the author it is the first construction of this type using the stator of an asynchronous motor as an inductor. For this reason, the device was covered by patent protection [28].

a)




b)

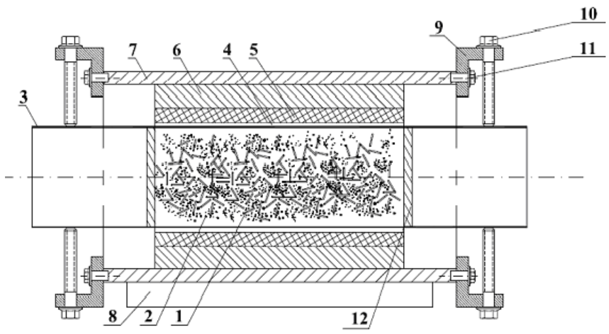



**Fig. 1.** Cross section of the electromagnetic mill [28]: a) view from the leading coils, b) view from the aluminum housing – section A-A (no cooling system); 1 – grinding media, 2 – ground material, 3 – working chamber, 4 – air gap, 5 –inductor winding in grooves, 6 – magnetic core of the inductor, 7 – body of the inductor, 8 –mill feet, 9 – linking element, 10 – adjusting screw of the working chamber, 11 – fixing bolt of the linking element, 12 – sealing element of the working chamber

The electromagnetic mill in question comprises:

– the three-phase inductor of the rotating field with latent poles, made on the basis of an asynchronous motor with one pair of poles;
– the working chamber made of non-magnetic material;
– ferromagnetic elements – grinding bodies placed in the working chamber and moving under the influence of the rotating electromagnetic field;
– the cooling system which allows for efficient removal of a large amount of heat generated during the grinding process.

## METHODOLOGY OF RESEARCH

The main determinant of the efficiency of the mill is to obtain the smallest granulation in the shortest possible time. Therefore, the criterion of research was the smallest particle size obtained in the milling process.

The study was performed according to the following procedure:

1. Preparation of the sample for grinding (defining the appropriate volume of feed relative to the volume of the working chamber).
   The grain size of the sand before grinding is shown in Figure 2.

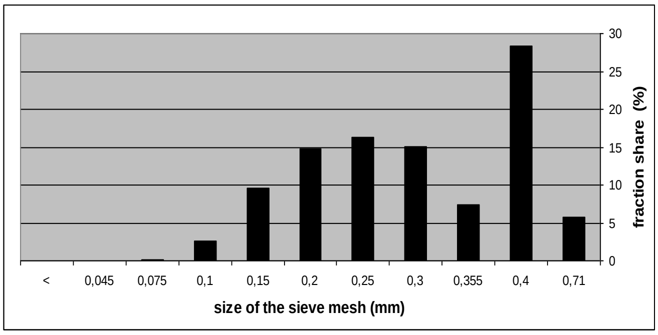



**Fig. 2.** Granulation of the feed

2. Preparation of the grinding media (determining the appropriate amount of grinding media in relation to the volume of the working chamber).
3. Defining the milling time and the value of the current flowing through the inductor winding (milling time was 300 seconds when the current supplying inductor I = 13 A).
4. In order to eliminate the method's errors five repetitions for each section were performed.
5. Separation of the grinding bodies from the product was made with a sieve having a mesh of 0.710 mm. This was to eliminate product loss during separation.
6. Determination of the fraction using a sieve analysis was performed according to the standards in force [17, 18, 19, 20, 21].

Figure 3 shows the shaker used in the studies with a set of sieves with the following mesh sizes:

– 0,710 mm
– 0,400 mm
– 0,355 mm
– 0,300 mm
– 0,250 mm
– 0,200 mm

– 0,150 mm
– 0,100 mm
– 0,075 mm
– 0,045 mm

**Fig. 3.** Shaker with sieves

Theoretical considerations on the design of the electromagnetic mill allow to conclude that the process of grinding in mills of this type is influenced by:
– ratio of the mass of raw material and grinding media;
– extent of filling the chamber in relation to its dimensions;
– type, shape and size of grinding media;
– diameter of the working chamber;
– grinding time;
– type and physico-chemical parameters of the raw material to be ground.

Because current references show no description of the processes taking place inside this type of constructions, there was a need for research on the laboratory scale.

## IMPACT OF THE PERCENTAGE SHARE OF THE GRINDING MEDIA AND THE FEED QUANTITY ON THE EFFECTIVENESS OF THE PROCESS

In order to find the optimal bulk value a test was performed of pouring into the chamber of the mill appropriate amounts of feed (quartz sand) and grinding media according to the proportion shown in Table 1. The rate and efficiency of the grinding process depends on the ratio of the volume or mass of the grinding media and the material to be ground.

**Table 1.** Percentage of raw materials and grinding media in the working chamber of the mill

| Lp. | shredded raw material | grinding media |
|---|---|---|
| 1. | 5% | 5% |
| 2. | 10% | 5% |
| 3. | 15% | 5% |
| 4. | 10% | 10% |
| 5. | 15% | 10% |
| 6. | 15% | 15% |
| 7. | 5% | 10% |

These values are referenced to the total volume of the working chamber of the mill.

In the technological processes of milling the division proposed by Koch is used, the criterion of which is attended by more than half the weight of grains in the product ground [11]. This means that the indication of the effectiveness of grinding was the determination of the size of the sieve opening through which will pass 50% of the grains of the product. The measurements carried out show that the optimal filling of the working chamber with the material ground with the grinding media is 20% of its

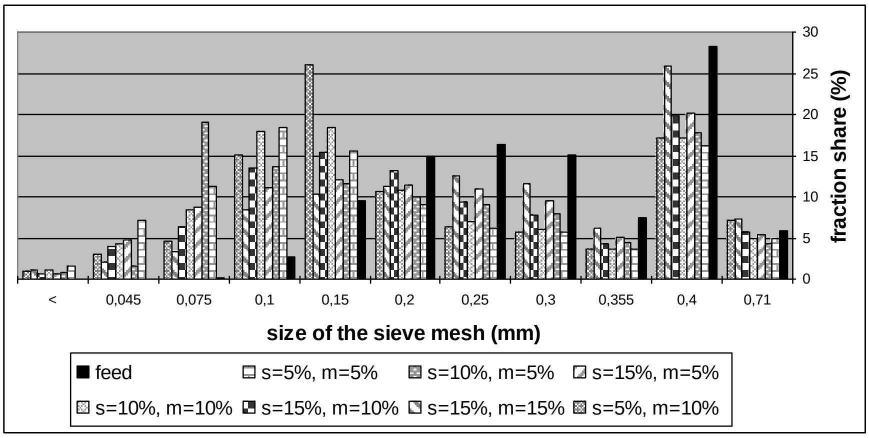



**Fig. 4.** Characteristics of the percentage share of fractions depending on the ratio of feed and grinding media: s – shredded raw material, m – grinding media

volume, with a 1:1 ratio of grinding media and feed. In order to illustrate the test results the characteristics shown in Figure 4 is plotted out.

The ratio of the mass of the shredded raw material to the weight of the grinding elements for the case in question is 0.5. Increasing the amount of feed in order to increase the efficiency of the mill entails a reduction of the amount of the grinding media (weight ratio > 0.5). The result is a reduction in the efficiency of grinding, which means a prolonged lifetime of the mill to obtain the desired granulation of the shredded material grains.

The approximate weight of the feed can be determined from the formula:

$$m_s = b_s \cdot \upsilon_k \cdot \rho_{us}\,, \tag{1}$$

while the mass of the grinding media from the formula:

$$m_m = b_m \cdot \upsilon_k \cdot \rho_{um}\,, \tag{2}$$

where:
$m_s$ – mass feed [kg];
$m_m$ – mass of grinding media [kg];
$b_s$ – degree of filling the mill chamber with material [%];
$b_m$ – degree of filling the mill chamber with grinding media [%];
$\upsilon_k$ – volume of the working chamber [m3];
$\rho_{us}$ – bulk density of the shredded material [kg/m$^3$];
$\rho_{um}$ –bulk density of the grinding media [kg/m$^3$].

The value of the degree of filling of the mill chamber with the shredded raw material $b_s$ and the grinding media $b_m$ was determined experimentally, while the cylindrical chamber volume is:

$$\upsilon_k = \pi \cdot r^2 \cdot l\,, \tag{3}$$

where:
$\upsilon_k$ – the volume of the working chamber [m$^3$];
$r$ – inner radius of the working chamber [m];
$l$ – length of the active region of the working chamber [m].

Substituting equation (3) to relationships (1) and (2) and taking as the optimum degree of filling the chamber with material and grinding media to be 0.1, the approximate formulas for the weight of the raw material and the grinding media placed in the working chamber of the mill take the respective form:

$$m_s = 0{,}1 \cdot \pi \cdot r^2 \cdot l \cdot \rho_{us}\,, \tag{4}$$

$$m_m = 0{,}1 \cdot \pi \cdot r^2 \cdot l \cdot \rho_{um}\,. \tag{5}$$

On the basis of equations (4) and (5) it is possible to calculate the optimal mass of the mill feed and the grinding media for the raw material and the construction of the electromagnetic mill tested.

## IMPACT OF THE SIZE OF THE GRINDING MEDIA ON THE EFFICIENCY OF THE PROCESS

The shape, size and material of which the grinding media are made have a decisive influence on the efficiency of grinding. Dimensions of the grinding components depend primarily on the type of material to be shredded.

Figure 5 shows the characteristics of the percentage fraction of the size of grinding media. It shows that the optimum dimensions of the grinding elements are grinding media with a diameter of 1.5 mm and a length of 15 mm (it is then that the greatest increase of the proper surface area of the ground material occurs). Tests have

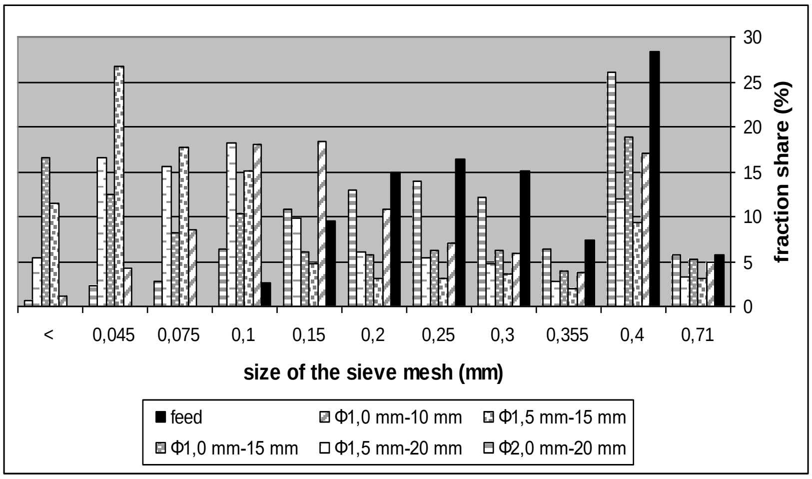



**Fig. 5.** Characteristics of the percentage share of the fraction depending on the size of the grinding media

also confirmed the theoretical assumptions of the proportion of length to diameter of the grinding media, which should be 1:10. If the ratio is smaller, then the grinding bodies "get stuck." This is manifested by their adhesion to the walls of the working chamber. A small length affects the inability to interact with the rotating field produced by the inductor mill.

In the case of preserving the proportions between the diameter and the length of the grinding media, but for sizeable lengths (over 20 mm for the working chamber with an outside diameter of 83 mm), the milling process subsides. The reason for this is the short-circuit between the magnetic poles of the inductor caused by the grinding media. In this case you can see a reduction in the temperature of the inductor as well as an oscillatory change in the current supplying the inductor in the range of Δ ± 0.3 A.

## EFFICIENCY OF THE MILL’S WORK

The term ‘efficiency of the electromagnetic mill’ can hide many meanings. The criterion here may be the particle size of the shredded material, short grinding time or low energy consumption.

Comparing the effectiveness of the electromagnetic mill with a conventional ball mill it can be concluded that the former produces fraction with a small particle size and within a very short time.

The analysis of the results shown in Figure 6 shows a 50% share of grains smaller than 0.100 mm. Gaining an even greater fragmentation in the electromagnetic mill requires the use of grinding elements with smaller dimensions or an extension of the operation.

The calculation adopted as a criterion is an 80% share of grains with smaller grain size of the feed and product in the total amount of material contained in the working chamber of the mill according to the form:

$$i_r = \frac{D}{d} \tag{6}$$

where:
$i_r$ – degree of fragmentation,
D – feed grain size [mm]
d – grain size of the product [mm].

For the electromagnetic mill this degree is $i_{80\%}=1,68$. The use of the 50% criterion, which corresponds to obtaining a much smaller particle size, increases the degree of fragmentation to $i_{50\%}=4,21$. This means that the electromagnetic mill achieves maximum efficiency during fine and very fine grinding. The exact determination of the degree of fragmentation in this respect is not possible by sieve analysis due to the large part of the fraction of the ground product with a particle size less than 0.025 mm. This is the limiting value of research for sieve analysis. In order to accurately determine the degree of fragmentation, tests should be performed using a microscope or laser device to study the grain size. It is worth pointing out that the grinding time in an electromagnetic mill during the study was very short in comparison to ball mills, which indicates a high efficiency of the grinding process in the electromagnetic mill. This time was 300 seconds. In ball mills, to achieve a particle size having similar properties, this time is much longer, i.e. up to several tens of minutes.

Figure 6 shows the standard deviation of the grinding product. The definition of "sample standard deviation" [30] was used, which is defined by the relationship:

$$\sigma_x = \sqrt{\frac{1}{N-1}\sum h_i^2}\,, \tag{7}$$

where:
$\sigma_x$ – standard deviation,
N – number of attempts,
$h_i$ – the deviation between the actual value and the average for the i-th measurement.

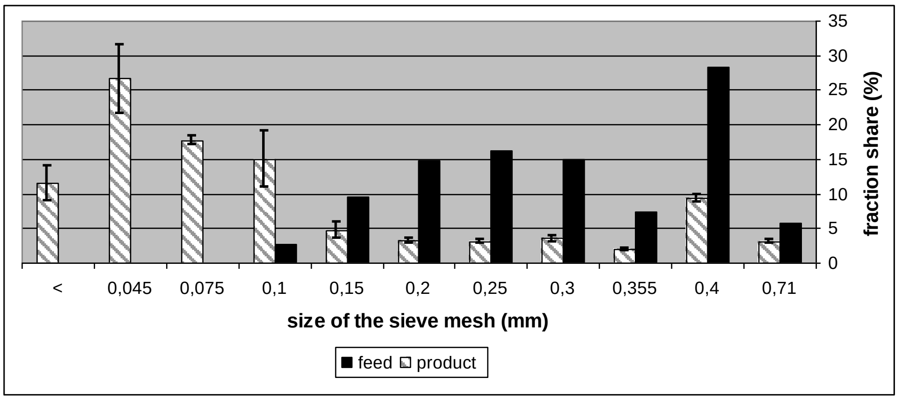



**Fig. 6.** Distribution of particle size before and after grinding in an electromagnetic mill

In the case of this research the standard deviation is less than 5%. A small value of the parameter *h* means that all the measurements are clustered and probably very accurate. This also demonstrates the reproducibility of the trials conducted.

## CONCLUSIONS

Based on the results obtained in the course of the above study the following conclusions were formed:

1. An electromagnetic mill with latent poles makes it possible to reduce the grinding time several times compared to conventional methods (rotating and vibrating mills), while keeping the same size of the fraction of the material to be shredded.
2. The efficiency of the mill depends primarily on the dimensions of the working chamber, the percentage of ferromagnetic elements and the material to be crushed. Empirical studies have shown that, for the raw material used, the optimal filling of the working chamber is from 20% to 25%, assuming the proportions of the grinding media and the material to be ground to be 1:1.
3. For different kinds of shredded material having different physical-chemical properties and different size fractions, one should optimize both the geometric dimensions of the grinding elements and the proportions of the grinding media and the amount of the raw material placed in the working chamber. Finding the optimum operating parameters may result from detailed laboratory tests.
4. Grinding raw material to the smallest particle size requires the use of ever-smaller grinding elements. It is also possible to use grinding elements of various sizes while grinding coarse-grained material.

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