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BUILDING A MODEL OF THE COMPRESSION GRINDING MECHANISM IN A TUMBLING MILL BASED ON DATA VISUALIZATION

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The object of the study reported here is the grinding process in a tumbling mill where the mechanism of destruction by crushing is implemented, which is caused by the mechanism of compression loading. The compressive interaction in the active zone of the lower end of the granular loading chamber of the rotating drum at the transition of the shear layer to the solid zone was taken into account.

The task to determine the parameters of the compressive action was solved, which was caused by the difficulties of modeling and the complexity of the hardware analysis of the behavior of the internal loading of the mill.

A mathematical model was built based on data visualization for the compression grinding mechanism.

The power of compressive forces was taken as an analog of grinding performance. The initial characteristic of compression was considered to be the mean speed of movement in the central averaged normal cross-section of the shear layer. The influence on the performance of the mass fraction of the shear layer and the reversibility of loading was taken into account.

The effect of rotation speed on productivity was evaluated by experimental modeling at a chamber filling degree of 0.45 and a relative size of grinding bodies of 0.0104. The maximum value of energy and grinding productivity was established at a relative speed of rotation ψ_ω***=0.6–0.65. The maximum value of the share of the shear layer loading was found at*** ψ_ω***=0.4–0.45.***

The results have made it possible to establish a rational speed during crushing by compression, ψ_ω***=0.55–0.65. This value was smaller in comparison with impact crushing,*** ψ_ω***=0.75–0.9. The observed effect is explained by the detected activation for the shear loading layer during slow rotation, in contrast to the fast rotation for the drop zone.***

The model built makes it possible to predict rational technological parameters of the process of medium and fine grinding in a tumbling mill by compression

Keywords: tumbling mill, intra-chamber loading, compressive loading, destruction by crushing, grinding performance

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1. Introduction

Grinding is a rather energy-intensive technological process. Grinding mineral raw materials and cement clinker consumes 3 % of the electricity produced in the world [1]. The high energy intensity of grinding in a tumbling mill is caused by energy dissipation due to the shear circulation of the internal chamber loading [2]. The problem of reducing the energy intensity of the working processes of these mills remains relevant [3].

The task of modeling and forecasting the energy consumption of tumbling mills constantly attracts the attention of researchers [4]. A number of methods have been proposed for forecasting mill power consumption. In particular, empirical models based on visualization [5] and the effect of positron emission [6] were developed, as well as empirical-numerical [7] and statistical [8] ones. However, those methods turned out to be quite controversial. In addition, those models do not provide insight into the relationship between capacity and performance of the grinding process [9].

It is well known that grinding in a tumbling mill is carried out as a result of the simultaneous combination of several load mechanisms, which ensure the implementation of the corresponding mechanisms of material destruction. In [10, 11], only impact and shear are considered load mechanisms. Impact or compression, chipping or shearing, and abrasion are considered separately in [12]. Finally, in [13, 14] impact, compression, and shear are attributed to three load mechanisms. Impact loading causes impulse accelerations and causes destruction by breaking. Compressive loading causes normal stresses in the material and destruction by crushing. Shear loading causes tangential stresses and surface friction and destruction by abrasion.

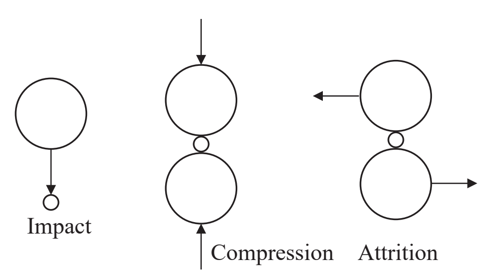

Fig. 1. Diagram of the three load mechanisms for grinding in a tumbling mill (according to [14])

Impact action occurs mainly with the cataracting (cataracting) mode of movement of the intra-chamber loading and high-speed rotation of the drum. Compressive and shearing action is realized under cascading and rolling modes of loading and low-speed rotation. It is believed that impacting mainly results in coarse grinding while compression and shearing allow medium and fine grinding to be achieved.

The most loaded part of loading is the active transition zone of the lower end (Fig. 2, *a*) [15], where intensive destruction of the crushed material occurs. The lower end of loading is considered the impact zone (Fig. 2, *b*) [16]. The emergence of the lower end zone is due to the transition of the shear layer into the solid zone and the implementation of the mechanism of predominantly compressive interaction (Fig. 2, *c*, *d*) [17]. The movement of the liquefied granular load in this zone has the character of a transient strongly unsteady turbulent flow, which is extremely difficult to model.

At the same time, a significant part of tumbling mills performs medium and fine grinding due to a significant part of the impact on the grinding of the mechanism of destruction by crushing under compressive load. However, determining compressive interaction parameters is quite problematic due to the insurmountable difficulties of analytical and numerical modeling and the increased complexity of the hardware analysis of loading behavior. Therefore, the quantitative results of the impact of the compressive action on the energy intensity and productivity of the grinding process remain unknown, which significantly limits the functionality of such equipment.

Considering the above, the task of predicting the impact of the compressive action of the grinding load on the performance of medium and fine crushing by compression in a tumbling mill seems to be quite relevant.

2. Literature review and problem statement

The implementation of three mechanisms of loading and destruction in a tumbling mill is determined by the mode of movement of intra-chamber loading, the modeling of which is associated with significant difficulties. The intra-chamber loading of the mill executes a circulation movement with the formation of three main zones in the cross-section of the chamber – a solid one, a flight zone, and a shear layer one [18].

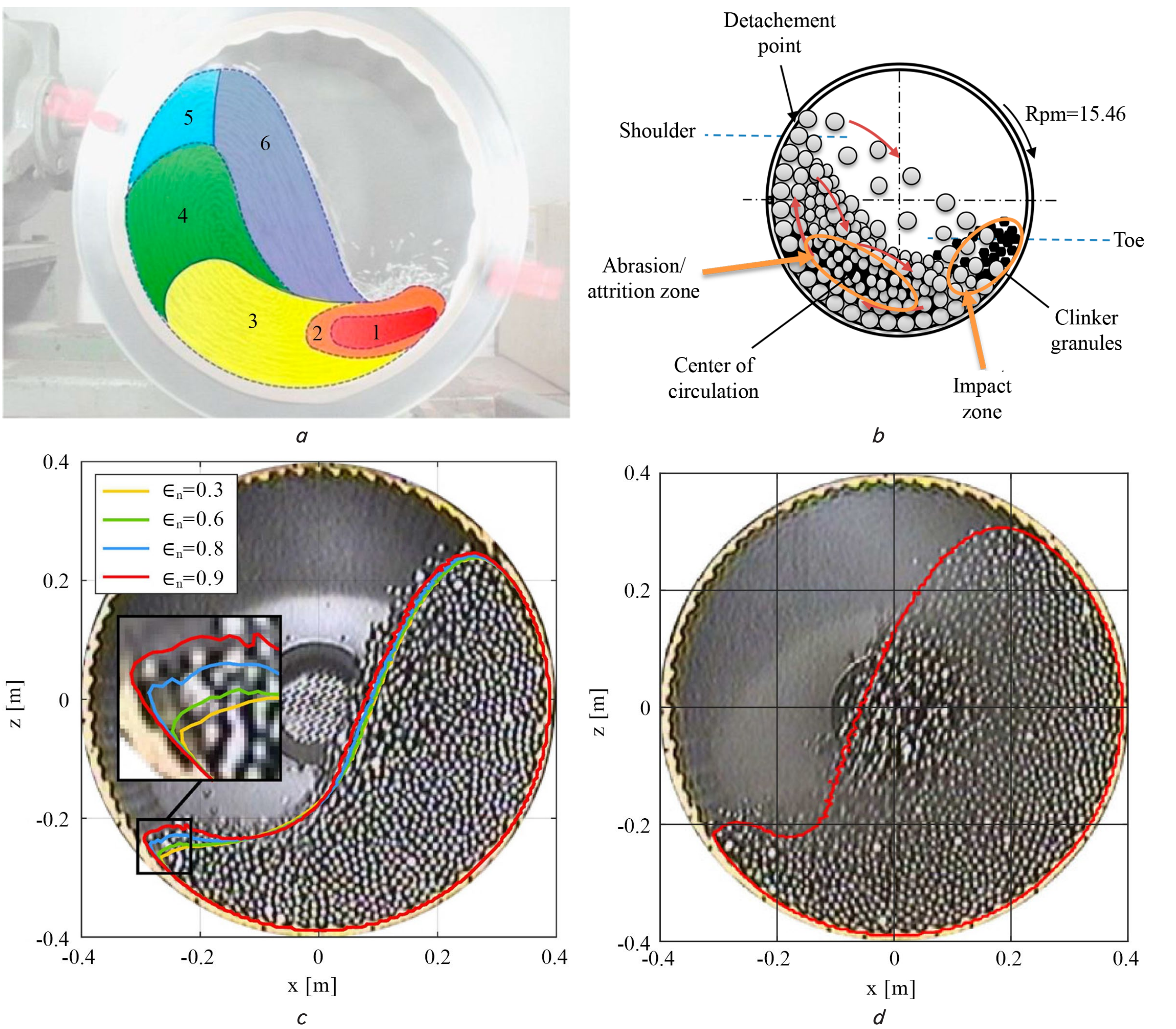

Fig. 2. The transition zone of the lower end of the load: *a* – scheme of the active zone (1–3) (according to [15]); *b* – schemes of the active zone of impulse interaction (impact zone) (according to [16]); *c* – movement pattern in the zone at the degree of chamber filling $\kappa=0.3$ and the relative speed of rotation $\psi_\omega=0.7$ for different recovery coefficients of milling bodies ε_n (according to [17]); *d* – movement pattern in the zone at $\kappa=0.4$ and $\psi_\omega=0.8$ (according to [17])

In [15], the position of the active transition zone of the lower end of loading in the cross section of the chamber was schematically highlighted. Intensive grinding of the material was found in that zone. However, the results obtained in the cited work do not allow us to quantitatively estimate the parameters of the transition zone of the lower end of loading.

The manifestation of the transition zone of the lower end of loading, which was defined as the zone of active impulse interaction (impact zone), was studied in [16, 19]. Compression and impact loading were believed to occur in that zone, causing crushing and shattering. However, the numerical parameters of the zone were not established.

Video recording of the manifestations of the transition zone of the volumetric lower end of the ball mill loading of the tumbling mill in the cascade mode of movement and compressive loading is given in [18]. It was found that the appearance of that zone is not related to impact loading, and the dispersion of loading in it due to impact interaction is insignificant. However, quantitative characteristics of the parameters of that zone were not established in [18].

Individual characteristics of the transition zone of the lower end of loading in the cross section of the rotating drum chamber were studied by numerical methods. In [20], the method of discrete elements was used for the numerical study of the limits and speeds of the zone movement. Two types of toe positions were identified. Bulk lower end toe occurs with a cascade and slow-moving cataract mode of movement and compressive loading. Impulsive lower end (impact toe) can occur with rapid cataract mode and impact load. However, the results are only qualitative in nature and have not acquired generalization.

In works [21, 22], the geometric parameters of the transition zone of the lower end of loading were studied using fluoroscopy. The structuring of the elements of the zone and their geometric characteristics were clarified and differentiated. The position of the generalized zone of the lower end of loading (toe region), which contains four components, was revealed. The bulk toe and the re-entry toe occur under cascade and slow-moving cataract mode and compressive loading. Impact toe and disperse toe lower extremities can occur with a slow-moving cataract mode of movement under impact loading. The position of the free surface [21] and the center of circulation [22] of loading was also determined. However, no analysis of the dynamic parameters of the movement in the area of the lower end of loading was carried out.

The numerical method of discrete elements was applied in [23, 24] to study the mechanism of loading during the interaction of compression loading elements. It was shown in [23] that crushing under compression loading is potentially a particularly important mechanism of particle destruction in a tumbling mill. Calculations have shown that the compression load occurs at the lower end of the loading of the semi-self grinding mill and is characterized by high energy, low force, and high concentration. Instead, only qualitative analysis results were obtained in [23]. In [24], 3 forms of loading interaction energy during grinding in tumbling mills were analyzed – impact, dissipation, and maximum impact energy. It is shown that it is the collision energy of large and small loading particles that determines the productivity of the grinding process and the grinding tone. However, the reported qualitative results are unsuitable for quantitative analysis.

The movement parameters of the shear layer loading chamber of the rotating drum were studied in [25, 26]. In [25], an experimental method of radiography of the movement of loading particles was used. However, the kinematic parameters of the shear layer zone were not considered. In [26], the numerical simulation of the behavior of the intrachamberl loading in the cataract mode of motion was performed using the discrete element method. The flight, shear layer, and passive zones were distinguished. However, the results concern only the geometric and kinematic parameters of the zones.

In works [27–29], a method of analytical-experimental modeling of movement zones of granular loading in the cross-section of a chamber of a rotating drum was devised. The algorithm for implementing the method is given in [27]. Modeling involves constructing movement patterns by determining the position of the boundary of the transition of the passive zone into the fall zone [28] and the parameters of the shear layer [29]. However, the results did not provide an assessment of the energy and technological characteristics of the grinding process by compressive action.

In [30–33], the geometric and kinematic parameters of the active zone of loading movement were studied using the visualization method. In [30], the dynamic parameters of the self-oscillating action of loading and the technological characteristics of grinding for one value of the degree of filling of the chamber were quantitatively evaluated. The influence of the degree of filling on the efficiency of self-oscillating grinding for one value of the content of particles of the crushed material in the load is considered in [31]. In [32], the effect of material content on the modes of movement of grinding bodies and the efficiency of self-oscillating grinding for one filling of the chamber was studied. The influence of the simultaneous change in the degree of chamber filling and the content of the crushed material on the grinding process was studied in [33]. However, the results relate only to the case of the self-oscillating mode of motion when implementing the established mechanism [34] of the loss of motion stability [35].

In work [18], a mathematical model was built based on data visualization for the grinding mechanism by breaking under the action of the impact loading mechanism in a tumbling mill. The effect on performance of the mass fraction of the flight zone, load reversibility, and rotation speed was considered. However, the results refer only to the impact grinding performance.

No models have been constructed to determine the compressive performance of an in-chamber mill loading on material being milled in a tumbling mill. This is due to the difficulties of analytical and numerical modeling and the complexity of the instrumental experimental study of the behavior of the active zone of the lower end of the granular loading chamber of the rotating drum. The lack of such models is especially negative in the case of the implementation of the energy-saving process of medium and fine grinding.

3. The aim and objectives of the study

The purpose of this work is to build a mathematical model of the loading mechanism by the compressive action of the grinding bodies of intra-chamber loading on the particles of the material crushed in the tumbling mill. This will make it possible to establish the dynamic characteristics of the compressive action of the grinding load and to predict the parameters of the grinding process by implementing the mechanism of destruction by crushing.

To achieve this goal, the following tasks were solved:

– to perform analytical modeling and set the parameters of the compressive interaction of the intra-chamber loading of the tumbling mill;

– to perform experimental modeling and evaluate the effect of rotation speed on the energy and productivity of the process of grinding by crushing as a result of the implementation of the compressive interaction mechanism.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our research is the process of grinding by compression in a tumbling mill. The subject of the study is the mathematical modeling of the process of compression loading, which causes the implementation of the mechanism of destruction by crushing.

It was believed that the compressive interaction of loading elements is carried out on the transition surface of the shear layer into the solid zone, which is the contact surface. This contact surface is located at the lower end of the chamber loading. The compressive interaction was assumed to be completely inelastic. The influence of shock and shear interaction forces on the grinding process was neglected.

The model of the compression grinding mechanism was based on the relative dynamic parameters of the compression interaction, which are criteria for the similarity of the loading movement and the grinding process. The power of the compressive interaction was considered to be an analog of the productivity of the compression grinding process.

It was assumed that the drum chamber is long. It was adopted that the interaction of the chamber with the load is carried out mainly on a cylindrical surface. The influence of the end walls of the chamber on the movement of loading was neglected.

The mode of movement of the load in the chamber of the rotating drum was assumed to be stable. It was accepted that the parameters of this regime are determined by the stationary patterns of loading movement.

As a simplification, the case of monofraction loading of the rotating drum chamber was considered. The accepted discrete value of the degree of filling of the chamber was 0.45, which corresponds to the grinding process in a tumbling mill with a high throughput for the yield of the finished product.

4. 2. Research methods

As a method of experimental research, physical data visualization was adopted since the marginal effect of the loading flow on the end wall of the chamber turned out to be insignificant.

To determine the parameters of the compressive interaction, an experimental method of numerical modeling was applied based on the experimental visualization of its behavior in the chamber of a rotating drum. Visualization was carried out by recording through a transparent end wall and further processing of images of loading movement in the cross-section of the chamber. The algorithm for implementing the data visualization method consists in the sequential implementation of such stages [18]. The peculiarities of the application of this method in the study of the parameters of the compressive interaction of loading are the implementation of the following stages:

1) select the central averaged normal cross-section of the shear layer on the obtained image of loading movement;

2) measure on the image of the radial coordinate of the base of the central averaged normal cross-section of the shear layer R_{sl};

3) measure on the image of the height of the central averaged normal cross-section of the shear layer h;

4) calculate the values for the parameters of the compressive loading interaction using the corresponding expressions.

A stroboscopic tachometer was used to measure the rotation speed. When using error propagation analysis, the error of velocity measurements was approximately ±3 %. The evaluation was carried out by measuring the steady-state rotation speed 5 times for one mode of loading motion.

Standard software was used to measure linear dimensions and areas of geometric shapes in motion images.

A laser-type analyzer was used to measure the size of the loading particles.

Laboratory beakers were used to dose the loading portion. Portion volume was determined at rest.

In order to exclude the influence of random factors on the reliability of the measurement results, 3 motion patterns were acquired for one value of the rotation speed ψ_ω. The deviations of the results of measurements of linear dimensions and areas of geometric shapes in motion images for each speed of rotation were 2–3 %.

The applied procedures for treating the results of the experiments corresponded to the set tasks.

When conducting experimental studies, the errors of the measurement results were determined and estimated, the values of which depended on the speed of rotation.

The content of the loading chamber was estimated by the degree of filling $\kappa = w/(\pi R^2 L)$, where w is the volume of the loading portion at rest, R is the radius of the chamber, and L is the length of the chamber. The discrete value of the degree of filling was $\kappa = 0.45$.

The speed of rotation was estimated by the relative speed $\psi_\omega = \omega\sqrt{R/g}$, where ω is the angular speed, g is the gravitational acceleration. The discrete values of the relative speed of the stationary rotation changed with a step of $\Delta\psi_\omega = 0.05$.

Loose granular material with spherical particles with average absolute d and relative size $\psi_d = d/(2R) = 0.0104$ was used as loading.

5. Results of investigating the crushing process in a tumbling mill with compressive action

5. 1. Results of analytical modeling of compressive interaction of intra-chamber loading of a tumbling mill

During the compressive interaction of the milling body located in the zone of the shear layer with the bodies of the solid loading zone, a jump-like final change in the speed of the body occurs. At the same time, an impulse force acts on the transition surface of the shear layer into the solid zone, which is the contact surface, for a short period of time. Momentum is a measure of the strength of the compressive interaction.

The duration of the compressive interaction is short. Since the compressive impulse has a finite value, the modulus of force of the grinding body can be quite large, which ensures the implementation of the grinding process by crushing action. The impulse interaction of loading elements was assumed to be inelastic. On the considered contact surface, which is the transition of loading movement zones, the influence of non-impulsive interaction forces on the grinding process is negligibly small.

The dynamic effect of the compressive action of milling loading can be estimated by the impulse, work, and power of the compressive interaction forces. Impulse characterizes the intensity of the compressive interaction, work – the energy of grinding by the compressive action. The technological effect of the compressive action is determined by the performance of the compression grinding process, the value of which is estimated by the power of the impulse interaction forces.

An approximate implementation of such an assessment is carried out using specific and absolute relative analogs of the dynamic parameters of compressive interaction. Initial data for determining the parameters are obtained in a simplified way by visualizing loading motion patterns in the cross-section of the rotating chamber.

The initial characteristic that approximately determines the magnitude of the compressive action is the average value of the speed of movement in the central averaged normal cross-section of the shear layer V_{sl}:

$$V_{sl}=\frac{\omega\left(R^2-R_{sl}^2\right)}{2h}, \tag{1}$$

where R_{sl} is the radial coordinate of the base of the central averaged normal cross-section of the shear layer; h is the height of the central averaged normal cross-section of the shear layer.

The magnitude of the impulse is determined by its correspondence to the change in the amount of movement of the load. It is believed that the value of the speed of movement after the compressive impulse interaction is small.

The specific relative momentum of the force of compressive interaction S_{slr} corresponds to the ratio of the averaged absolute momentum of a unit of loading mass to the value $\sqrt{Rg}$:

$$S_{slr}=\frac{V_{sl}}{\sqrt{Rg}}. \tag{2}$$

After the transformations, expression (2) takes the form:

$$S_{slr}=\frac{\omega\left(R^2-R_{sl}^2\right)}{2h\sqrt{Rg}}. \tag{3}$$

The magnitude of work of the force of compressive interaction is determined from its correspondence to the change in kinetic energy during the duration of the interaction.

The specific relative work of the vertical component of the force of compressive interaction A_{cbrs} corresponds to the ratio of the averaged absolute work of a unit of loading mass to the value $\left(\sqrt{Rg}\right)^2$:

$$A_{cbrs}=\frac{1}{2}\left(\frac{V_{sl}}{\sqrt{Rg}}\right)^2. \tag{4}$$

After the transformations, expression (4) takes the form:

$$A_{cbrs}=\frac{\omega^2\left(R^2-R_{sl}^2\right)^2}{8h^2Rg}. \tag{5}$$

The relative energy of grinding by crushing for one circulation cycle of loading in the rotating drum chamber E_{cbrc} corresponds to the full relative work of the compressive interaction forces for one circulation cycle:

$$E_{cbrc}=A_{cbrs}K_{sl}, \tag{6}$$

where K_{sl} is the mass fraction of the loading shear layer zone.

The expression for K_{sl} takes the form:

$$K_{sl}=\frac{m_{sl}}{m}, \tag{7}$$

where m_{sl} is the mass of the loading shear layer; m is the mass of the entire load.

The value of K_{sl} can be approximately determined by the method of visualizing loading movement patterns using the expression:

$$K_{sl}=\frac{F_{sl}}{\pi R^2\kappa\upsilon_{sl}}, \tag{8}$$

where F_{sl} is the area of the shear layer zone in the movement pattern; υ_{sl} is the dilatancy of the shear layer.

Since the increase in the volume of the shear layer during movement is small, the value of its dilatancy tends to zero $\upsilon_{sl}\to 1$.

After transformations, expression (6) takes the form:

$$E_{cbrc}=\frac{\omega^2\left(R^2-R_{sl}^2\right)^2}{8h^2Rg}K_{sl}. \tag{9}$$

The relative crushing energy for one revolution of the drum E_{cbrt} corresponds to the complete relative work of the vertical component forces of the compressive interaction in one revolution:

$$E_{cbrt}=E_{cbrc}n_{to}, \tag{10}$$

where n_{to} is the reversibility of loading movement, which determines the number of cycles of loading circulation in the chamber during one revolution of the drum [18].

After the transformations, expression (10) becomes:

$$E_{cbrt}=\frac{\omega^2\left(R^2-R_{sl}^2\right)^2}{8h^2Rg}K_{sl}n_{to}. \tag{11}$$

The analog of the relative productivity of grinding by crushing Q_{cbr} corresponds to the relative power of the vertical component forces of the compressive interaction:

$$Q_{cbr}=\frac{E_{cbrt}}{T_{tr}}, \tag{12}$$

where $T_{tr}=(2\pi)/\psi_\omega$ is the relative drum rotation period.

After the transformations, expression (12) takes the form:

$$Q_{cbr}=\frac{\omega^2\left(R^2-R_{sl}^2\right)^2}{16\pi h^2Rg}K_{sl}n_{to}\psi_\omega. \tag{13}$$

The applied relative parameters (2) to (13) are dynamic criteria for the similarity of loading motion and grinding process in a tumbling mill by crushing action. The values of the dynamic parameters according to expressions (3), (5), (9), (11), (13) make it possible to numerically evaluate the changes in the technological effect of the compressive action of loading depending on the initial characteristics of the grinding process.

5. 2. Results of experimental simulation of compressive interaction of intra-chamber loading of a tumbling mill

Using the method of physical data visualization, patterns of the steady motion of loading in the chamber of a stationary rotating drum at κ=0.45 were obtained [18]. The resulting patterns characterize the influence of the rotation speed on the position and mass fractions of the load movement zones in the rotating chamber.

The plots of results of the experimental determination of change in the parameters of the compressive interaction of loading at κ=0.45 are shown in Fig. 3–8.

The plot of change in the specific relative momentum of the force of the load compressive interaction S_{slr} on the relative speed of rotation ψ_ω is shown in Fig. 3. The S_{slr} values were determined from expression (3).

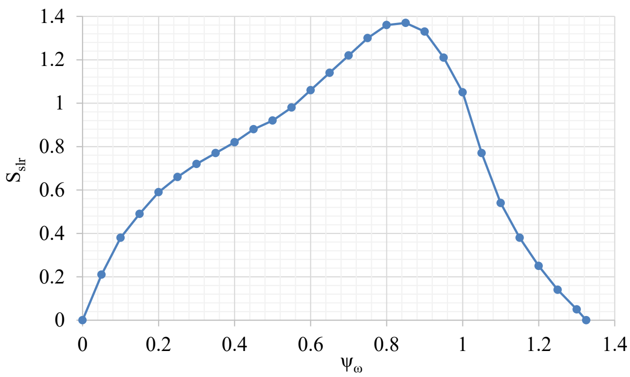

Fig. 3. Experimental dependence of change in the specific relative momentum of the force of the compressive interaction of loading S_{slr} on the relative speed of rotation ψ_ω

The plot of change in the specific relative work of the compressive interaction force A_{cbrs} on the relative speed of rotation ψ_ω is shown in Fig. 4. The A_{cbrs} values were determined from expression (5).

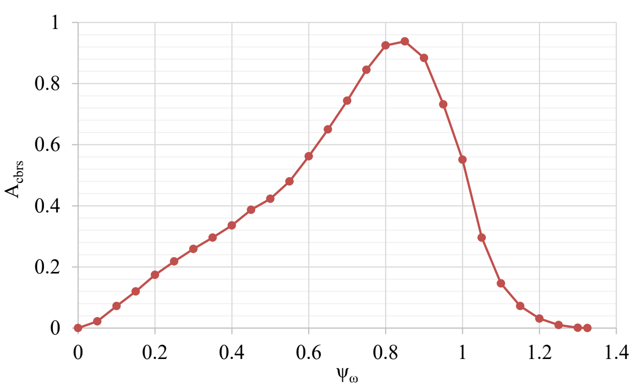

Fig. 4. Experimental dependence of change in the specific relative work of the force of compressive interaction A_{cbrs} on the relative speed of rotation ψ_ω

The plot of change in the mass fraction of the shear layer zone K_{sl} as a function of the relative speed of rotation ψ_ω is shown in Fig. 5. The K_{sl} values were determined from expression (8).

The plot of change in the relative energy of crushing by compression for one cycle of circulation of loading in the chamber of a rotating drum E_{cbrc} on the relative speed of rotation ψ_ω is shown in Fig. 6. The E_{cbrc} values were determined from expression (9) taking into account (8).

The plot of change in the relative energy of grinding by compression for one rotation of the drum E_{cbrt} on the relative speed of rotation ψ_ω is shown in Fig. 7. The E_{cbrt} values were determined from expression (11) taking into account (8).

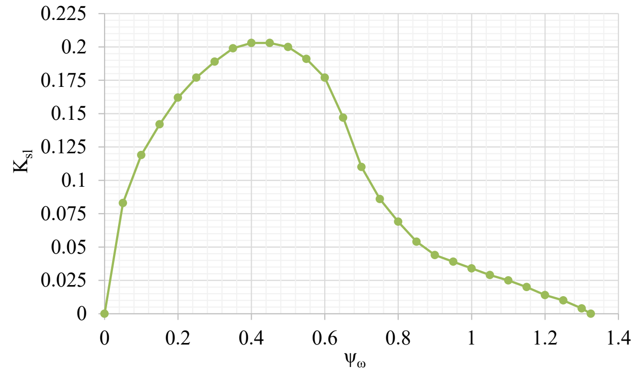

Fig. 5. Experimental dependence of change in the mass fraction of the shear layer zone K_{sl} on the relative speed of rotation ψ_ω

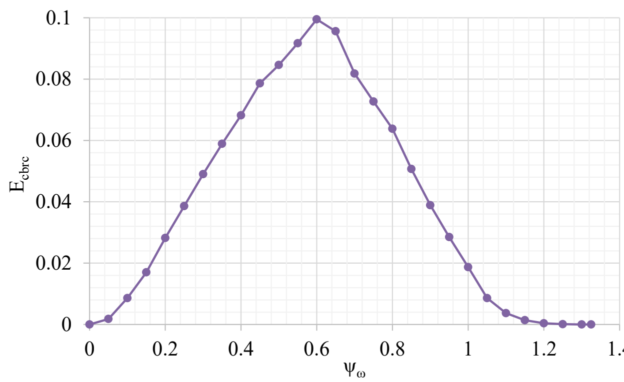

Fig. 6. Experimental dependence of change in the relative energy of crushing by compression during one cycle of loading circulation in the chamber of a rotating drum E_{cbrc} on the relative speed of rotation ψ_ω

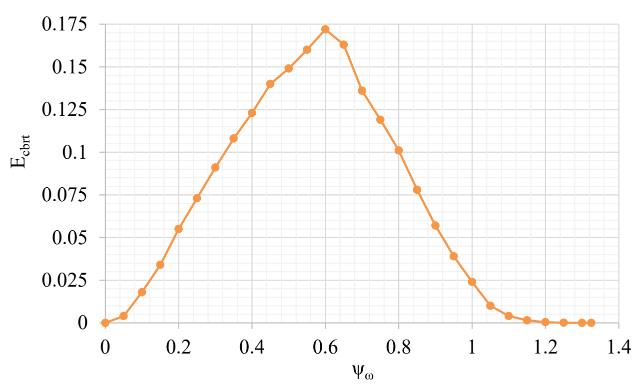

Fig. 7. Experimental dependence of change in the relative energy of grinding by compression in one revolution of the drum E_{cbrt} on the relative speed of rotation ψ_ω

The plot of change in the analog of the relative productivity of grinding by compression Q_{cbr} on the relative speed of rotation ψ_ω is shown in Fig. 8. The Q_{cbr} values were determined from expression (13) taking into account (8).

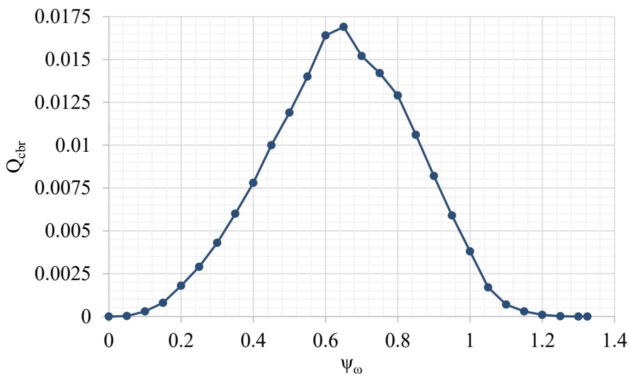

Fig. 8. Experimental dependence of change in the analog of the relative productivity of grinding by compression Q_{cbr} on the relative speed of rotation ψ_ω

The resulting experimental dependences of the numerical values of the parameters of the compressive interaction of loading characterize the quantitative influence of the rotation speed on the process of crushing by compression in a tumbling mill.

6. Discussion of results of investigating the grinding process in a tumbling mill by compressive action

The results of analytical and experimental modeling have made it possible to qualitatively and quantitatively assess the influence of the load movement parameters in the rotating chamber on the compressive interaction.

The initial characteristic, which approximately determines the value of the compressive action, was revealed. This is the averaged value of the speed of movement in the central averaged normal cross-section of the shear layer V_{sl} (1). The compressive interaction is realized during the pulsed transition of the shear layer into the solid zone at the boundary, which is located at the lower end of the loading chamber of the rotating drum.

It was established that the value of the analog of grinding performance in a tumbling mill by compression Q_{cbr} (13) is proportional to the square of the initial characteristic V_{sl} (1). In addition, the performance is proportional to the value of the shear layer zone mass fraction K_{sl} (8), loading reversibility n_{to} [18], and drum rotation speed ψ_ω. A significant effect exerted on the performance by the mass fraction K_{sl} was revealed, the value of which reaches its maximum value at the relative speed of rotation ψ_ω=0.4–0.45 (Fig. 5). The influence of reversibility n_{to} increases with a decrease in ψ_ω [18]. The defining characteristic of the compressive interaction is the speed ψ_ω, which determines the values of parameters V_{sl}, K_{sl}, and n_{to}.

The conditions for achieving the maximum values of the parameters of the compressive loading interaction have been established. The impulse S_{slr} (Fig. 3) and work A_{cbrs} (Fig. 4) reach their maximum at the speed ψ_ω=0.85. And the energies E_{cbrc} (Fig. 6) and E_{cbrt} (Fig. 7) reach their maximum at ψ_ω=0.6 while the productivity Q_{cbr} (Fig. 8) – at ψ_ω=0.65. This is due to the fact that with a decrease in the speed ψ_ω from 0.85 to 0.6–0.65, there is a significant, approximately 3-fold, increase in the mass fraction K_{sl} (Fig. 5). In addition, the turnover value n_{to} increases by 1.11 times [18].

Analysis of Fig. 7, 8 proves that the rational range of rotation speed values for crushing in a tumbling mill with compressive action can be considered to be ψ_ω=0.55–0.65. At the same time, the values of energy E_{cbrt} (Fig. 7) and productivity Q_{cbr} (Fig. 8) of grinding by compression acquire a fraction of 0.83–0.92 and more, from the maximum possible values.

The results reported in this work regarding the rational range of rotation speed ψ_ω=0.55–0.65 coincide well with the data from [2, 36, 37], as well as with GOST 10141-91 and its analogs [38, 39]. In those sources, the processes of medium grinding in tumbling mills were considered, mainly by compression during the compressive interaction of loading elements. In [2, 36] it was experimentally shown that the lowest energy consumption of dry grinding of cement clinker, limestone, and quartz in a ball mill is achieved at ψ_ω=0.55. In work [36], the rotation speed ψ_ω=0.5–0.6 was experimentally determined to be rational for reducing the energy consumption of the process of wet grinding of limestone. In [37] it was experimentally shown that the highest productivity of wet grinding of iron ore in a laboratory ball mill is achieved at ψ_ω=0.6. Technical standard GOST 10141-91 «Rod and ball mills. General technical requirements» and [38, 39] regulate the processes of wet grinding of ore and non-ore minerals in tumbling mills. According to GOST 10141-91 and [38, 39], the rated rotation speed of rod tumbling mills with peripheral unloading is ψ_ω=0.55–0.65.

The difference between the rational values of the rotation speed for grinding in a tumbling mill by compression with compressive interaction of loading and grinding by breaking with impact interaction was found. The comparative analysis concerned the results of the work and article [18], which were obtained for the same conditions of experimental modeling. It turned out that the efficiency of crushing by compressive action is achieved at a lower speed ψ_ω=0.55–0.65 and crushing by impact action – at a higher speed ψ_ω=0.75–0.9.

The applicability of the established dynamic characteristics of the compressive action and the results of forecasting the parameters of the medium and fine grinding process by implementing the compression mechanism is limited by the discrete values of the initial parameters. The value of the degree of filling the drum chamber with loading was κ=0.45, which corresponded to the grinding process in a tumbling mill with a high throughput. The relative particle size of the granular loading in the chamber was 0.0104.

The use of a discrete value of the degree of filling imposes certain restrictions on the application of our results, which can be interpreted as the shortcomings of this study. Therefore, identifying the characteristics of the interaction of the elements with a different, in particular, lower filling of the chamber with loading, appears to be a potentially interesting direction of further research. This could reveal new dynamic effects of the compression grinding mechanism.

Disadvantages of the applied approach to assessing the influence of the dynamic action of loading on the grinding process include the failure to take into account the sliding grinding mechanism.

In the future, it is advisable to find out the dynamic parameters of the loading mechanism by the shearing action of the grinding bodies loading on the particles of the crushed material. This would make it possible to establish rational conditions for the implementation of the abrasion destruction mechanism during the implementation of the fine grinding process in drum-type mills.

7. Conclusions

1. The simulation of the compressive action of the intra-chamber loading of the tumbling mill is based on taking

into account the final change in the speed of movement of the shear layer on the surface of the impulse contact. The inelastic compressive interaction occurs in the active zone of the lower end of the loading chamber at the border of the transition of the shear layer into the solid-state zone. The factor of compressive action is the averaged value of the speed of movement in the central averaged normal cross-section of the shear layer. Analogs of the dynamic parameters of compressive interaction are momentum, work, and power of compressive forces. The relative power of compressive forces can be taken as an analog of the relative productivity of the compression grinding process. The applied relative dynamic parameters of the compressive interaction are criteria for the similarity of the loading movement and the grinding process in the tumbling mill by compression.

Determining parameters of influence on the analog of compression grinding productivity are the speed and mass fraction of the shear layer, the reversibility of the charge circulation in the chamber, and its rotation speed.

2. It was established that the energy of grinding by compression reaches its maximum value at the value of the relative speed of rotation of the drum chamber ψ_ω=0.6, and the analog of productivity – at ψ_ω=0.65. It was found that the mass fraction of the loading shear layer zone acquires its maximum value at ψ_ω=0.4–0.45. A rational condition for grinding in a tumbling mill by compression at a lower rotation speed ψ_ω=0.55–0.65, in contrast to the condition of impact grinding at ψ_ω=0.75–0.9, has been established.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

References

1. Deniz, V. (2013). Comparisons of Dry Grinding Kinetics of Lignite, Bituminous Coal, and Petroleum Coke. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 35 (10), 913–920. doi: https://doi.org/10.1080/15567036.2010.514591
2. Gupta, V. K. (2020). Energy absorption and specific breakage rate of particles under different operating conditions in dry ball milling. Powder Technology, 361, 827–835. doi: https://doi.org/10.1016/j.powtec.2019.11.033
3. Góralczyk, M., Krot, P., Zimroz, R., Ogonowski, S. (2020). Increasing Energy Efficiency and Productivity of the Comminution Process in Tumbling Mills by Indirect Measurements of Internal Dynamics – An Overview. Energies, 13 (24), 6735. doi: https://doi.org/10.3390/en13246735
4. Golpayegani, M. H., Rezai, B. (2022). Modelling the power draw of tumbling mills: A comprehensive review. Physicochemical Problems of Mineral Processing, 58 (4). doi: https://doi.org/10.37190/ppmp/151600
5. Govender, I., Powell, M. S. (2006). An empirical power model derived from 3D particle tracking experiments. Minerals Engineering, 19 (10), 1005–1012. doi: https://doi.org/10.1016/j.mineng.2006.03.017
6. Bbosa, L. S., Govender, I., Mainza, A. N., Powell, M. S. (2011). Power draw estimations in experimental tumbling mills using PEPT. Minerals Engineering, 24 (3-4), 319–324. doi: https://doi.org/10.1016/j.mineng.2010.10.005
7. Bbosa, L. S., Govender, I., Mainza, A. (2016). Development of a novel methodology to determine mill power draw. International Journal of Mineral Processing, 149, 94–103. doi: https://doi.org/10.1016/j.minpro.2016.02.009
8. Tohry, A., Chehreh Chelgani, S., Matin, S. S., Noormohammadi, M. (2020). Power-draw prediction by random forest based on operating parameters for an industrial ball mill. Advanced Powder Technology, 31 (3), 967–972. doi: https://doi.org/10.1016/j.apt.2019.12.012
9. Tavares, L. M. (2017). A Review of Advanced Ball Mill Modelling. KONA Powder and Particle Journal, 34, 106–124. doi: https://doi.org/10.14356/kona.2017015
10. Kelly, E. G., Spottiswood, D. J. (1982). Introduction to mineral processing. Wiley, 491.
11. Gupta, A., Yan, D. (2016). Mineral processing design and operations: An introduction. Elsevier. doi: https://doi.org/10.1016/c2014-0-01236-1
12. Wills, B. A., Finch, J. (2015). Wills' mineral processing technology: an introduction to the practical aspects of ore treatment and mineral recovery. Butterworth-Heinemann. doi: https://doi.org/10.1016/c2010-0-65478-2
13. King, R. P. (2001). Modeling and simulation of mineral processing systems. Butterworth-Heinemann. doi: https://doi.org/10.1016/c2009-0-26303-3
14. Chieregati, A. C., Delboni Júnior, H. (2001). Novo método de caracterização tecnológica para cominuição de minérios. São Paulo: EPUSP.
15. Malyarov, P., Dolgov, O., Kovalev, P. (2020). Mineral raw material disintegration mechanisms in ball mills and distribution of grinding energy between sequential stages. Mining of Mineral Deposits, 14 (2), 25–33. doi: https://doi.org/10.33271/mining14.02.025
16. Azooz, K. (2021). Improving productivity based on the movement of materials inside a grinding cement mill. Kufa Journal of Engineering, 10 (4), 1–15. doi: https://doi.org/10.30572/2018/kje/100401

17. Boemer, D., Ponthot, J.-P. (2016). DEM modeling of ball mills with experimental validation: influence of contact parameters on charge motion and power draw. Computational Particle Mechanics, 4 (1), 53–67. doi: https://doi.org/10.1007/s40571-016-0125-4
18. Naumenko, Y., Deineka, K. (2023). Building a model of the impact grinding mechanism in a tumbling mill based on data visualization. Eastern-European Journal of Enterprise Technologies, 3 (7 (123)), 65–73. doi: https://doi.org/10.15587/1729-4061.2023.283073
19. Napier-Munn, T. J., Morrell, S., Morrison, R. D., Kojovic, T. (1996). Mineral comminution circuits: Their operation and optimisation. Vol. 2. Julius Kruttschnitt Mineral Research Centre, University of Queensland, 413.
20. Powell, M. S., McBride, A. T. (2004). A three-dimensional analysis of media motion and grinding regions in mills. Minerals Engineering, 17 (11-12), 1099–1109. doi: https://doi.org/10.1016/j.mineng.2004.06.022
21. Morrison, A. J., Govender, I., Mainza, A. N., Parker, D. J. (2016). The shape and behaviour of a granular bed in a rotating drum using Eulerian flow fields obtained from PEPT. Chemical Engineering Science, 152, 186–198. doi: https://doi.org/10.1016/j.ces.2016.06.022
22. de Klerk, D. N., Govender, I., Mainza, A. N. (2019). Geometric features of tumbling mill flows: A positron emission particle tracking investigation. Chemical Engineering Science, 206, 41–49. doi: https://doi.org/10.1016/j.ces.2019.05.020
23. Cleary, P. W. (2001). Recent advances in dem modelling of tumbling mills. Minerals Engineering, 14 (10), 1295–1319. doi: https://doi.org/10.1016/s0892-6875(01)00145-5
24. Wang, M. H., Yang, R. Y., Yu, A. B. (2012). DEM investigation of energy distribution and particle breakage in tumbling ball mills. Powder Technology, 223, 83–91. doi: https://doi.org/10.1016/j.powtec.2011.07.024
25. Govender, I., Richter, M. C., Mainza, A. N., De Klerk, D. N. (2016). A positron emission particle tracking investigation of the scaling law governing free surface flows in tumbling mills. AIChE Journal, 63 (3), 903–913. doi: https://doi.org/10.1002/aic.15453
26. Yin, Z., Peng, Y., Li, T., Wu, G. (2018). DEM Investigation of Mill Speed and Lifter Face Angle on Charge Behavior in Ball Mills. IOP Conference Series: Materials Science and Engineering, 394, 032084. doi: https://doi.org/10.1088/1757-899x/394/3/032084
27. Naumenko, Y. (2017). Modeling a flow pattern of the granular fill in the cross section of a rotating chamber. Eastern-European Journal of Enterprise Technologies, 5 (1 (89)), 59–69. doi: https://doi.org/10.15587/1729-4061.2017.110444
28. Naumenko, Y. (2017). Modeling of fracture surface of the quasi solid-body zone of motion of the granular fill in a rotating chamber. Eastern-European Journal of Enterprise Technologies, 2 (1 (86)), 50–57. doi: https://doi.org/10.15587/1729-4061.2017.96447
29. Naumenko, Y., Sivko, V. (2017). The rotating chamber granular fill shear layer flow simulation. Eastern-European Journal of Enterprise Technologies, 4 (7 (88)), 57–64. doi: https://doi.org/10.15587/1729-4061.2017.107242
30. Deineka, K., Naumenko, Y. (2019). Revealing the effect of decreased energy intensity of grinding in a tumbling mill during self-excitation of auto-oscillations of the intrachamber fill. Eastern-European Journal of Enterprise Technologies, 1 (1), 6–15. doi: https://doi.org/10.15587/1729-4061.2019.155461
31. Deineka, K., Naumenko, Y. (2019). Establishing the effect of a decrease in power intensity of self-oscillating grinding in a tumbling mill with a reduction in an intrachamber fill. Eastern-European Journal of Enterprise Technologies, 6 (7 (102)), 43–52. doi: https://doi.org/10.15587/1729-4061.2019.183291
32. Deineka, K., Naumenko, Y. (2020). Establishing the effect of decreased power intensity of self-oscillatory grinding in a tumbling mill when the crushed material content in the intra-chamber fill is reduced. Eastern-European Journal of Enterprise Technologies, 4 (1 (106)), 39–48. doi: https://doi.org/10.15587/1729-4061.2020.209050
33. Deineka, K., Naumenko, Y. (2021). Establishing the effect of a simultaneous reduction in the filling load inside a chamber and in the content of the crushed material on the energy intensity of self-oscillatory grinding in a tumbling mill. Eastern-European Journal of Enterprise Technologies, 1 (1 (109)), 77–87. doi: https://doi.org/10.15587/1729-4061.2021.224948
34. Deineka, K., Naumenko, Y. (2022). Revealing the mechanism of stability loss of a two-fraction granular flow in a rotating drum. Eastern-European Journal of Enterprise Technologies, 4 (1 (118)), 34–46. doi: https://doi.org/10.15587/1729-4061.2022.263097
35. Deineka, K. Yu., Naumenko, Yu. V. (2018). The tumbling mill rotation stability. Scientific Bulletin of National Mining University, 1, 60–68. doi: https://doi.org/10.29202/nvngu/2018-1/10
36. Gupta, V. K., Sharma, S. (2014). Analysis of ball mill grinding operation using mill power specific kinetic parameters. Advanced Powder Technology, 25 (2), 625–634. doi: https://doi.org/10.1016/j.apt.2013.10.003
37. Hanumanthappa, H., Vardhan, H., Mandela, G. R., Kaza, M., Sah, R., Shanmugam, B. K. (2020). A comparative study on a newly designed ball mill and the conventional ball mill performance with respect to the particle size distribution and recirculating load at the discharge end. Minerals Engineering, 145, 106091. doi: https://doi.org/10.1016/j.mineng.2019.106091
38. ISO 924:1989. Coal preparation plant – Principles and conventions for flowsheets. Available at: https://www.iso.org/standard/5340.html
39. Maschinen für die mechanische Aufbereitung von Mineralien und ähnlichen festen Stoffen – Sicherheit – Teil 3: Spezifische Anforderungen für Brecher und Mühlen; Deutsche Fassung EN 1009-3:2020. Available at: https://www.din.de/de/mitwirken/normenausschuesse/nam/veroeffentlichungen/wdc-beuth:din21:316006092