Аналітично знайдено рівняння зв'язку між технологічними параметрами кульового млина, подрібнюваного матеріалу і параметрами стержневого первинного перетворювача енергоефективності подрібнення руди. Методом використання основного стержневого первинного перетворювача з більшою площею перерізу, на торці якого руйнуються крупні шматки руди при ударах куль, і додаткового стержневого перетворювача з однаковими параметрами і меншою площею перерізу, який взаємодіє лише з кулями, досягнута інваріантність визначення енергоефективності подрібнення руди кульовим млином до зміни швидкості руху мольних тіл. Аналітично отримана математична модель енергоефективного подрібнення руди кульовим млином з трифазним рухом мольних тіл, інваріантна до зміни довжини стержнів в процесі спрацювання. Модель здатна оцінювати енергоефективність подрібнення крупних шматків руди за отриманим об'ємом зруйнованого крупношматкового матеріалу. Математична модель містить константи – площі поперечних перерізів стержневих первинних перетворювачів, початкову довжину стержневих первинних перетворювачів, довжину базової ділянки встановлення тензодатчиків, значення модуля Юнга матеріалу первинних перетворювачів, а також змінні константи, які визначаються подрібнюваним матеріалом. Також аналітично отримана залежність для визначення довжини основного стержневого первинного перетворювача, відповідно якій можливо оцінювати висоту футеровки, що спрацьовується в процесі роботи.

Розроблена функціональна схема системи автоматичного контролю енергетичної ефективності подрібнення руди кульовим млином дозволяє знаходити розрахункові параметри сучасними мікропроцесорними засобами. Згідно розробленій схемі можна побудувати алгоритми визначення об'єму руди, що підлягає руйнуванню, та товщини футеровки в кульовому млині, які відкривають перспективи створення програмних продуктів.

Комп'ютерним моделюванням доведена можливість застосування запропонованого методу для оцінювання енергоефективності подрібнення руди кульовим млином з трифазним рухом куль. Встановлена висока чутливість запропонованого підходу до відхилення ефективності подрібнення руди від найкращого значення. Доведена можливість оцінювання параметра з відносною похибкою ±2,5 %

Ключові слова: енергетична ефективність, автоматичний контроль, подрібнення руди, кульовий млин, пружні перетворювачі

IDENTIFICATION OF ENERGY EFFICIENCY OF ORE GRINDING AND THE LINER WEAR BY A THREE-PHASE MOTION OF BALLS IN A MILL

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1. Introduction

A breakthrough in ore preparation has been the design of a technological unit with a low discharge level [1]. In these mills, balls move in a three-phase cycle, in contrast to two phases in units of previous structures [2]. This research field has been advanced in papers [3–6]. The velocity fields of a shear layer at low and medium rotation speeds of the drum were reported in [3]. The three-phase ball motion in the mill's drum was simulated in studies [4, 5] and other publications. Great improvement in the characteristics for this ball mill is achieved via adaptive control over pulp rarefaction [6]. An improved mill with a low discharge of pulp and a three-phase movement of balls can increase the growth of specific performance at the first stage of grinding by 28–30 %.

Despite the significant advantages of the new type of a ball mill, such units are slowly introduced to production.

One of the main obstacles is the lack of means of automated control over energy efficiency of ore grinding and the wear of a liner, which leads to an increase in the cost of the resulting product – iron ore concentrate.

2. Literature review and problem statement

Initially, automated control over the energy efficiency of ore grinding at ball mills was executed based on a generalized indicator. A given indicator took into consideration the ball and ore loading, as well as water, by measuring the magnitude of oil pressure in supporting bearings, the mean power of a drive electric motor, the acoustic signal formed in the mill. Later, the vibroacoustic means of control over the operation of ball mills were developed [7]. That approach was subsequently improved through signal processing [8, 9].

However, these means do not resolve the task on estimating the state of loading even in terms of quantity, to say nothing about its qualitative performance and energy efficiency of ore grinding.

A new direction of research was initiated in paper [10]. The authors devised a model of a nonlinear observer, which includes a series of technological parameters and derivatives from some of them. However, the article concluded that under available measurements of technological parameters it is not possible to distinguish between ore and balls, not to mention the characteristic size of ore and its shredding.

In addition, especially following the advent of a new type of ball mills, there is an increased interest in determining the wear of a liner without stopping the units, because a possibility to predict its service life is uncertain in the industry. Thus, a new model was proposed to predict the wear rate of a liner. The model includes the following basic parameters: the type of ore, relative speed between ore and a liner, the rigidity of a liner, conditions for friction, etc. [11]. The model proposed could determine the liner wear depending on operating conditions. However, this is an indirect determination of the liner wear and it does not provide for adequate accuracy.

In this situation, it appears promising, as shown in [12], to select and study parameters that can be controlled automatically, which would directly characterize the energy efficiency of the process of a material destruction in the mill's drum. Such a parameter could be the deformation of a homogeneous rod that interacts with balls and red at three-phase motion of grinding bodies. A given converter makes it possible to measure the liner wear as well.

The above components of the task show that it is required to solve a generalized problem, which comes down to identifying the energy efficiency of ore grinding, as well as the liner wear, at three-phase movement of balls in the mill.

3. The aim and objectives of the study

The aim of this study is to identify the energy efficiency of ore grinding, as well as the liner wear, at three-phase movement of balls in the mill based on homogeneous rod primary converters intended to measure technological parameters.

To achieve the set aim, the following tasks have been solved:

– to analytically derive the equation that relates the technological parameters of a ball mill and the parameters of a primary rod converter when shredding large pieces of ore;

– to achieve invariance of the volume of shredded ore to a change in the motion speed of balls in a technological unit;

– to derive a mathematical model of determining the volume of shredded ore at the end side of a rod primary converter, invariant to a change in the motion speed of balls and its length in the process of operation;

– to derive the equation that relates parameters of the length of a rod primary converter that is excited in the upright position by the impact of a reference ball against the idle end side to measuring parameters;

– to design a circuitry for the implementation of an automated control system over the energy efficiency of ore grinding by mills with a three-phase movement of balls, as well as the liner wear.

4. Research methods to control the energy efficiency of ore grinding and the liner wear in a ball mill

4. 1. Choosing a primary converter of energy efficiency of ore grinding and the liner wear in a ball mill

In the current work, a principal structural measuring element is the homogeneous rod converter of constant cross-section with one fixed end. At the other end of the converter, ore pieces are shredded by the normal impacts from balls, which in a given mill move under in a three-phase mode. The length of the rod under these conditions is 250 mm. The impact of a ball leads to an elastic deformation along the rod primary converter. First, there is the compression of the rod primary converter, followed by the reverse process – its unloading. If force F is a variable function of time, the speed c of compression deformation wave propagation remains unchanged, while velocities v of cross sections motion at any time are different along the rod. The same features are characteristic of the reverse process. If F=const, then the velocity of cross sections motion remains unchanged as well. The devised model is capable of simulating the shredding of ore and wear of the mill's liner.

4. 2. Development of a generalized model for a rod primary converter

Based on [13], the expression for determining the absolute value for the contraction of a rod primary converter under the action of force F takes the following form

$$\Delta l = \frac{l_0 F}{E\,S},\tag{1}$$

where Δl is the absolute value for contractions; l_0 is the initial length of a rod; E is the Young modulus (modulus of longitudinal elasticity); S is the cross-sectional area of a primary rod converter.

The propagation speed of a compression deformation wave along the axis of the rod is equal to

$$c = \sqrt{\frac{E}{\rho}},\tag{2}$$

where ρ is the density of a material of a primary rod converter.

The deformation at velocity v makes all the particles of a material in the compressed part of the primary rod converter move. A given velocity v is many times less than the wave propagation speed c. The speed is equal to

$$\upsilon = \frac{F}{S\sqrt{\rho E}}.\tag{3}$$

The force applied along the rod primary converter, which caused the contraction f, will equal

$$F = \frac{E \cdot S \cdot f}{l_0},\tag{4}$$

where f is the complete contraction of a rod primary converter under the action of force F.

The time required for all the particles of a material of a rod primary converter to pass at deformation along direct and reverse directions is

$$t_d = \frac{2l_c}{\upsilon},\tag{5}$$

where l_c is the current length of a rod primary converter that wears together with a liner.

The work of deformations in the deformed volume of a shredded piece of ore, which dissipates in the form of heat is determined from dependence [14]

$$A_d = kk_1 V_p, \qquad (6)$$

where k is the coefficient of proportionality that depends on the strength of ore; k_1 is the dimensionless coefficient of proportionality; V_p is the volume of a shredded piece of ore.

Dependence (6) makes it possible to determine the work spent for shredding a piece of known technological variety of ore based on its defined volume.

In long ball mills, which include ore milling as well, along a drum there form the zones of grinding environment with approximately the same size of balls in the outer layer of their particular cross-section [15]. A given distribution of balls is confirmed experimentally at existing ball mills by a sound-metric method. In addition, such an effect of balls arrangement can be enhanced by using the specialized profiles of a liner [16].

Features of a three-phase movement of balls in the mills with a low discharge of pulp, dependences of parameters for a rod primary converter and balls arrangement in the drum, make it possible to execute automated control over energy efficiency of ore grinding and the liner wear.

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5. Results of research into control over the energy efficiency of ore grinding by mills with a three-phase movement of balls and the liner wear

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5. 1. Analytical derivation of equation that relates the technological parameters of the process and converter

Grinding of large pieces of ore occurs at the upper side end of a rod through the kinetic energy of moving balls. Kinetic energy, in contrast to potential, depends not on the coordinates of a body but on its speed, and remains constant until a numerical value for speed changes. If a body moves at constant speed, the sum of all forces acting on it equals zero; in this case, no work is performed. If a body acts at some force along the motion direction towards another body, it can perform work. In this case, the body's kinetic energy changes. A change in the body's kinetic energy equals the work performed in this case. Since the kinetic energy used to shred a piece of ore equals the work that is performed when it is shredded, then one can record $E_{kd}=A_d$, where E_{kd} is the kinetic energy spent on shredding, A_d is the work performed when shredding a piece of ore. The work performed at shredding a piece of ore is expressed by dependence (6).

Kinetic energy $\dfrac{m_k \upsilon_k^2}{2}$ of the ball of mass m_k moving at velocity υ_k is spent on performing the work of shredding a piece of ore at the upper end side of a rod and on the deformation of compression of a rod primary converter. The deformation of compression of the rod primary converter uses the kinetic energy of a moving ball, reduced by the magnitude A_d. The velocity of a ball after the deformation of compression of a rod primary converter is zero. The body that has completely stopped is unable to carry out work, so all the energy due to its movement equals the work that is performed when moving a body to the full stop: $A=F \cdot s$, where F is force, s is the path traveled. In our case, the work of compression deformation is

$$A_{dc} = F_1 \cdot f_1, \qquad (7)$$

where F_1 is the force that develops when a rod converter is compressed; f_1 is the full contraction of a rod under the action of force F_1.

Given that a change in the kinetic energy of a moving ball is equal to the work performed in this case, one can record the following equation

$$\frac{m_k \upsilon_k^2}{2} = kk_1 V_p + F_1 f_1. \qquad (8)$$

In equation (8), force F_1 is uniquely associated with the full contraction of rod f_1 via dependence (4). Substitute F_1 from equation (4) in (8) and obtain

$$\frac{m_k \upsilon_k^2}{2} = kk_1 V_p + \frac{ES}{l_0} f_1^2. \qquad (9)$$

Equation (9) relates the technological parameters of a ball mill, the shredded material, and the parameters for a rod primary converter of energy efficiency of ore grinding.

5. 2. Achieving the invariance of control over energy efficiency of ore grinding by a ball mill to a change in the motion speed of balls

The velocity of balls υ_k under a three-phase movement mode will vary within a significant range when changing operational conditions of a ball mill. Given that the velocity of balls, in addition, is included squared in the equation, one should expect significant errors in determining the volume of ore V_p.

We shall introduce the concept of basic and auxiliary rod primary converters of energy efficiency of ore grinding by a ball mill (Fig. 1). The basic rod primary converter (Fig. 1, a) has a greater cross-sectional area compared to the auxiliary rod converter (Fig. 1, b). It concentrates and destroys large pieces of ore under the impacts of balls. For the basic rod primary converter, equation (9) takes the form

$$\frac{m_k \upsilon_k}{2} = kk_1 V_p + \frac{ES_1}{l_{01}} f_1^2, \qquad (10)$$

where S_1 and l_{01} are, respectively, the cross-sectional area and the initial length of a basic rod primary converter.

It is possible to improve the accuracy of determining the volume of ore V_p at the upper end side of the basic rod primary converter by discarding a variable parameter υ_k in the dependence. For this purpose, an auxiliary rod primary converter, whose upper end side, given its small cross section, does not receive large pieces of ore that must be shredded (Fig. 1, b), is installed next to the basic one. The auxiliary converter must be installed independently of the basic one. Such a primary converter is characterized by that the entire kinetic energy of a moving ball would convert into the work on compression deformation. In this case, the following equality holds

$$\frac{m_k \upsilon_k^2}{2} = F_2 f_2, \qquad (11)$$

where F_2 is the force that develops when an auxiliary rod converter is compacted; f_2 is the full contraction of an auxiliary primary converter under the action of force F_2.

In a general case, the auxiliary converter has other structural parameters. Therefore, by using dependence (4), write down

$$\frac{m_k \upsilon_k^2}{2} = \frac{E_2 S_2}{l_{02}} f_2^2.$$

(12)

Considering that under particular conditions for the operation of a ball mill the velocities of ball motion are the same, we equate the right-hand sides of equations (10) and (12)

$$\frac{E_2 S_2}{l_{02}} f_2^2 = k k_1 V_p + \frac{E_1 S_1}{l_{01}} f_1^2,$$

(13)

hence

$$V_p = \frac{1}{k k_1} \left(\frac{E_2 S_2}{l_{02}} f_2^2 - \frac{E_1 S_1}{l_{01}} f_1^2 \right).$$
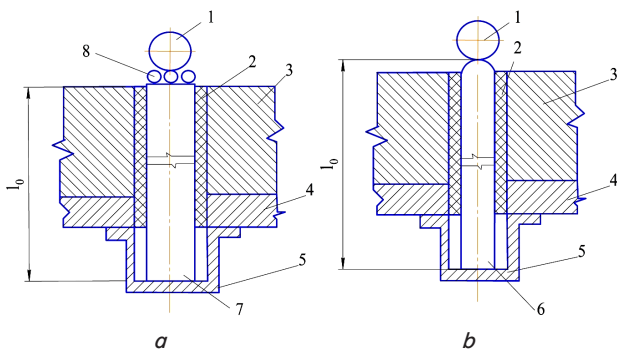
(14)

Fig. 1. Schematic representation of rod primary converters of energy efficiency of ore grinding in a ball mill: a — basic; b — auxiliary; 1 — ball; 2 — waterproofing and amortization fastening; 3 — liner; 4 — fragment of a mill's drum; 5 — support; 6 — auxiliary rod converter; 7 — basic rod converter; 8 — large pieces of ore

We fabricate the basic and auxiliary converters using the same material of the same length, but with different cross-sectional areas. Then $E_1 = E_2 = E$, $l_{01} = l_{02} = l_0$. Considering it, equation (14) takes the form

$$V_p = \frac{E}{k k_1 l_0} \left(S_2 f_2^2 - S_1 f_1^2 \right).$$

(15)

Equation (15) links the technological parameters of shredded material, the structural parameters of rod primary converters, their deformations, and does not depend on the motion velocity of balls.

Contraction of the basic and auxiliary rod primary converters could be determined through secondary converters. There are many methods to measure deformations. A study into characteristics of the mechanical properties of structural steel has established that reliable results could be obtained from a strain gauge [17]. Measurements of deformations in real conditions of operation on steel structures have shown close coherence between the measured and simulated deformations [18]. A research into optimization of strain gauge arrangements when estimating the characteristics of a structure has proven that the unified model for the optimization of strain gauge arrangement forms through maximizing the coverage [19]. That is, strain gauges should cover the entire

length of rod primary converters, thus registering complete contractions.

5. 3. Construction of a mathematical model invariant to a change in the length of rods

It is impossible to determine the volume of large pieces of ore inside the working space of a converter based on the complete contraction of length f_1 and f_2 from dependence (15), since these parameters are not available while the rods wear out. Therefore, the deformation parameters for the compression of rods are most appropriately measured based on their final section at a certain distance x from the fastening point. The region for measuring parameter B can be represented as part of the entire length of the converter, that is, $B = k_2 l_0$, where k_2 can theoretically accept a value from 0 to 1. Assume that the distance of planes and a base B for measuring the parameters of both converters are the same. Given the proportionality of deformations along the converters under certain forces, values for the contraction of parts of the rods on bases B for measuring contraction accept

$$f_{11} = f_1 \frac{B}{l_0},$$

(16)

$$f_{21} = f_2 \frac{B}{l_0}.$$

(17)

Define complete contractions of rods in the process of measurement from dependences (16) and (17), which would equal

$$f_1 = \frac{l_0}{B} f_{11},$$

(18)

$$f_2 = \frac{l_0}{B} f_{21}.$$

(19)

Substituting the found values for f_1 and f_2 in dependence (15), we obtain

$$V_p = \frac{E l_0}{k k_1 B^2} \left(S_2 f_{21}^2 - S_1 f_{11}^2 \right).$$

(20)

The derived dependence (20) is a mathematical model for the energy-efficient ore grinding in a ball mill, according to which one can control a given technological parameter during operation.

5. 4. Determining the wear of a mill's liner

In the operation of a ball mill, one needs to know the state of the liner wear. It is advisable to elucidate by defining the length of rods because they wear out along with the liner. The current length l_z of rods that partially worn out during operation of a ball mill of initial size l_0 can be determined based on one of them, for instance basic, from dependence

$$l_z = \upsilon \frac{T_i n_c}{2} + l_P,$$

(21)

where υ is the velocity speed of particles of a material under the strain of compression and unloading of a rod primary converter; T_i is the period of oscillations of a measuring generator; n_c is the number of pulses over a separate cycle of measurement; l_P is the distance between the idle end of

the basic rod to the point of mounting a strain gauge at base distance B. The liner's wear is $l_c = l_0 - l_z$.

The measurements that are performed in line with formula (21) are carried out using a strain gauge signal. The strain gauge perceives fluctuations in the rod over the idle cycle when a wave propagates in direct and reverse directions. The wave is excited by the impact of a reference ball against the idle end of the basic converter at each rotation of the mill's drum.

5. 5. The circuitry for implementing the identification of energy efficiency of ore grinding and the liner wear

A functional scheme of implementing the automated control over energy efficiency of ore grinding in a ball mill is shown in Fig. 2. When the mill's drum rotates around axis 12, the balls in the outer layer first move along a circular trajectory, since they are pressed to the liner. In the upper part, they detach from the liner and move along a parabolic trajectory, followed by their movement along a straight line at the surface of the supporting layer of grinding bodies, coated with pulp, until they hit a liner in the bottom part of the drum. Along the parabolic trajectory, the motion velocity of balls is constant, so their kinetic energy is permanent. Part of this energy is lost in the process of moving along the straight line. There, the motion velocity changes; it can accept different values at the time a ball hits a liner because the kinetic energy is lost depending on the position of a supporting layer of grinding bodies, the level of pulp, pulp density and its viscosity, and other factors. In a particular technological situation, the motion velocity of balls and their kinetic energy would remain constant prior to the impact against a liner.

A ball mill is loaded with large fractions of ore, residing in the pulp formed by a small firm solid. The volume of large fractions of solid in a unit volume of pulp is a measure of the energy efficiency of ore grinding in a ball mill. This volume of large solid 2 will stay at the upper end of basic rod 11 at the moment of impact of ball 1. The same processes would occur at liner 3, located at the inner surface of drum 4; they, however, are out of control.

The energy required to shred large fractions at the upper end of rod 11 depends at certain strength of ore 2 on its volume in the controlled zone of shredding. Thus, a given energy is a measure of the energy efficiency of ore grinding in a ball mill. The energy applied to the rod upon impact is equal to the kinetic energy of a moving ball, reduced by the magnitude of energy required to shred large fractions of solid at the upper end of the basic rod. The more a mill is loaded with ore (the concentration of large solid in pulp, the volume of ore at the upper end of the basic rod), the greater the energy that is used by a ball to destroy large solid. In this case, the residual energy of the ball that ensures the compression of a basic rod at the moment of impact will be lower. Basic rod 11, rigidly fixed by support 9, would contract less in this case. Thus, the contraction of basic rod 11 can be used to estimate the energy efficiency of ore grinding in a ball mill. The same information is acquired from the contraction of the controlled section of rod 11. However, when the balls' kinetic energy is lost along the section of rectilinear motion in the pulp, the results would be distorted. That would introduce a considerable error to the identification of a ball mill's loading. This is because the level, the density of pulp, and other factors, may accept different values during operation, which are characteristic of a given technological regime in a particular situation.
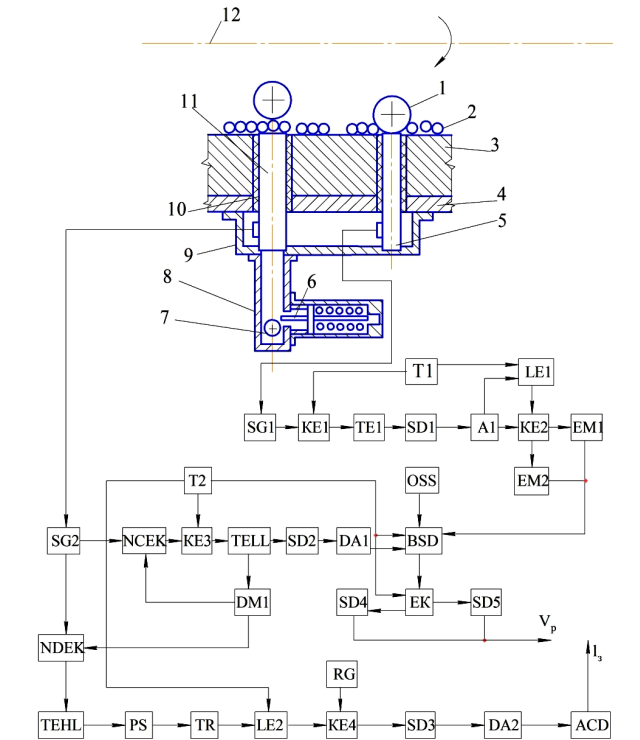

Fig. 2. A functional scheme of implementing the automated control over energy efficiency of ore grinding in a ball mill: 1 — ball; 2 — pieces of ore; 3 — liner; 4 — wall of the drum; 5 — auxiliary rod; 6 — lock; 7 — reference ball; 8 — oscillation exciter; 9 — support; 10 — waterproofing and shock-absorbing sleeve; 11 — basic rod; 12 — mill's rotation axis; SG1, SG2 — strain gauges; T1, T2 — timers; KE1, KE2, KE3, KE4 — key elements; TE1 — threshold element; SD1, SD2, SD3, SD4, SD5 — storage devices; A1 —amplitude selector; EM1, EM2 — elements of memory; LE1, LE2 — logical elements «AND»; NCEK — normally closed element of key; TELL — threshold element of low level; DA1, DA2 — devices to average signals; BSD — basic computing device; OSS — ore strength setter; EK — element of key; DM1 — decelerated multivibrator; NDEK — normally disabled element of key; TEHL — threshold element of high level; PS — pulse shaper; TR — trigger with two stable states; ACD — auxiliary computing device, RG — reference generator

Auxiliary rod 5 is fabricated with a small cross-section, which is why hitting its end by ball 1 is an unlikely event compared to basic rod 11. Even more unlikely is the situation when a particle of large solid is arranged at the time when ball 1 hits the end of auxiliary rod 5. Therefore, the current work will mostly register the impacts of ball 1 against the end of auxiliary rod 5. In the time interval, preset by timer T1, strain gauge SG1 generates signals that, through key element KE1 and threshold element TE1, arrive to storage device SD1. Threshold element TE1 does not let the random pulses of small amplitude enter storage device SD1. Storage device SD1 accumulates, in the time interval preset by timer T1, the signals that correspond to the direct hit of the ball against rod 5, and, possible, against rod 5 through a large chunk of ore. A pulse of the highest amplitude would correspond to a direct collision between auxiliary rod 5 and ball 1. The pulse is displayed at device A1 and is sent to the input of key element KE2, which enables the in-turn recording of

the highest value from rod 5 in a given time interval, preset by timer T1, and erases the preceding value. The command to execute such an operation is triggered by logical element «AND» LE1, the input of which must receive a signal from the timer about the end of the cycle, and a signal on the largest value for a measured parameter. If device A1 failed to generate such a signal, then the operation of a control system would continue based on the previous value for the largest signal from auxiliary rod 5. This corresponds to a highly unlikely event when there was no, in the time interval preset by timer T1, any collision between ball 1 and the end of auxiliary rod 5. Thus, the outputs of memory elements EM1 and EM2 will always produce the signal from auxiliary rod 5. A contraction in the controlled section of auxiliary rod 5 describes the magnitude of the kinetic energy of a ball under these technological conditions. Because the mass of a ball and its speed at the end of a parabolic section remain unchanged, the contraction of the controlled section of auxiliary rod 5 carries information only about the level of change in the kinetic energy in the process of ball motion along a straight section prior to its hitting the liner and contraction f_{21}. The same changes in the kinetic energy of a ball in this technological situation would be characteristic of basic rod 11.

The contraction of a section of basic rod 11, measured by strain gauge SG2, is converted into an electrical signal, which, via a normally closed element of key NCEK, a key element KE3 in case timer T2 is enabled, enters the threshold element of low level TELL, set to a certain level of the signal. Under the largest loading of the mill will ore the signal from strain gauge SG2 would be minimal, especially when the strongest ore is used. However, the signal would be even much smaller when a ball hits a junction, thereby covering part of the working end of rod 11 and waterproofing and shock-absorbing sleeves 10 or liner 3. The level of setting threshold element ПЕНР should be slightly higher that this signal. Then storage device SD2 receives signals whose amplitude exceeds the threshold level of element TELL. These signals correspond to objective information about the volume of large fractions of ore 2 at the working end of basic rod 11. The signals that arrived to storage device SD2 are averaged by device DA1.

The averaged signal characterizing the volume of shredded ore at the working end of basic rod 11, through its contraction, arrives to one of the inputs of basic computing device BSD, whose other inputs receive a signal from ore strength setter OSS, a signal that corresponds to the contraction of auxiliary rod 5. Other quantities at devices are physical or accepted to be stable, defined by the design of the control system over energy efficiency of ore grinding in a ball mill and are recorded to permanent storage devices. The primary computing device, in accordance with dependence (20), defines the volume of ore to be shredded. The result of computation is sent via EK to storage device SD4 or SD5.

The fact of ball 1 hitting or missing the working end of basic rod 11 at rotation of the drum of a ball mill around axis 12 is a random event. Thus, it can be guaranteed to happen only over a specific period of time or after certain number of the drum rotations. A given time interval is set by timer T2. Since the probability of ball 1 hitting the end of auxiliary converter 5 is significantly smaller compared with such a probability for the basic converter, then the time interval to register the contraction of a section of auxiliary converter 5 should be several times longer. The time interval is se by

timer T1. Given that one should not accept it to be too long considering a possible certain change in the technological situation, it is advisable to operate at shorter intervals and their actual prolongation only in cases when there were no collisions between balls and auxiliary rod 5 over the pre-defined cycle. This is provided by logical element LE1.

A channel for determining the thickness of a liner in a ball mill functions in the following way. Passing a signal by threshold element of low level TELL triggers decelerated multivibrator DM1, which, over the period of exposure, disables connection between strain gauge SG2 and key element KE3 and enables, during exposure time, the chain of normally disabled element of key NDEK connecting strain gauge SG2 to threshold element of high level TEHL, which is also set to a certain amplitude of the signal. At the same time, when a mill's drum rotates around axis 12 vibration exciter 8 enters the zone close to the vertical state. Reference ball 7, while overcoming the resistance of support 6, deals a severe blow to the idle end of basic rod 11, which excites a wave process in the rod – a wave of compression propagates to the working end and, bouncing off it, a wave of unloading moves to the idle end. In this case, strain gauge SG2 generates a signal of significant amplitude, however, due to the disabled element of key NCEK, they do not enter the channel where a signal about the amount of shredded ore forms and, conversely, they arrive, through a temporarily disabled element of key NDEK, at the input of threshold element of high level TEHL, then pass it, forming a pulse in PS, thereby changing the state of the trigger with two stable states TR, which, along with a signal from timer T2, generates at the output of logic element «AND» LE2 a permissive signal at the input to key element KE4. Fluctuations from reference generator RG arrive to storage device SD3. When strain gauge SG2 generates a signal of significant amplitude when an unloading wave passes trigger TR enters a second stable position. If there is a signal from timer T2 and a change in the signal from trigger TR a permissive signal at the output to logical element «AND» LE2 disappears and memory device SD3 terminates counting the pulses. Therefore, the number of high-frequency pulses in ACD corresponds to double the distance from strain gauge SG2 to the working end of basic rod 11. Thus, as a result of ending the exposure of decelerated multivibrator DM1, switches are executed in elements NCEK and NDEK. The circuit is again ready to receive the main signal about crushed ore from strain gauge SG2. The signal, averaged by device DA2, is sent to the input of auxiliary computing device ACD, which, according to dependence (21), determines the current length of rods that matches the thickness of the liner in a ball mill.

6. Discussion of results of the identification of energy efficiency of ore grinding and the liner wear

The energy efficiency of ore grinding in ball mills is defined by the concentration (volume) of large particles of ore over a section limited by its area. The volume of the ore can be determined by shredding it, as it was established in the derived equation of relationship between the technological parameters of a ball mill and the parameters for a primary rod converter. A given approach is characterized by the direct measurement of a parameter, which guarantees high accuracy. Prior to this, the indirect measurements were performed at rather low precision.

Mills with a three-phase movement of balls during the final phase typically change their speed, which depends on the state of ball environment, the density and level of pulp over a supporting layer, which would severely affect the accuracy of control. Achieving the invariance to a change in speed almost eliminates the disadvantage of these ball mills in terms of measurement.

A mathematical model of two-rod determination of the volume of shredded ore at the end of a primary rod converter is invariant both to a change in the velocity of balls and to a change in the length of converters in the process of wear. The model makes it possible to measure the volume of shredded ore with high accuracy, since the major disturbing factors do not affect it.

Determining the thickness of a liner is also performed by direct measurement of the parameter, which ensures high accuracy compared to the indirect estimation [11] that does not warrant high accuracy.

The circuitry that was used to implement the proposed system of automated control over operating parameters at grinding ore in mills with a three-phase movement of balls has shown the feasibility of a given approach. It is possible to accurately determine the operational parameters of grinding by using modern microprocessor tools. Mathematical modelling has established that the relative error in determining the parameters would not exceed ±2.5 %. That will significantly improve the effectiveness of ore preparation at modern enrichment plants.

The results obtained (the equations for rod primary converters, a mathematical model of control over energy efficiency of ore grinding, the equations for determining the thickness of a liner in a ball mill) could be used for both analytical and computational experiments. They could be applied when implementing control operations in ball mills with a three-phase motion of balls of different sizes. The equations for determining the thickness of a liner in a ball mill might be used when implementing control operations in mills with a two-phase mode of ball movement. The technique for achieving measurement invariance with the application of an additional rod primary converter could be implemented for converters of other types.

Note that there are still unresolved issues related to the development of both means of control and tools for signal processing. The disadvantages of this approach also include the need to replace rod primary converters when the liner of a ball mill wears out, as well as certain difficulties in transferring signals from a rotating object to a stationary one.

In the future, it is planned to design and investigate the systems of automated control over energy efficiency of ore grinding in mills with a three-phase motion of balls of specific sizes and to explore the impact of speed of a compaction deformation wave's propagation along the axis of a rod on the readings by strain gauges. The first specified shortcoming is easily eliminated by fabricating rod primary converters in units that are mounted in the hatch of a mill's drum. The second drawback, characteristic of rotating objects, is typically removed by applying radio engineering tools. In order to almost completely eliminate it, noise-resistant radio equipment is designed that could automatically set operation modes.

The results reported in the current work need no experimental verification, since all the provisions have been proven analytically. There are no assumptions that could have deviated results from those obtained. The only parameter that might affect the accuracy of identification is a coefficient k_1 in dependence (6), which characterizes the shredded volume of ore and the volume exposed to the pressure of a falling ball. If these volumes are the same, then there is no error in the identification of a technological parameter. Experimental verification would be appropriate when designing means of identification for specific operational conditions.

7. Conclusions

1. We have analytically derived an equation that relates the technological parameters of a ball mill and the parameters of a primary rod converter when the balls destroy large pieces of a material at its end. That proves the possibility to use a converter as a means of control over energy efficiency of ore grinding at the early stages of ore preparation at concentrating mills. The energy efficiency of ore grinding is estimated based on the volume of shredded large chunks of a material in the pulp, which are at the end of a rod primary converter at the time point of contact with the ball. The volume of the shredded ore must match the value determined with precision.

2. Using two rod primary converters – the basic one with a greater cross-sectional area, where ore is shredded, and the auxiliary one with a lower cross-sectional area, which interacts with the ball without ore – we have achieved the invariance of the volume of destroyed material to a change in the motion velocity of balls within a technological unit with a low level of pulp discharge. That warrants high precision in estimating the technological parameter under conditions of change in the state of ball loading, as well as parameters for pulp.

3. We have analytically derived a mathematical model of the two-rod determination of the volume of shredded ore based on the contractions of basic and auxiliary rod primary converters using the accepted deformation measurement bases by strain gauges. The model is invariant to both a change in the motion velocity of balls and in the current length of converters in the process of wear. This ensures the independence of the measured technological parameter on the magnitude of forces applied by balls and the length of rod primary converters that wear out during operation. By using the proposed mathematical model, it is possible to estimate not only the fact of energy efficiency of ore grinding, but to track when a ball mill approaches an emergency as a result of overload. This can be achieved due to that the sensitivity to deviations in the volume of a material from recommended levels is high enough. Testing the method by computer simulation has shown that it is possible to estimate the energy efficiency of ore shredding with a relative error not exceeding ±2.5 %.

4. We have derived an equation relating the parameters of length of a basic rod primary converter that is excited in the upright position by the impact of a reference ball against the idle end, and the measured parameters. The measured parameters include: the motion velocity of particles in a material inside a converter at deformation of compression and unloading, the period of oscillations of a reference generator, and the number of pulses over a separate cycle of measurement. A given equation makes it possible to determine the current length of partially worn-out rods, and, consequently, the thickness of the liner and to determine the magnitude of its waer as the difference between the starting and current

lengths. Information about the liner thickness in a ball mill is rather valuable because it makes it possible to estimate dynamically the performance of a technological unit and to prolong the inter-service periods of technological units that work under loaded modes.

5. The designed circuitry for the implementation of a system of automated control over energy efficiency of ore grinding in mills with a three-phase movement of balls and the liner wear has demonstrated the feasibility of a given approach in automated mode. By using modern microprocessor means, based on the proposed mathematical model, it is possible to determine with high accuracy the volume of destroyed large pieces of ore that corresponds to the energy efficiency of material grinding. Similarly assessed is the thickness of a liner in a ball mill. That makes it possible to significantly improve the performance of ball mills with a three-phase movement of balls, to reduce the consumption of power, balls, and liner.

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