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MASS FLOW CONTROL IN A JET MILL BASED ON ACOUSTIC MONITORING

Purpose. To justify the control of the jet grinding process by building a closed cycle model using Markov chains and acoustic monitoring of the grinding operation zones.

Methodology. Modeling is carried out on the basis of system analysis using a cell model. To describe the grinding process, acoustic signals from the operation mill zones are used. Theoretical calculations of changes in the grain-size composition are compared with the results of experimental fireclay grinding.

Findings. The material particle size change in the mass flow of the jet mill and the classifier was considered regarding the characteristic changes of the acoustic signals recorded in these parts of the grinding units. According to the results of continuous monitoring of the operation zones of the grinding plant, a model of mass flow movement in a closed cycle and changes in the particle size distribution of the initial material from the loading bunker to the unloading of the ready ground product was created. Based on the model, the possibility of the grinding process control is shown. A functional scheme for controlling the mill operation as a whole has been developed. The created hardware base for jet mill control was tested in experimental and industrial processes of grinding various materials.

Originality. For the first time, a cell model of the material flow movement in all elements of a grinding plant using acoustic signals recorded in them was created. The granulation kinetics in the mill, in the classifier and in the unloading bunker of the ready material is described by matrices containing the acoustic signal characteristics of these zones. The number of matrices corresponds to the number of installation functional elements, and they are combined into one common block matrix.

Practical value. The obtained results are used to build an automatic control system for the jet mill productivity according to its loading control based on the acoustic monitoring results of operation areas.

Keywords: *mass flow, grinding, modeling, control, automatic control system, jet mill*

Introduction. Dry-grinding mills, in particular jet plants, are characterized by high energy consumption that hinders their widespread use. In usual operating conditions, the mill modes are not optimal. In the industrial grinding process, the operational parameters change depending on the raw material type and insignificant permissible deviations of the technological parameters. These parameter changes sometimes lead to the technological process violation, the specified mass flows in the elements of the grinding plant become unstable, which causes overload, stopping the mill. For improving the grinding installation efficiency, the mass flow modeling and the current control development of their operation modes are relevant.

Literature review. In Linch's works, the operation features of various grinding plants and the process modeling occurring in them were considered. Open-cycle grinding plants provide for material single loading, i. e. all the material from the grinding zone passes a classifier where the entire material flow is divided into the ready product (the required size class) and larger than it, after that the grinding cycle is finished [1]. From the beginning of grinding, small particles are formed, their further presence in the flows leads to overgrinding and waste of energy. Therefore, the process in closed grinding cycles is organized in such a way that in the mill the material is ground to a predominantly larger class, then after the classifier the fine fraction is released into the ready material bunker, and the large one feeds the mill again.

The main direct task of a grinding model constructing in a closed cycle has been considered in many papers [2] and usually consists of determining the particle size distribution of the grinding product according to a well-known scheme and process characteristics in the grinding installation elements. Most research is based on integro-differential equations using balance equations.

The grinding describing process is quite complex and this is due to several reasons [3]. First of all, it is the random nature of the process itself. The characteristics of the initial material, the strength and shape of its particles vary in a wide range. The particle movement in a two-phase flow in the installation elements also has a stochastic character. For its implementation, stochastic models are more suitable, which, according to the applied mathematical methods, practically do not differ from the flow motion models or diffusion models of real processes. This is due to the process similarity. Stochastic models are hydrodynamic models of the probability density evolution, while the concentration is replaced by the probability density of staying in the cell, and the diffusion coefficient and drift coefficient are calculated according to certain curves with the characteristics of the random effect spectrum on the system.

Recently, stochastic models based on the theory of Markov chains [4] have been widely used. The basic structural unit of such models is the transition probability matrix from one layer (cell) to another, taking into account the mill shape and the mass flow characteristics in it.

A new approach to the jet grinding optimization is considered in [5]. The authors proposed a methodological framework for the fine grinding regime assessment based on the acoustic monitoring results of grinding plant operation zones. The recording method, analyzing acoustic signals and using information methods for identifying modes and optimizing them is discussed in [6].

Thus, an advanced approach is the combination of stochastic entire chain modeling of technological closed scheme elements with the use of the process acoustic monitoring results. The solution of this problem allows controlling grinding modes and improving the jet grinding plant productivity as a whole.

Unsolved aspects of the problem. Typically, the technological installations of dry fine grinding materials include mills (jet, vortex, planetary), a classifier, and bunkers for initial material loading and the ready ground product unloading. In each element, combined into a technological grinding unit, the material granulometric composition is converted in mass flows. Therefore, at the grinding process modeling, it is necessary to consider the changing process of the fraction particle size in the mass flows.

In the works by the authors [5, 6], connections were established between technological parameters and characteristics of acoustic signals (AS) recorded in the operation zones of the mill and the classifier. On this basis, the possibility of describing a grinding process based on the acoustic monitoring results of the operation mill zones is substantiated. However, the simulation of particle collisions was considered only in the operation area of the grinding chamber. For stable operation of the entire grinding plant, the classification mode has a great importance. A complete model of the grinding process in a closed cycle should include a change description in mass flow in the classifier, too. The studies have shown the predominant effect of grinding chamber loading degree on the mill productivity as a whole. Therefore, modeling the size reducing process in a grinding plant for mill productivity control should take into account the operation of the material loading bunker and the ready product unloading one.

Results. The hardware scheme of acoustic monitoring was developed and described in studies [5]; it includes a waveguide connected to a piezoceramic sensor, then an analog-digital converter that captures, stores and transmits signals to a computer. Fig. 1 shows a general grinding plant scheme with the process acoustic monitoring. In Fig. 1 the following notation are adopted: *1* – loading bunker; *2* – classifier; *3* – ready ground product bunker; *4* – piezoceramic sensor; *5* – programmable logic controller (PLC); PC – personal computer, ADC-analog digital convertor; *6* – power control unit; *7* – solenoid

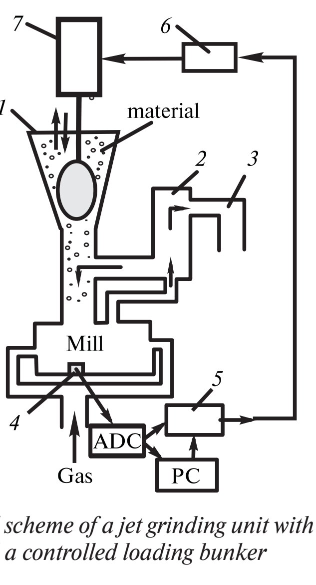


Fig. 1. General scheme of a jet grinding unit with acoustic monitoring and a controlled loading bunker

In this work, the material flow modeling is realized in the main operation areas of the grinding plant, which are of great importance for monitoring and controlling of the technological process efficiency: in the grinding chamber, classifier and auxiliary areas – the loading unit and the unloading ready product bunker. Thus, the grinding process in the grinding plant operation areas is considered as a dynamic system, for which the state is uniquely determined by the acoustic signal aggregate at a given time. The grinding system change laws, consisting in changing the initial state over time, are described by a cell model based on the acoustic signal analysis using Markov chains.

Mass flow modeling in the mill. We consider the whole mill as an elementary volume for modeling the grinding process in a mill that operates in a batch mode. To describe the material size class transformation in the grinding chamber, the signal characteristics recorded by the sensor through a waveguide installed in the grinding zone with constant acoustic monitoring [5] are used. The mathematical model is based on the acoustic signals (AS) amplitude analysis recorded at each discrete point in time of the grinding process in a closed cycle.

To create a cell model, all recorded signals are divided into sub-bands, signal groups with average amplitude sizes A_i, $i = 1, 2, \ldots, m$ in each i cell, where $i = 1$ corresponds to A_{max}. Thus, all signals recorded during acoustic monitoring are divided into m cells according to their amplitude size, starting with the maximum value.

The elementary cell state is described by the number of signals with amplitudes that correspond to a given cell. Then any unit cell state can be described by a vector column with the number of signals $N = (n_i)$, $i = 1, \ldots, m$ of this i cell. On the other hand, the particular cell state can be characterized by the occurrence probability of a given number of signals with corresponding amplitude A_i. Therefore, the entire system state at a given time can be represented as a set of signals with an amplitude value $A^k = \{A_{i,j}\}$.

In the grinding process, each cell state changes, however, any time period is represented as a sequence of infinitely small gaps Δt, which are the transition time from one state to another. Then the current time moment can be represented as the sum of these transitions, i. e. $t_k = k\Delta t$ where integer is the transition number $k = 1, 2, \ldots$. The state of the material in the chamber at this current moment is described by a vector N^k by a set of signals, while the amplitudes of these signals, associated with the particle size in the chamber, make the cell field corresponding to the fractional material composition at the moment.

The change in the recorded signal amplitude during grinding per time step Δt is calculated, as is customary in the constructing cell model theory, from matrix equality $A_{k+1} = GA^k$, where G is the grinding matrix with g_{ij} elements, whose values can be interpreted as the transition probabilities to other cells. These coefficients form a triangular matrix.

$$G = \begin{bmatrix} g_{11} & 0 & \cdots & 0 \\ g_{21} & g_{22} & 0 & 0 \\ \cdots & \cdots & \cdots & \cdots \\ g_{m1} & g_{m2} & g_{m3} & 1 \end{bmatrix} = \begin{bmatrix} 1 - S_1\Delta t & 0 & \cdots & 0 \\ S_1 b_{21}\Delta t & 1 - S_2\Delta t & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots \\ S_1 b_{m1}\Delta t & S_2 b_{m2}\Delta t & \cdots & 1 \end{bmatrix},$$

where S and b are auxiliary functions related to the acoustic signal characteristics in the mill operation area. The grinding rate is described by a function $S(A_i)$, and in our case, it describes the reduction rate per unit time of the signal number with an amplitude from the A_i subband. Signals with a reduced amplitude level set in the neighboring blocks, where signals with a smaller magnitude are located. The probability of signal transition from the j cell to the i cell is described by the function $B = \{b_{i,j}\}$. The technological grinding process in terms of the characteristics of the acoustic monitoring signals can be shown as reducing the signal amplitude of the grinding zone, i.e. to increasing in the number of currently recorded signals placed on sub-bands with smaller amplitudes.

The particle destruction, when signals with amplitude A_i appear, occurs at a specific power of signals P_{ij}. The elements P_{ij} represent the value of the signal specific power in each i cell (i. e., signal sub-band with amplitude A_i) at the j step

$$P(A) = \frac{1}{t}\sum_{i=1}^{m} n_i A_i^2.$$

The expression for the auxiliary acoustic function definition is

$$S_i = \frac{1 - P_i}{\Delta t}; \quad B_i = \frac{P_i}{S_i \Delta t}.$$

Thus, with periodic mill loading, the process can be described by auxiliary acoustic functions from the recorded signal amplitudes of the process acoustic monitoring. This fact is used to control the grinding modes.

Mass flow in the classification area. In the classification zone, the mass flow of the ground material from the mill separates into two streams, the solid phase of which differs in particle size relative to the control size x_c of the ready product. One two-phase stream with a predominant content of fine particles is sent to the bunker of the ready product. Another stream is a circulating load of the grinding plant and contains an unacceptable (according to the technological quality requirements of the grinding product) particle number sized larger than the control size. This stream is sent for regrinding. To build the classification process model, a classification matrix is usually used, constructed using the classifier separation curve $C(x)$, the elements of which reflect the probability of selected size particles appearance into a thin product [7]. In this paper, the classification process is also described with the characteristics of acoustic signals recorded in the classification zone.

During acoustic monitoring of material different fraction transportation in a flow, different acoustic signals are recorded, having their own characteristic frequency and amplitude [8]. Therefore, in the cell model based on the AS, the classifier can be described by the matrix C

$$C = \begin{bmatrix} C_{11} & 0 & \cdots & \cdots & 0 \\ 0 & C_{12} & 0 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & \cdots & C_{1m} \end{bmatrix}.$$

Each element of the matrix corresponds to the signal proportion characteristic to the fraction sent to the ready product. For two product classifications, which mainly occur in industrial classifiers, the material is divided into two fractions: large C_l and small C_s. Then the modeling task is simplified. In this case, the classification matrix is expressed

$$C = \begin{bmatrix} C_{1i} & 0 \\ 0 & C_{1k} \end{bmatrix}.$$

In the ready product bunker, the material accumulates, no longer participates in the grinding. In a stable operating mode, ready material accumulation and its periodic unloading occur. Therefore, in the entire stable process matrix, it is possible to designate the operation of the ready product bunker with the conventional zero matrix.

On a continuous material feeding of the closed system, there are states A^0, FA^0, F^2A^0, ..., etc. The full vector describing the material state in the flows of the grinding plant as a whole, after a finite number of transitions (k time intervals) is

$$A^{k+1} = A^0 + FA^0 + F^2A^0 + \ldots + F^kA^0 =$$
$$= (I + F + F^2 + \ldots + F^k)A^0.$$

This expression is the sum of the matrix geometric progression with the matrix denominator F. This progression is decreasing because in the zone of the unloading ready product bunker, the sum of probabilities over columns is less than one (equal to zero), and by analogy with a normal progression, its sum can be calculated as

$$A^{\infty} = (I - F)^{-1} A^0 = -F_i^{-1} A^0;$$

$$F_i = \begin{bmatrix} I & I - C & 0 \\ G & -I & 0 \\ 0 & C & -I \end{bmatrix}, \quad (1)$$

where G is the matrix describing the mill signal change; C is the matrix describing the signal change in the classification zone, the symbol $^{-1}$ means the matrix inversion.

So, the grinding process in the jet installation with acoustic monitoring of the operation zones can be described by matrices containing the characteristics of the acoustic signals of these zones. Moreover, the matrices number corresponds to the number of installation functional elements, and they are combined into one common block matrix. On its main diagonal there are single matrices with a minus sign. Each column of the combined matrix corresponds to the installation element, and its matrix is placed in the row with the element number where the material is sent from it. The steady-state process parameters with the AS amplitude are calculated from (1).

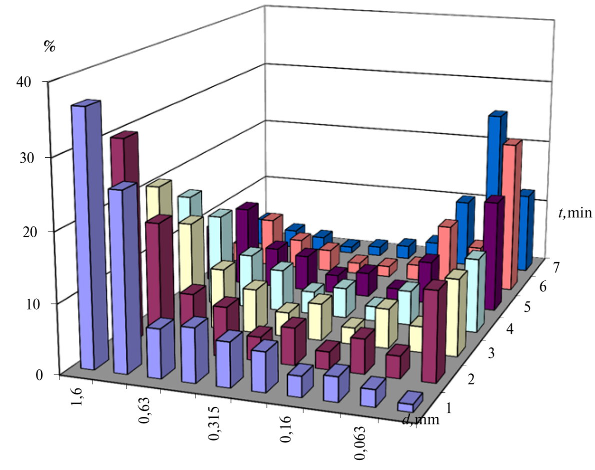
Calculation of the kinetics of the process. For the numerical jet grinding process representation, a material was chosen – a slag fraction (1.0 + 0.63), the grinding kinetics of which in the ITM National Academy of Sciences of Ukraine and the State Space Agency of Ukraine (ITM) experimental grinding plant is shown in Fig. 2. Fig. 2, *a* shows the particle size changing of the selected fraction in a closed grinding cycle, and Fig. 2, *b* – grinding process measurement without taking into account the accumulation in the bunker of the ready product.

The grinding process of the specified fireclay fraction was described by the created cell model. The initial matrix A^0 of the loading process signals was recorded when the fraction was ground at an experimental mill. In this case, the change in the material particle size distribution during grinding was taken into account; the established links between the acoustic signal amplitudes in the grinding zone and the material size were used [8]. For blast furnace slag, the established dependence was: $\lg d = 0.5 \lg A + 1.3$. As a result of the calculations, the grinding matrix was determined and the process was simulated in the grinding zone. Fig. 3 shows the result of the grinding process simulation.

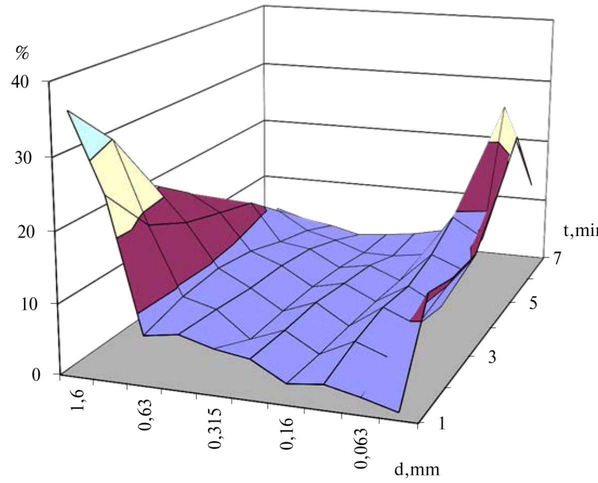
The results of experimental studies. The results of theoretical studies were verified by the acoustic monitoring results of the grinding process of blast furnace slag at the ITM laboratory jet mill with a capacity of 20 kg/h. The hardware complex for the automatic control system of the grinding process is shown in Fig. 4.

Signals were recorded at a frequency of 200 kHz. Process technological parameters are: energy carrier (air) pressure $P =$ $= 0.3$ MPa, classification mode – classifier rotor speed $n =$ $= 1000$ c^{-1}, time of one grinding cycle without additional material feed $t = 10$ min. Fig. 5 shows the acoustic process monitoring signal recording.

Comparing the results of numerical simulation (Fig. 3) and recording acoustic signals of the working area during the experimental fireclay grinding (Fig. 5) at the jet set USI-20, one can note a satisfactory coincidence. Fig. 6 shows the signal record sections of the calculated and experimental data in the



a



b

Fig. 2. Kinetics of fraction (1.0 + 0.63) of fireclay in the experimental grinding

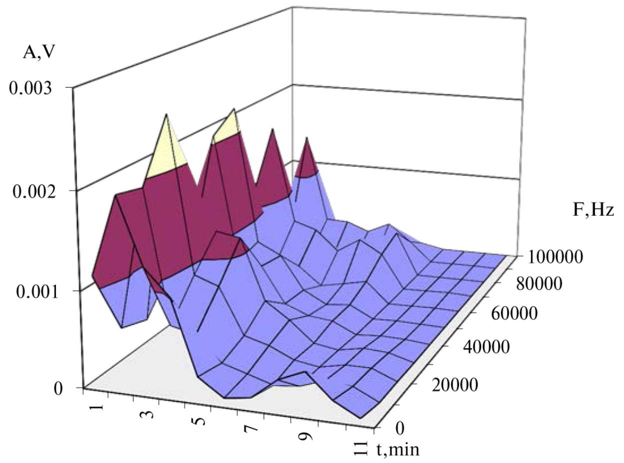


Fig. 3. Modeling the process of grinding slag by acoustic signals

steady-state reduction mode, and the modeled signals of mode 1 indicate the need for additional loading, i.e. to make a signal to open the loading bunker, which corresponds to the time t_{feed} in Fig. 6.

According to the acoustic monitoring of the slag grinding process under the specified technological conditions, a steady state was established from 4 to 8 minutes of grinding.

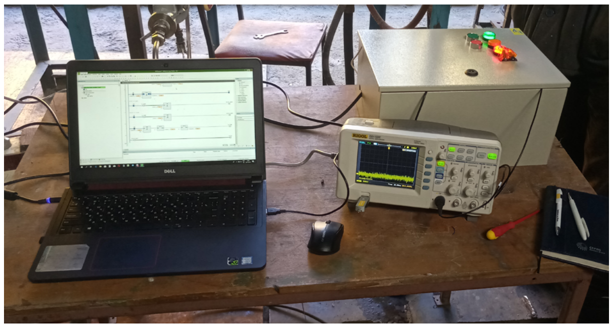


Fig. 4. Research control complex of jet grinding mill USI-20

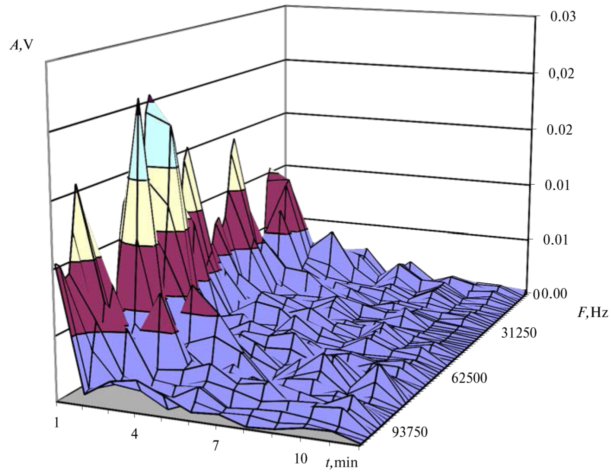


Fig. 5. Signal recording of blast-furnace slag grinding process at the USI-20

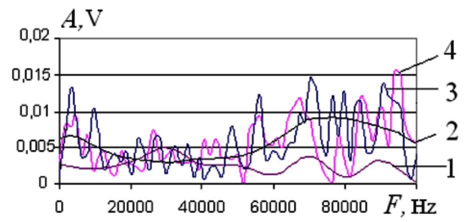


Fig. 6. Comparison of signal records obtained in the simulation (1, 2) and the experimental fireclay grinding (3, 4)

For one-time loading after the specified interval, the grinding operates in the non-optimal mode and there is underloading of the working zone, which reduces the process efficiency. With constant continuous material loading into the mill, the jets may be overload with the material and the grinding mode may be interrupted. It has been established that the signals of the operating mode and the overload or underload of the grinding chamber are significantly different [5]. Moreover, the mass flows depend on the classification mode, which forms recycling in the grinding plant.

For each required ready product size, its own grinding and classification mode and, accordingly, its range of acoustic signal characteristics for an optimal grinding mode (in the sense of achieving maximum productivity) are established. This is the basis for controlling the mass flow in the mill based on the results of acoustic monitoring.

Grinding process control. The grinding process control system is based on the physical model of the process and the results of its acoustic monitoring. As a regulated parameter of the control system, the change in the mass flow concentration in the grinding zone was used. The main disturbing effect during grinding is the change in the jet filling with material.

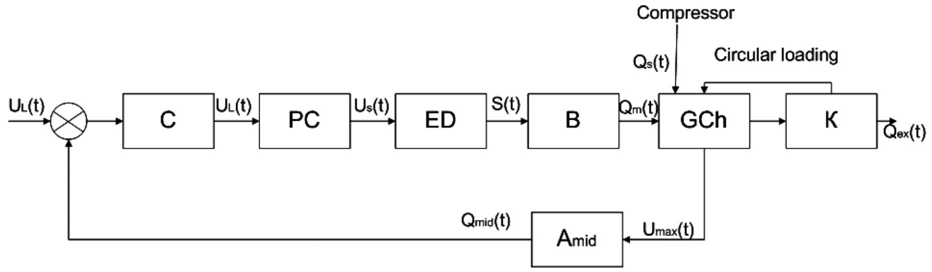


Fig. 7. Functional scheme of ACS for jet mill

While developing the control system, it is necessary to take into account the circulating load presence (material return flow after the classifier) and delay of the initial material passage through the supply channels. The task signal is formed on the basis of mass flow modeling taking into account technological conditions (energy carrier parameters, classifying mode), properties and size of the initial material, as well as the results of an acoustic signal analysis of the operation zones of the grinding plant [9]. In particular, for slag grinding, it was found that the optimal operation of the grinding plant is achieved at the signal level from the acoustic sensor $A = 1.2$ *V,* which corresponds to $A_{mid.} = 0.075$ V in the amplitude-frequency representation of the signals (Fig. 5). The lower limit of the permissible signal range in the implementation of grinding is $A_{mid.} = 0.0003$ V, with these signals (the state of the empty chamber at time $t = t_{feed}$), the grinding does not occur. Proceeding from this, the task signal is formed at the ACS input. In Fig. 7 a functional diagram of the automated jet mill control system is shown, where *C* is a controller, *PC* is a power converter, *ED* is electric bunker drive, *B* is a loading bunker, GCh-grinding chamber, *K* is a classifier, A_{mid} is signal processing and filtering.

The function of the power converter in the presented circuit is the conversion of the control signal into the corresponding voltage for the solenoid. This converter is presented in the form of aperiodic link of the 1st order. A solenoid with an operating current in a steady state of 5 A and a voltage of 12 V, with a return spring, which activates (lowers) the shutter in the form, revives and closes the loading bunker in case of power supply failure (Fig. 1).

After processing all the data, the control signal comes from the PLC TM3DQ8U expansion module to the solenoid control unit, which is assembled on the basis of the STP100N6F7 field-effect transistor with an operating voltage of 60 V and a maximum current of up to 100 A. (Fig. 4). The control signal is transmitted to the opening or closing of the loading bunker valve. To describe the change in the material output from the bunker with a change in the area of the outlet bunker opening a model of the bunker [10] was compiled.

This grinding process control system has been tested at a jet grinding unit USI-20, an industrial test is being prepared under the conditions of the Vilnohirsk Mining and Metallurgical Plan.

Conclusions.

1. A model has been developed for changing the mass flows in a closed grinding cycle. On the basis of the Markov chain theory, models of continuous grinding and classification have been developed, which are reduced down to constructing a block grinding matrix, which consists of grinding unit element matrices and describes the transformation of the material fractional composition with the help of the acoustic signal kinetics of operation zones.

2. The mass flows stability loss in a jet grinding unit, leading to a decrease in the efficiency of its operation, depends on the mode of loading jets with material, and the loading level for each classification mode forming a cycle in a grinding unit, has its own characteristics.

3. A mill loading control system has been developed through a controlled bunker based on the results of continuous acoustic monitoring of the grinding process.

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Керування масопотоками струминного млина на основі акустичного моніторингу

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Мета. Надати обґрунтування управління процесом струминного подрібнення шляхом побудови моделі замкнутого циклу за допомогою ланцюгів Маркова й результатів акустичного моніторингу робочих зон подрібнювальної установки.

Методика. Моделювання здійснюється на базі системного аналізу із застосуванням осередкової моделі. Для опису процесу подрібнення використовуються акустичні сигнали робочих зон млина. Теоретичні розрахунки зміни гранулометричного складу первинного матеріалу порівнюються з результатами експериментального подрібнення на прикладі шамоту.

Результати. Зміна крупності матеріалу в масопотоках у струминному млині, класифікаторі розглянуті з позицій зміни характеристик акустичних сигналів, що записуються в цих частинах подрібнювальної установки. За результатами безперервного моніторингу робочих зон подрібнювальної установки створена модель руху масопотоків у замкнутому циклі та зміни гранулометричного складу вхідного матеріалу від завантажувального бункеру до вивантаження готового продукту подрібнення. На основі моделі показана можливість управління процесом подрібнення. Розроблена функціональна схема управління роботою млина в цілому. Створена апаратна база для управління струминним млином випробувана при експериментальних і промислових процесах подрібнення різних матеріалів.

Наукова новизна. Уперше створена осередкова модель руху потоків матеріалу в усіх елементах подрібнювальної установки з використанням акустичних сигналів, записаних у них. Кінетика гранулометричного складу у млині, класифікаторі та бункері готового матеріалу описана матрицями, що містять характеристики акустичних сигналів цих зон. Число цих матриць відповідає числу функціональних елементів установки, і вони об'єднуються в одну загальну блочну матрицю.

Практична значимість. Отримані результати використовуються для побудови автоматичної системи управління продуктивністю струминної установки на основі управління її завантаженням за результатами акустичного моніторингу робочих зон.

Ключові слова: *масопотоки, подрібнення, моделювання, контроль, система автоматичного управління, струминна установка*

Управление массопотоками в струйной мельнице на основе акустического мониторинга

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Цель. Дать обоснование управления процессом струйного измельчения путем построения модели замкнутого цикла с помощью цепей Маркова и результатов акустического мониторинга рабочих зон измельчительной установки

Методика. Моделирование осуществляется на базе системного анализа с применением ячеечной модели. Для описания процесса измельчения используются акустические сигналы рабочих зон мельницы. Теоретические расчеты изменения гранулометрического состава сравниваются с результатами экспериментального измельчения на примере шамота.

Результаты. Изменение крупности материала в массопотоках в струйной мельнице, классификаторе рассмотрены с позиций изменения характеристик акустических сигналов, записываемых в этих частях измельчительной установки. По результатам непрерывного мониторинга рабочих зон измельчительной установки создана модель движения массопотоков в замкнутом цикле и изменения гранулометрического состава исходного материала от загрузочного бункера до выгрузки готового продукта измельчения. На основе модели показана возможность управления процессом измельчения. Разработана функциональная схема управления работой мельницы в целом. Созданная аппаратная база для управления струйной мельницей опробована при экспериментальных и промышленных испытаниях процесса измельчения различных материалов.

Научная новизна. Впервые создана ячеечная модель движения потоков материала во всех элементах измельчительной установки с использованием акустических сигналов, записанных в них. Кинетика гранулометрического состава в мельнице, классификаторе и в бункере выгрузки готового материала описана матрицами, содержащими характеристики акустических сигналов этих зон. Число этих матриц соответствует числу функциональных элементов установки, и они объединяются в одну общую блочную матрицу.

Практическая значимость. Полученные результаты используются для построения автоматической системы управления производительностью струйной установки на основе управления ее загрузкой по результатам акустического мониторинга рабочих зон.

Ключевые слова: *массопотоки, измельчение, моделирование, контроль, система автоматического управления, струйная установка*

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