Analysis of Possiblilities of Obtaining the Fine Particle Size in Mills of Various Designs

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Abstract

The paper presents the problem of obtaining the fine grained material in mills of different constructions. Various types of mills have been characterized, taking into account the type of grinding media used. Characteristics of selected mills and grinding media used were presented and the movement of the particles in the drum of the ball mill has been shown. Mills with mixed grinding media have been described. Model of "transport energy pulses" for free grinding media in the Kurrer's tubular chamber of the vibratory mill were described.
Paper discusses the advantages and opportunities for fine grinding in the electromagnetic mill, performance and in particular the energy cost of commimtion, that is achievable in this device.

Keywords: mills, grinding process, grinding media, electromagnetic mill, ball mill, vibratory mill, IsaMill

Introduction

Crushing operation of the raw material is widely used in many industries, from mineral processing to the chemical industry, construction, food, cosmetics and pharmaceuticals. Therefore, we have to deal with diverse expectations regarding the degree of fineness and characteristics of the crushing product. The process is energy intensive and is the subject of many scientific and industrial research conducted around the world [Sztaba, 2000; Gawenda, 2009]. Industrial operations of the feed material size reduction are the most energy-consuming processes in ore processing technological circuit and amount from 30 to 45% of total costs in mining industry [Saramak, 2013]. By itself, the process is very complex and depends on many factors such as: the size and form of crushed particles, the arrangement of the machine's crushing chamber, crushers technological parameters, physico-chemical properties of the material, the trajectory and speed of the grains movement [Gawenda, 2010].

The selection of the mill and its technical parameters in processing of raw materials determines the degree of product fineness. Also, the process of grinding is used for refinement of mineral aggregates. Types of mills, their use and basic parameters are shown in Table 1. The milling process can be described as the interaction of the ground structure of the body by means of force exerted by the grinding media, which leads to cracks and degradation into smaller components [Sławiński et al., 2014].

The yield of the grinding product is closely dependent on the type of feed and parametrs of grinding process. Considering the case of a particular material, the final efficiency of grinding is affected by the moisture content of the feed and its particle size as well as grinding media to feed ratio. Therefore, a direct comparison of various types of mills to each other is difficult and its yield is difficult to estimate. It is worth mentioning that parameters such as efficiency and energy consumption in various types of grinding plant, because their knowledge is essential to the initial assessment of the suitability of the mill and crusher at the specific application [Sławiński et al., 2014].

Characteristics of selected mills and grinding media used in them

The proper selection of grinding media in the mill is very important because it affects directly to the grinding process results and (quality of the product). Grinding is a process which depends on many factors related both to the construction of the mill and the nature of the feed material ground. Properly selected device parameters affect the effectiveness of its work both technologically and economically [Tumidajski et al., 2010].

Operating by impact and abrasion tumbling mills are the most commonly used in industrial

Tab. 1. Distribution of mills used in the energy sector (www.ppik.pl/sites/default/files/nr17%20MŁYN.pdf (21.04.2015)

Tab. 1. Podział młynów używanych w energetyce

Mills classes	Application	Parameters	Mills types
High-speed mills	grinding of lignite and hard coal with a granularity of 0-30 mm and a maximum moisture content of 65%	400 – 1500 RPM	hammer mills, fan mills
Medium-speed mills	for grinding lignite and coal by crushing between: the rings and balls, bowl and rollers, plate and rollers	30 – 150 RPM	Ball-ring mills, roller tylpe mills, cylindrical roller,
Slowly-rotating mills	for installation in central milling plants and systems with intermediate storage tank dust	15 – 30 RPM	Drum-ball mills
Mills finely and ultra grinding	to homogeneous fragmentation of lignite and coal with as little sizes to simultaneously increase productivity and reduce operating costs	parameters depend on the size scale of the installation.	electromagnetic mill, high pressure mills, micropowders mills.

plants. The division into ball mills or rod is applied based on the type of grinding (grinding media). The speed of grinding media is a function of the initial velocity of the ball at the moment of detachment from the working surface of the drum and the speed obtained by gravity and by collision descent. The initial ball velocity approximately equals to the peripheral speed and is limited to overcome the centrifugal force provided by the force of gravity. Typically, a peripheral speed selected in the range 70-80% of the critical speed, ie. the minimum speed at which the permanent circulation of the ball with the mandrel (the ball does not detach from the drum). According to the literature, higher speeds recommended to be used for the firmer feed, while smaller for feed with less brevity [Napier-Munn et al., 1996]. Brand and Pierow recommend to determine the speed of the empirical formula [Trybalski et al., 2005]:

$$n = \frac{b}{\sqrt{D}}[rot/\min] \qquad (1)$$

where: b – coefficient depending on the diameter of the mill, D – diameter of the mill, [m].

Typically, together with increasing the number of rotations of the drum the efficiency of the mill increases, while the device energy consumption takes a disproportionate increase beyond a certain optimum number of rotations. The increase in the final velocity is achieved by increasing the path of descent, and thus by increasing the diameter of the drum, which is crucial for the effect of grinding [Trybalski et al., 2005].

Rittinger (1867) assumed that the energy consumed by the grinding of solid materials is proportional to the newly created surface. It is expressed algebraically as follow

$$K\left(\frac{1}{D_2^3}\cdot D_2^2 - \frac{1}{D_1^3}\cdot D_1^2\right) = K\left(\frac{1}{D_2} - \frac{1}{D_1}\right) \qquad (2)$$

where: D_1 and D_1 – the selected feed particle size (D_1) and the product (D_2) [Foszcz et al., 2006].

There is an optimal size limit of balls in the mill, lower for the finer the particle size of the feed. There are many shapes of grinding media: cubic, octahedral, disks, ellipsoids, cylpebs, spheres and rods. The shape of the grinding fineness the predetermined range was selected in a number of industrial experiments that demonstrated the desirability of the use of rods for coarse grinding (0,8–0,6 mm), the balls to the average (product grain size 0.6–0.2 mm) and the cylpebs for small grinding (less than 0.15 mm) [Kasińska-Pilut, 2015]. From the seperation effect curves the relation of efficiency index to particle size can be read and the value of this index grows as the particle size becomes smaller [Surowiak, 2013].

In the classical drum mills – ball or rod – grinding media movement is caused by rotation of the drum mill (cylindrical operating chamber filled with grinding mediums). However, in the mills with loose grinding media: gravity, vibration, electromagnetic planetary or rotary vibratory, the grinding process is affected by the following kinematic parameters of movement of grinding media:

- movement,
- speed,
- energies,

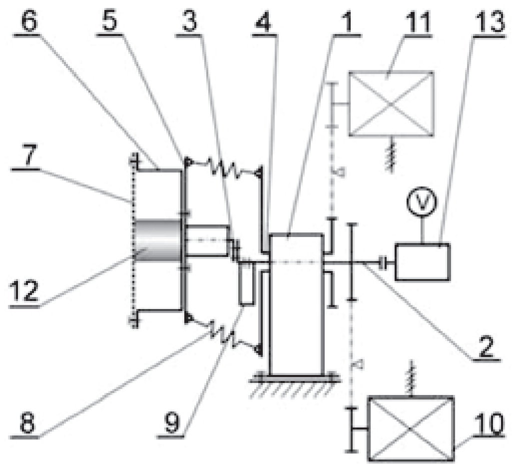


Fig. 1. Schematic diagram of the vibratory mill: 1 – drive module, 2 – shaft vibrator, 3 – an eccentric shaft, 4 – shaft drive enclosure, 5 – shield, 6 - chamber, 7 – bonnet, 8 – an elastic element, 9 – weight, 10 – a vibrating motor, 11 – the engine compartment, 12 – the insert, 13 – the vibration frequency measurement sensor [Sidor & Tomach, 2013]

Rys. 1. Schemat budowy młyna wibracyjnego: 1 – moduł napędu, 2 – wał wibratora, 3 – wał mimośrodowy, 4 – wał napędu komory, 5 – tarcza, 6 – komora, 7 – pokrywa komory, 8 – element sprężysty, 9 – obciążnik, 10 – silnik wibratora, 11 – silnik komory, 12 – wkład– ka, 13 – czujnik pomiaru częstotliwości drgań [Sidor & Tomach, 2013]

- the number of mutual collisions,
- the number of collisions between grinding mediums and carpeted chamber [Sidor, 2013].

Quantitative determination of these parameters should be done by the determination of the most favorable parameters of the grinding process, derived from real object or a laboratory or industrial mill. For some mills one can intuitively predict how traffic parameters chambers can affect the movement of the grinding media and consequently the grinding process. As an example, vibratory mill take the higher value of the frequency and amplitude of the vibration and the grinding process is more intense. However, it is difficult to determine in this way the most preferred degree of filling of the chamber, which has a significant influence on the grinding process. The aim of the constructor when designing this type of mill is to take only the values of the maximum oscillating motion, at which the grinding process has the highest efficiency and the greatest durability mill – at the lowest possible investment and operating costs [Sidor, 2013].

Vibratory mill

Milling in a vibratory mill, as in any mill with free grinding media, occurs by the use of part of the kinetic energy of the grinding media. This energy is the total energy of the progressive movement and rotational motion of the grinding bodies, usually in the shape of a sphere, and is a function of linear velocity and angular grinding aid in the second power [Sidor, 2013]. The vibratory mills grinding media receive energy from the vibrating chambers – several times greater than gravity mills. This energy can be readily increased by the increase in the frequency and amplitude of vibration of the working team on which are arranged the grinding chamber (1 to 6). Oscillatory motion of this unit, it generates mechanical vibrator inertia [Sidor et al., 2015]. Scheme of vibratory mill is shown in Figure 1.

The grinding process is dynamic, and its intensity is determined by linear velocity and angular frequency of grinding media collisions, as well as collision forces and energy transfer mechanism necessery for inter-particle grinding. The highest speed and energy gain grinding media contained in the layer in contact with the vibrating chamber. Successive layers of grinding medias located closer to the geometric axis of the chamber are less and less energy. This model is called "pulse energy transport model" and is shown in Figure 2 [Sidor & Tomach, 2010].

Kurrer developed this model for the mill with a chamber diameter of 0.3 m and verified diameter in the range of 0.2–0.7 m. The mill had a 15–30 Hz natural frequency, the amplitude of vibration 2,0–4,5 mm. a grinding mediums were round with a diameter of 20 mm, 25 mm and 40 mm. The results of the study confirmed the effect of enlarging the size of the zone with reduced activity grinding media with increasing diameter of the chamber [Sidor & Tomach, 2010].

Tumble mills: a ball and rod

In this type of mills, conventional grinding is performed by the grinding media. Tumble mills are used for grinding a variety of materials for wet and dry to afford a fine or very fine product. In the case of dry grinding, there is a fairly serious limitation in humidity of the raw material. Generally, it is required that in the case of grinding in a ball mill humidity should not exceed 3–5%. The disadvantage of this type of mill is a high energy consumption and spare parts (lining) and the grinding bodies [http://foresight.cuprum.wroc.pl/genetateTechnologies.php?id=91]. This solution results in low efficiency of the process due to the high loss of energy supplied to the grinding media, which only marginally reflects in the actual grinding process. There is no influence over the obtained shape of the grains, with the result that, obtained is often a product of low technological value.

Drum mill is a general name of mills made in the form of a rotatable drum with different ratios of length (l) to D (diameter). The mill can be completed in the middle of the grinding various factors such as rods, spheres and cylpebs [http://foresight.cuprum.wroc.pl/genetateTechnologies.php?id=91]. For grinding lump ore can also be use and then we deal with an autogenous grinding. If ore lumps and a little spheres (less than is needed for normal grinding) are used to grind then we are dealing with half self miling or so called half autogenous milling [http://foresight.cuprum.wroc.pl/genetateTechnologies.php?id=91].

The grinding of the material takes place as a result of the rotation of horizontally arranged drum. Under the influence of the rotational motion of the grinding media are being carried to a certain height, dependent primarily on the size of the grinding media, the type of carpet and rotational speed, then at some point the centrifugal force produced by the rotation of the drum is no longer sufficient and balls roll off down the top layer of spheres [Mateuszuk, 2012]. If the rotational speed of the mill is increased, the grinding media are beginning to be emptied above the point where the previous starting to roll away. As a result of further movement of the mill, grinding aid finally pulled away from the drum and falls down on the parabola, hitting the end of the grinding media layer lying at the bottom and rolls down after their upper layer at the bottom. In this case, the grinding is done primarily a result of abrasion by cascading balls and hitting by falling bullets. After crossing a certain speed of rotation of the drum (critical speed), the centrifugal force becomes so large that the grinding media "stick" to the drum and rotate with it, not doing grinding work [http://foresight.cuprum.wroc.pl/genetateTechnologies.php?id=91].

Rod mills are constructed in the form of a drum having an l:d ratio of approximately 1.4. The mill is filled with bars with a diameter of approx. 100 mm, made of high-strength steel that will not crack during the nesting load. Inside the drum mill is lined with steel plates resistant to wear. Manganese steel linings are not recommended [http://foresight.cuprum.wroc.pl/genetateTechnologies.php?id=91]. There are generally rubber lining because at their use would be too great.

Because the need to protect the rods from tangling, rod mills are normally carried out with a ratio l:d inside liners equal to 1.4 to 1.6. When the ratio was reduced to 1.25 tangling danger increases significantly. The size of rod mills is limited primarily by the ability to produce good quality rods which to the great length still retain the ability to hold straightness even in the final stage of wear of the bar. [http://foresight.cuprum.wroc.pl/genetateTechnologies.php?id=91].

Ball mills have been known for over 200 years. They are used mainly for the production of powder chemicals and minerals in the majority of bets mills used gravity called by ball mills [1-4]. In these mills it is very difficult to obtain ground material particle size less than 10 mm [http://foresight.cuprum.wroc.pl/genetateTechnologies.php?id=91]. This is due to the low energy of grinding media, which is a result of the operation of the mill, and the accompanying process of grinding detrimental effects coating system and agglomeration. The grinding process can be the selection of mills intensit, the value of technological parameters, i.e. the degree of filling of the chamber, a set of grinding bodies, the liner structure suitable aeration chamber and the use of a substance weakening the negative effects of the coating system and the agglomeration or grinding activator. Some substances can adversely affect the ground material and may also increase the costs of production of powder. These mills are used in grinding systems operating in an open or closed cycle. By convention adopted is to divide the coal mills ($l / d < 1.5$) and a tube mill in which the ratio exceeds a value of 1.5 with a value of

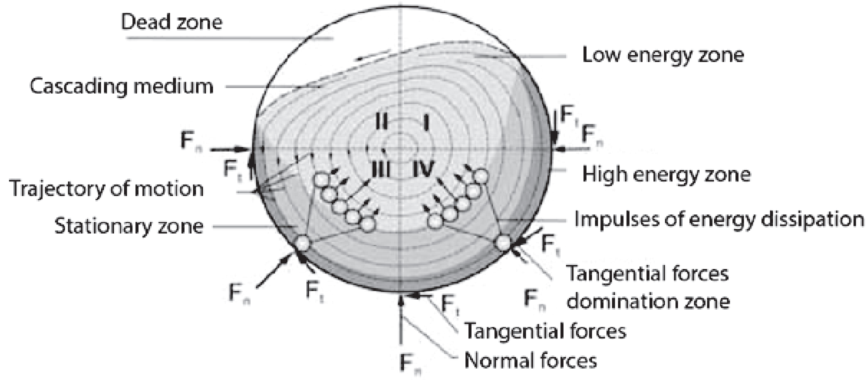


Fig. 2. Q [1]: F_n – normal pulse force F_t – tangential pulse forces and IV – quarters of the chamber [Sidor & Tomach, 2010]

Rys. 2. Model „transportu impulsów energii" swobodnym mielnikom w rurowej komorze młyna wibracyjnego według Kurrera [1]: F_n – normalne impulsy siły, F_t – styczne impulsy siły, I–IV – ćwiartki komory [Sidor & Tomach, 2010]

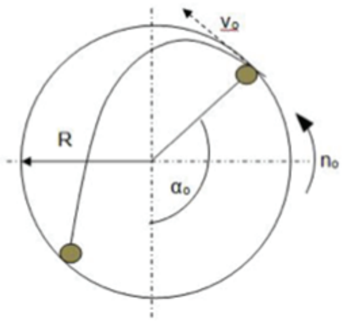


Fig. 3. The movement of the particles in the drum of the ball mill, according to [Skoczkowska et al., 2014]

Rys. 3. Ruch cząstki w bębnie młyna kulowego, wg [Skoczkowska et al., 2014]

generally about 5. Tube mills may have several compartments separated by diaphragms in which different grinding aids, and where there are different milling conditions. The size of the balls can be very varied from 35 to 150 mm [Skoczkowska et al., 2014].

Ball mills / cylpebs are both used for wet and dry grinding but they are usually not suitable for grinding material with a moisture content exceeding 1%. As cylpeps are designed for very fine grinding, the diameter generally does not exceed 35 mm. Because rods are not applicable as the grinding media, mills do not have the limitation of the unit size [Sidor & Tomach, 2013]. Different shapes of grinding aid can be used, such as polygons, cones, cubes, cylinders, discs, ellipsoids, etc. The experience shows that there is no better shape as a bullet. The construction of the mill drum is similar to a rod mill. The size of the feed particle size in the case of fine grinding should not exceed 1 mm Speed at which moves a grinding aid (particle) before reaching the critical speed can be calculated using the formula: [Skoczkowska et al., 2014]

$$V_0 = n2R\pi[m/s] \quad (3)$$

The angle at which a grinding medium (particle) breaks away from the wall drum can designate the following formula: [Skoczkowska et al., 2014]

$$\alpha_0 = \arccos\left(-\frac{(n2\pi)^2 R}{g}\right)[°] \quad (4)$$

The moment of detachment of grinding medium (particles) from the wall is shown in Fig. 3. Depending on the speed of the ball mill can be divided into several states the behavior of the fill. The figure illustrates suggested in Figure 4.

Mills with mixed grinding media

Stirred mills grinding media depending on the type of the mill and its technical solutions which enable implementation of the grinding operation for both dry and wet. For example, so-called

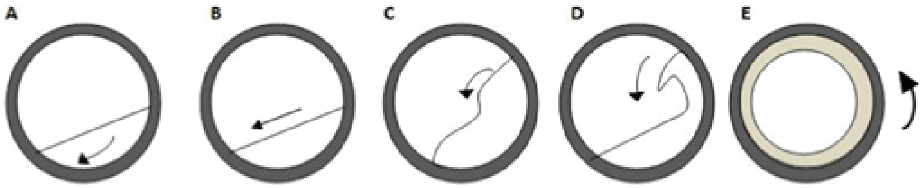


Fig. 4. Five of grading to fulfill a) to slide, b) the roll, c) cascading, d) cataracting e) centrifugation [Skoczkowska et al., 2014]

Rys. 4. Pięć stanów zachowania się wypełnienia: a) poślizg, b) toczenie się, c) kaskadowanie, d) kataraktowanie, e) wirowanie [Skoczkowska et al., 2014]

mixed mills (Agitated Mill - SAM) manufactared by METSO, allow both dry and wet grinding. The maximum feed particle size should not exceed 1 mm, and the particle size of the product is about 2 micrometers [http://foresight.cuprum.wroc.pl/genetateTechnologies.php?id=93].

Vertimill, also manufactured by METSO, can work in an open or closed circuit, and the feed rate and particle size of the product is the same as SAM mills.

According to the manufacturer, Vertimill generally has a feed particle size less than 15 microns at a lower cost than any other existing technology, but also enables the grinding of feed less than 7 microns in economic way. Due to the principle of operation, it seems that there are no limitations for obtaining the same particle size as in SAM and SMGM mills [http://foresight.cuprum.wroc.pl/genetateTechnologies.php?id=93].

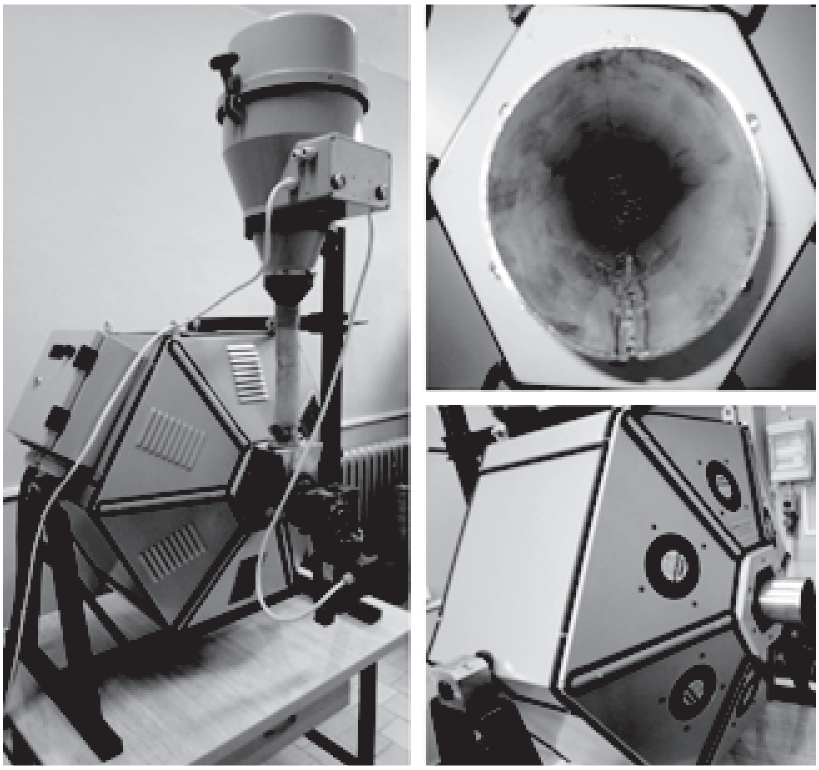
In the case of VertiMill mill, the feed particle size should not exceed 6 mm. The mill is designed for precise regrinding or for the preparation oflimestone flour. Due to the special purpose of this mill, the grinding technology of this device will be discussed separately.

Isa Mill is a new technology for fine grinding developed by Mount Isa Mines Ltd (MIM), a major international mining company based in Australia. It is a mill with a horizontal stationary mixing chamber equipped with a fast-rotating grinding discs for imparting the movement of the grinding media contained in the grinding chamber. Such a construction makes it possible to obtain high power density, and as grinding aids can be used river sand, slag or ceramic beads [http://foresight.cuprum.wroc.pl/genetateTechnologies.php?id=93]. The mill has a relatively low energy consumption compared with ball mills. The main disadvantage of this solution is, significant footprint in relation to electromagnetic mill, and thus the investment costs [http://foresight.cuprum.wroc.pl/genetateTechnologies.php?id=93].

Electromagnetic mill

Electromagnetic mill is a device in which the ferromagnetic grinding media are moved intentionally into rotation by electromagnetic field, as an energy carrier. The basic elements of the mill is an inductor, generating the magnetic field and placed in the axis of the tube constituting the working chamber (Figure 1). The working chamber is filled with approximately 20% of the ferromagnetic grinding media. They should be selected to the particle size of the particulate material [Bińczyk et al., 1999].

In the case of large variation of particle size of the material, a blend of grinding media of different sizes is applied.. Possible changes in the size of the grinding media adapts to the physical properties of ground material and final fineness of the product [Sławiński et al., 2014]. One of advantages of electromagnetic mill is possible intensification of many processes by carrying out grinding in the area in which the effect of the electromagnetic field maximise the rotate vortex of ferromagnetic rods [Bińczyk et al., 1999]. The mill operates efficiently in terms of both a high hydration material and low humidity, while the reduction in grinding efficiency of about 30% takes part for results in a material with a moisture content between 15–30% especially if it has the occasion of high viscosity. In contrast to conventional mill (ball, rod, or cylpebs), the housing of the mill is stationary, and the milling (or blending) takes place in the working chamber, inside which moves a small ferromagnetic elements – called grinding media. Their movement is caused by the action of a vortex electromagnetic field [Sławiński et al., 2014]. The effectiveness and efficiency of the process conducted in this mill is dependent on the proper selection of the physical parameters of the structure and process parameters such as feed flow (residence time), feed particle size, rotating speed and intensity of the electromagnetic field, temperature, humidity, and other parameters of



Pic. 1. Electromagnetic Mill

Zdj. 1. Młyn elektromagnetyczny

the workpiece (e.g. the lithological) [Drzymała, 1992].

The ability to control the size of the feed and grinding media, ongoing analysis of grain size and the operating status of the mill and recycle flow will allow for the full and far more effective mechanical activation of produced grains with specific physical and mechanical properties (size, shape, surface area and energy surface properties) as well as a significant increase in grinding efficiency and a reduction in energy consumption. Heat losses in the working chamber can be used for simultaneous drying and heating the material to be processed, what results in increased milling capacity [Bińczyk et al., 1999].

Summary

The paper presents overview of different types of mills. At the design stage it is extremely important to select proper parameters of grinding media (size, diameter, amount, material). They have a significant impact on the economic assessment of the process. Such electromagnetic mill will be designed during the project. Realization of crushing system in this electromagnetic mill with the control unit allow for the grinding of raw materials dry or wet in a closed cycle, with the possibility of arbitrary and very broad selection of speed of movement of the grinding media with different parameters. The ability to control the size of the feed and grinding media, ongoing analysis of particle size and the operating status of the mill and recycle flow will allow for the full and far more effective mechanical activation of produced particles with specific physical and mechanical parameters (size, shape, surface area and energy, surface properties), and also for significant increase in grinding efficiency and reduction of the energy consumption.

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22. http://foresight.cuprum.wroc.pl/genetateTechnologies.php?id=91 (dostęp 20.04.2015)

Analiza możliwości uzyskania drobnego uziarnienia w młynach o różnych konstrukcjach

W artykule przedstawiono problematykę uzyskiwania drobno uziarnionych materiałów w młynach o różnych konstrukcjach. Dokonano charakterystyki różnych rodzajów młynów z uwzględnieniem typu stosowanych mielników. Pokazano charakterystykę wybranych młynów i użytych w nich mielników. Opisano ruch ziarna w bębnie młyna kulowego, a także model „transportu impulsów energii" ku mielnikom w rurowej komorze młyna wibracyjnego według Kurrera. Omówiono zalety i możliwości w zakresie drobnego mielenia w młynie elektromagnetycznym w szczególności wydajność oraz wydatek energii na rozdrabnianie, jakie możliwe jest do uzyskania w tym urządzeniu.

Słowa kluczowe: młyny, rozdrabnianie surowców, mielniki, młyn elektromagnetyczny, młyn kulowy, młyn wibracyjny, IsaMill