UDC 621.926.5:539.215
DOI: 10.15587/1729-4061.2023.283073

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

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A mathematical model was built based on data visualization for the impact grinding mechanism in a tumbling mill, which is mainly implemented during coarse grinding.

The determination of impulse interaction parameters is problematic due to the difficulty of modeling and the complexity of hardware analysis of the behavior of intramill loading.

Conceptually, it was envisaged to identify the relative dynamic parameters of the impact action as components of the model, which are criteria for the similarity of the loading movement and the grinding process. Impact power was taken as an analog of grinding performance. The initial characteristic of the impact was considered to be the averaged vertical component of the speed of loading movement in the flight zone at the boundary of contact with the shear layer. The formalization of the model revealed the effect on the performance of the mass fraction of the flight zone and the reversibility of loading.

The method of numerical modeling was applied, based on experimental visualization of the behavior of granular loading in the cross section of a rotating chamber.

The influence of the rotation speed on the performance at a chamber filling degree of 0.45 and a relative particle size of a milling load of 0.0104 was estimated by experimental simulation. The maximum productivity value was found at the relative speed of rotation ψ_ω***=1–1.05. A rational condition for impact grinding at*** ψ_ω***=0.75–0.9 has been established.***

The test proved the effectiveness of using visualization to evaluate dynamic loading interaction analogs. Verification of modeling results was implemented by comparison with the data of the technical standard. The use of similarity criteria unifies approaches to modeling different mechanisms of destruction.

The model built makes it possible to predict the rational parameters of the grinding processes by impact, crushing, and abrasion

Keywords: tumbling mill, intra-chamber loading, impact action, flight zone, similarity criteria, grinding performance

Received date 04.04.2023
Accepted date 09.06.2023
Published date 30.06.2023

How to Cite: *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*

1. Introduction

Fine grinding of solid materials in many industries is carried out in tumbling mills. The widespread use of such disintegrators is due to the reliability and simplicity of operation.

It is well known that grinding in a tumbling mill is an energy-inefficient process with limited productivity [1–5]. It is believed that the efficiency of such a mill is only 1–5 % [6, 7]. The high energy intensity of grinding is caused by energy dissipation due to the shear circulation of internal mill loading [2, 8–10]. The estimate of the consumed power can be considered as an indirect indicator of the mill's productivity [11–13]. Therefore, the problem of reducing the energy intensity of work processes of tumbling mills remains relevant [14].

The task to construct an effective model for accurate prediction of energy consumption of tumbling mills has attracted the attention of researchers for a long time [15]. Numerical empirical and computational methods have been developed to predict power consumption for different types of tumbling mills [16–19]. However, such models turned out to be quite controversial. As input variables, they use parameter values, the practical setting of which causes significant difficulties. This makes it difficult to accurately estimate the energy intensity of grinding. In addition, these models do not provide insight into the relationship between operational factors and energy intensity, in particular between the capacity and productivity of the grinding process in a tumbling mill [20].

The process of grinding in a tumbling mill is carried out by combining three mechanisms of interaction of grinding bodies with particles of the processed material impact action, crushing, and abrasion [21–24]. It is believed that as a result of the impact action, coarse grinding occurs mainly, abrasion makes it possible to achieve fine grinding, and crushing has an intermediate technological result of the action. The occurrence and ratio of such grinding mechanisms is determined by the mode of movement of the intra-chamber milling loading.

A significant proportion of tumbling mills carry out high-performance coarse grinding due to the mainly impact action of internal mill grinding loading. However, the quantitative results of impact effect on the energy intensity and productivity of the grinding process are still unknown, which significantly limits the functionality of such equipment.

Taking into account the above, the task of predicting the effect of impact action of the milling load on the grinding performance in a tumbling mill seems to be quite relevant.

2. Literature review and problem statement

The implementation of three grinding mechanisms in a tumbling mill by impact action, crushing, and abrasion is determined by the mode of movement of the intra-chamber loading, the modeling of which is associated with significant difficulties.

In work [25], the impact effect of the mill loading of a tumbling mill was investigated experimentally and numerically by the method of discrete elements. An attempt was made to detect the magnitude of the impact force and the energy intensity of the impact loading action. However, the obtained results do not allow us to evaluate the performance of the shock loading mechanism.

According to the traditional classification of movement modes of granular loading of the chamber of a rotating drum, grinding in tumbling mills is carried out under rolling mode, cascade mode, and cataract mode. For the first time, such a classification was proposed in [26]. Only the case of a slow rolling mode with a thin shear layer was analytically considered. At the same time, the manifestation of the flight zone was completely neglected. In [28], the mid-travel mode of rolling with an increased shear layer on the border of a possible transition of such a mode to a cascade mode was analytically studied. However, the occurrence of the loading flight zone was also not taken into account. The conditions for the mutual transition of the cascade, cataract, and centrifugation modes based on an extremely simplified model of the behavior of granular loading are proposed in [28]. However, the geometric and kinematic parameters of the loading flight zone were not determined.

When the three indicated loading modes occur, a passive flow zone is formed in the lower part of the cross-section of the chamber, and an active zone is formed in the upper part. The passive zone is characterized by quasi-solid motion of particles without relative sliding. The active zone contains a shear layer, in the lower part, and a flight zone, in the upper part, the proportion of which increases with increasing rotation speed. The shock effect of the loading acquires the greatest value under the cataract mode of movement when the share of the flight zone reaches a maximum. However, the analysis of load movement modes in [26–28] is only qualitative in nature and does not allow quantitative estimation of flow zone parameters.

The position of the active movement zone of the loading chamber of the rotating drum was studied in works [29–33]. Experimental studies were carried out by the method of visualizing motion patterns in transverse [29] and longitudinal [30] sections of the chamber of a rotating drum. In [31], a numerical analysis was carried out using a continuous model with experimental verification. The numerical method of discrete elements was applied in [32]. In [33], an experimental method of fluoroscopy of the movement of loading particles was used. However, the kinematic parameters of the flight zone were not considered in these works.

In [34], the behavior of intra-chamber loading under the cataract mode of movement was numerically modeled by the method of discrete elements. The flight, shear layer and passive zones were distinguished. However, the obtained results concern only the geometric and kinematic parameters of the zones.

Individual characteristics of the flight zone were studied by experimental and numerical methods. In work [35], the boundaries and characteristic points of the loading flight zone of the dry semi-self-grinding mill were determined using video recording. However, mass and kinematic parameters of the zone were not considered. The method of discrete elements was applied in [36] for a numerical study of the limits and speeds of movement of the flight zone. However, the dynamic characteristics of the impulse interaction of the elements and the total shock action of loading were not established.

In works [37, 38], the geometric parameters of loading movement zones were studied using X-ray microscopy. A detailed structuring of elements and parameters of zones and their geometric characteristics is given. The position of the free surface [37] and the center of circulation [38] of loading is established. However, the analysis of the dynamic parameters of the movement was not carried out.

The method of analytical-experimental modeling of movement zones of granular loading in the cross-section of the rotating drum chamber was proposed in [39]. Modeling is performed by constructing movement patterns based on the determination of the position of the border of the transition of the passive zone into the fall zone [40] and the parameters of the shear layer [41]. However, the obtained results did not provide an assessment of the energy and technological characteristics of the impact grinding process.

In works [42–45], the geometric and kinematic parameters of the loading flight zone were studied using the visualization method, in particular, the dilatancy and amplitude of pulsations. The dynamic parameters of the self-oscillating shock action of loading and the technological characteristics of grinding for one value of the degree of filling of the chamber were quantitatively evaluated in [42]. In [43], 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. The effect of material content on the modes of movement of grinding bodies and the efficiency of self-oscillating grinding for one value of filling the chamber was studied in [44]. In [45], the influence of a simultaneous change in the degree of chamber filling and the content of the crushed material on the grinding process was studied. However, the results were obtained only for the case of the self-oscillating mode of motion due to the implementation of a specific mechanism [46] of the loss of motion stability [47].

No models have been developed to determine the impact performance of an in-chamber grinding charge on material being milled in a tumbling mill. This is due to the insurmountable difficulties of analytical and numerical modeling and the increased complexity of the instrumental experimental study of the behavior of the flight zone of the granular loading chamber of the rotating drum. The lack of such models is especially negative in the case of implementing the energy-saving grinding process.

3. The aim and objectives of the study

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

To achieve this goal, the following tasks were solved:

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

– perform experimental modeling and evaluate the effect of rotation speed on the energy and productivity of the grinding process due to the implementation of the impact interaction mechanism.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is the mechanism of impact grinding in a tumbling mill. The subject of the research is mathematical modeling of the impact grinding process.

It was believed that the impact interaction of loading elements is carried out on the transition surface of the flight zone into the shear layer zone, which is the contact surface. This interaction was assumed to be completely inelastic. The impact of non-impact interaction forces on the grinding process was neglected. The vertical component of impact interaction was considered to be the largest in size and decisive for the effectiveness of the grinding process. The value of the vertical component of the velocity of the load movement after the shock interaction was neglected.

The model of the impact grinding mechanism was based on the relative dynamic parameters of the impact interaction, which are criteria for the similarity of the loading movement and the grinding process. The power of impact interaction forces was considered to be analogous to the performance of the impact grinding process.

It was assumed that the drum chamber is long. It was assumed 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 assumed that the parameters of this mode are determined by the stationary patterns of loading movement.

As a simplification, the case of monofractional intra-chamber loading of a rotating drum was considered. The accepted discrete value of the degree of chamber filling was 0.45, which corresponds to the process of coarse grinding in a tumbling mill. It was assumed that, in this case, the mechanism of shock action of loading prevails over the mechanisms of crushing and abrasion.

4. 2. Research methods

The movement of intrachamber granular loading of a rotating drum in the form of a steady gravity flow is extremely difficult to study experimentally. The high sensitivity of the flows of the granular medium to external influences causes significant disturbances in the complex nature of the interaction of particles due to the manifestation of local boundary effects. The main difficulties arise as a result of the increased sensitivity of the grain flow to internal hardware probing. Therefore, physical visualization of data was adopted as the main method of experimental research since the marginal marginal effect of loading on the end wall of the chamber turned out to be insignificant.

To determine the impact interaction parameters, an experimental method of numerical modeling was applied based on experimental visualization of its behavior in the chamber of a rotating drum. Visualization was carried out by recording and further processing pictures of loading movement in the cross-section of the chamber, which were obtained through its transparent end wall. The algorithm for implementing the data visualization method consists in the sequential implementation of the following stages:

1) filling the drum chamber with a portion of granular loading with discrete values of the degree of κ;

2) achievement of a stable mode of movement of the loading during stationary rotation of the drum with a discrete value of the relative speed ψ_ω;

3) performing video recording of the loading movement in the cross-section of the rotating chamber, which has a transparent end wall;

4) obtaining a picture of the loading movement;

5) selection of flat geometric shapes on the picture corresponding to the zones of movement – solid, flight, and shear layer;

6) measurement on the picture of the chamber radius R;

7) measurement on the picture of the vertical distance from the highest to the lowest point on the free surface of the loading flight zone h_{fr};

8) measurement on the picture of the radial coordinate of the load circulation center relative to the axis of rotation R_c;

9) measurement of the values of the areas of selected geometric figures – the solid zone F_{sr} and the zone of the shear layer F_{sl};

10) calculation of the values of the parameters of the shock interaction of the loading according to the corresponding expressions.

A stroboscopic tachometer was used to measure the drum rotation speed. The value of the rotation speed was constantly checked to ensure the correctness of the measurements. 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 the linear dimensions and areas of geometric figures on motion pictures obtained by video recording.

A laser-type analyzer was used to measure the particle size of the granular charge.

Laboratory beakers were used to dose the loading portion. The portion volume was determined at rest, without compaction when filling the measuring chamber.

In order to exclude the influence of random factors on the reliability of the measurement results, 3 motion pictures were obtained 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 pictures for each speed of rotation were 2–3 %.

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

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

The content of the loading chamber was estimated by the volumetric 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 value of the speed of rotation of the drum was estimated by the value of the relative speed of rotation

$\psi_\omega = \omega\sqrt{R/g}$, where ω is the angular speed of rotation, g is the gravitational acceleration. The discrete values of the relative speed of the stationary rotation changed from the state of rest to the appearance of the loading motion mode in the form of a near-wall layer, with a step of $\Delta\psi_\omega$=0.05.

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

5. Research results of the process of crushing in a tumbling mill by impact action

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

The intra-chamber granular loading of the drum, which rotates with a small angular velocity around the horizontal axis, carries out a circulation movement mainly under a three-phase flow mode (Fig. 1).

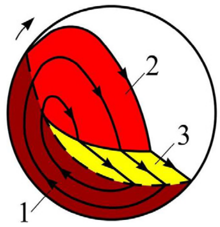

Fig. 1. Scheme of movement zones of granular loading of the rotary drum chamber: 1 – solid zone, 2 – flight zone, 3 – shear layer zone

At a low rotation speed, the mass fraction of zone 1 prevails. As the speed increases, the fractions of zones 2 and 3 increase at the expense of zone 1. As the speed approaches the critical value, the fraction of zone 2 reaches its maximum value, and the fraction of zone 3 goes to zero. At a high speed of rotation, a mode of motion occurs in the form of a near-wall layer consisting only of zone 1.

During the shock interaction of the milling body in the flight zone with the shear loading layer, there is a jump-like final change in the velocity of the body. At the same time, an impact force acts on the transition surface of the flight zone into the shear layer, which is the contact surface, for a short period of time. The measure of the strength of the impact interaction is the impact impulse.

The duration of the shock interaction is very short. Since the shock impulse has a finite value, the force modulus of the milling body can be quite large, which ensures the implementation of the grinding process by shock action. Impact interaction of loading elements can be considered completely inelastic. On the considered contact surface, which is the transition of loading movement zones, the influence of non-impact interaction forces on the grinding process can be neglected.

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

For an approximate implementation of such an assessment, it is convenient to apply specific and absolute relative analogs of the dynamic parameters of impact interaction. The initial data for determining such parameters can be obtained in a simplified way by means of visualization of loading movement patterns in the cross-section of the rotating chamber. Hereafter, it is considered that the largest and determining component of the impact interaction, in terms of the effectiveness of the grinding process, is vertical.

The initial characteristic, which approximately determines the magnitude of the impact, is the average value of the vertical component of the speed of movement of the loading flight zone before the impact interaction V_{fr}. This component of speed is realized at the border of the transition of the flight zone into the shear layer, which is the contact surface of the shock interaction:

$$V_{fr} = \sqrt{\frac{h_{fr} g}{2}}, \quad (1)$$

where h_{fr} is the vertical distance from the highest to the lowest point on the free surface of the loading flight area in the movement pattern, determined by the visualization method.

The magnitude of the impact pulse is determined from its correspondence to the change in the amount of movement of the load. At the same time, it is considered that the value of the vertical component of the speed of loading movement after the shock interaction is small, the value of which can be neglected.

The specific relative momentum of the vertical component of the force of the impact interaction S_{frr} corresponds to the ratio of the averaged absolute momentum of the loading mass unit to the quantity $\sqrt{Rg}$:

$$S_{frr} = \frac{V_{fr}}{\sqrt{Rg}}. \quad (2)$$

After transformations, expression (2) changes to

$$S_{frr} = \sqrt{\frac{h_{fr}}{2R}}. \quad (3)$$

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

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

$$A_{ibrs} = \frac{1}{2}\left(\frac{V_{fr}}{\sqrt{Rg}}\right)^2. \quad (4)$$

After transformations, expression (4) takes the form:

$$A_{ibrs} = \frac{h_{fr}}{4R}. \quad (5)$$

The relative impact crushing energy for one circulation cycle of loading in the chamber of the rotating drum E_{ibrc} corresponds to the full relative work of the vertical component forces of the impact interaction for one circulation cycle:

$$E_{ibrc} = A_{ibrs} K_{fr}, \quad (6)$$

where K_{fr} – mass fraction of the flight area loading.

The expression for Kfr is:

$$K_{fr} = \frac{m_{fr}}{m}, \quad (7)$$

where m_{fr} is the mass of the loading flight area, m is the mass of the entire load.

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

$$K_{fr} = 1 - \frac{F_{sr} + \dfrac{F_{sl}}{\upsilon_{sl}}}{\pi R^2 \kappa}, \quad (8)$$

where F_{sr} is the area of the solid zone in the movement picture,

F_{sl} is the area of the shear layer zone,

υ_{sl} is the dilatancy of the shear layer.

At the same time, it is considered that the increase in the volume of the shear layer during movement is small, and the value of its dilatancy goes to zero $\upsilon_{sl} \to 1$.

After transformations, expression (6) takes the form:

$$E_{ibrs} = \frac{h_{fr}}{4R} K_{fr}. \quad (9)$$

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

$$E_{ibrt} = E_{ibrc} n_{to}, \quad (10)$$

where n_{to} is the reversibility of loading motion, which determines the number of cycles of loading circulation in the chamber during one revolution of the drum [28].

The expression for n_{to} looks like this:

$$n_{to} = \frac{2\pi}{t_{cp}\omega}, \quad (11)$$

where t_{cp} is the duration of the load circulation period in the rotating drum chamber.

The value of n_{to} can be roughly determined by the method of visualizing loading movement patterns by the expression:

$$n_{to} = \left[1 - \left(\frac{R_c}{R}\right)^2\right] \frac{1}{\kappa}, \quad (12)$$

where R_c is the radial coordinate of the load circulation center relative to the axis of rotation in the movement pattern.

After transformations, expression (10) takes the form:

$$E_{ibrt} = \frac{h_{fr}}{4R} K_{fr} n_{to}. \quad (13)$$

An analog of the relative productivity of impact crushing Q_{ibr} corresponds to the relative power of the vertical component forces of the impact interaction

$$Q_{ibr} = \frac{E_{ibrt}}{T_{tr}}, \quad (14)$$

where $T_{tr} = T_t \sqrt{g/R}$ is the relative drum rotation period, $T_t = 2\pi/\omega$ is the absolute period of rotation.

After transformations, expression (14) takes the form:

$$Q_{ibr} = \frac{h_{fr}}{8\pi R} K_{fr} n_{to} \psi_{\omega}. \quad (15)$$

The applied relative parameters (2) to (15) are dynamic criteria for the similarity of loading movement and grinding process in a tumbling mill by impact action. The values of the dynamic parameters according to the expressions (3), (5), (9), (13), and (15) make it possible to numerically evaluate the changes in the technological effect of the shock action of loading depending on the initial characteristics of the grinding process.

5. 2. Results of experimental modeling of impact interaction of intra-chamber loading of a tumbling mill

Separate obtained pictures of the steady movement of loading in the chamber of a stationary rotating drum at $\kappa=0.45$ are shown in Fig. 2.

Experimental motion pictures in Fig. 2 characterize the effect of rotation speed on the position and mass fractions of loading movement zones in the rotating chamber.

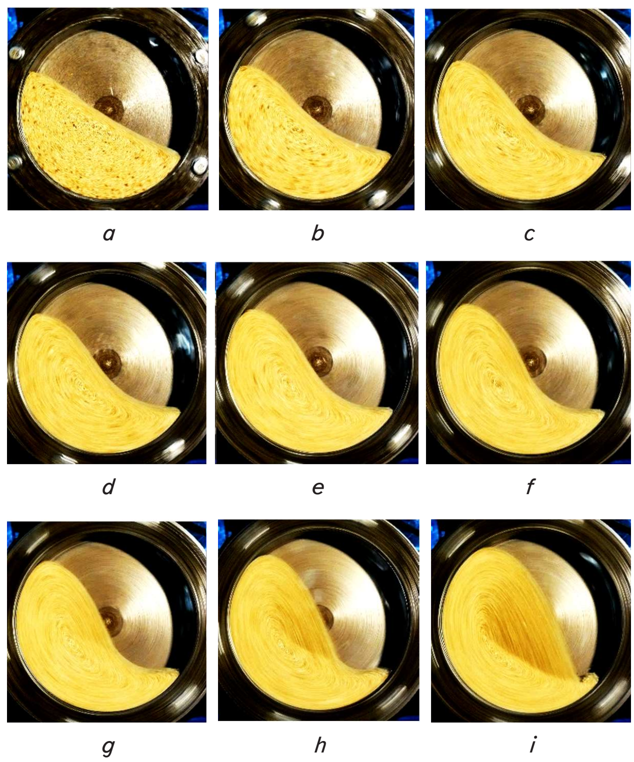

Fig. 2. Patterns of granular loading motion at relative particle size $\psi_d=0.0104$ and the degree of filling of the chamber $\kappa=0.45$: *a* – $\psi_\omega=0.1$; *b* – $\psi_\omega=0.2$; *c* – $\psi_\omega=0.3$; *d* – $\psi_\omega=0.4$; *e* – $\psi_\omega=0.5$; *f* – $\psi_\omega=0.6$; *g* – $\psi_\omega=0.7$; *h* – $\psi_\omega=0.8$; *i* – $\psi_\omega=0.9$

The plots of the obtained results of the experimental determination of the change in parameters of the shock interaction of loading at $\kappa=0.45$ are shown in Fig. 3–9.

The plot of change in the specific relative momentum of the vertical component of the force of the shock interaction of loading S_{fr} from the relative speed of rotation ψ_ω is shown in Fig. 3. The values of S_{fr} were determined from expression (3).

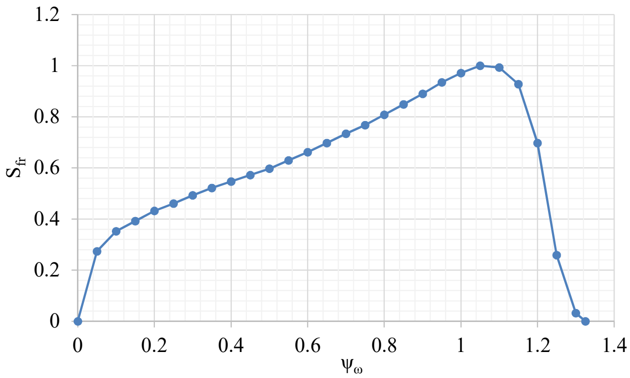

Fig. 3. Experimental dependence of the change in the specific relative momentum of the vertical component of the force of the shock interaction of loading S_{fr} on the relative speed of rotation ψ_ω

The plot of change in the specific relative work of the vertical component of the force of the shock interaction loading A_{ibrs} from ψ_ω is shown in Fig. 4. The values of A_{ibrs} were determined from expression (5).

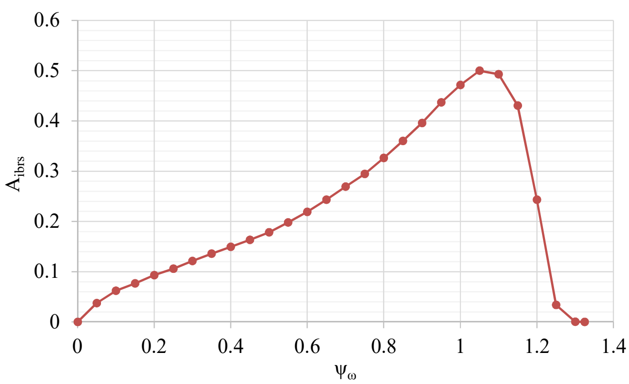

Fig. 4. Experimental dependence of the change in the specific relative work of the vertical component of the force of the shock interaction of loading A_{ibrs} on the relative speed of rotation ψ_ω

The plot of change in the mass fraction of the loading flight zone K_{fr} from ψ_ω is shown in Fig. 5. The K_{fr} values were determined from expression (6).

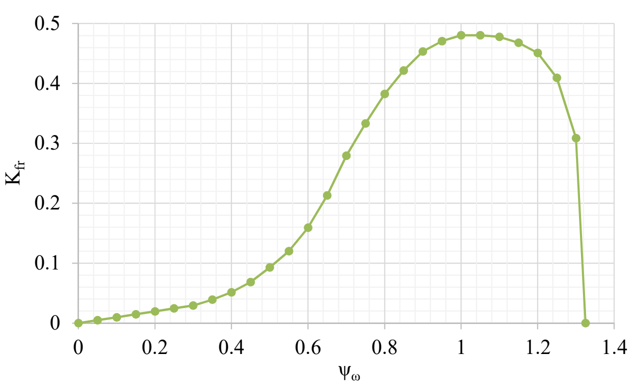

Fig. 5. Experimental dependence of the change in the mass fraction of the loading flight zone K_{fr} on the relative rotation speed ψ_ω

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

The plot of change in the reversibility of the movement of loading n_{to} from ψ_ω is shown in Fig. 7. The values of n_{to} were determined from expression (12).

The plot of change in the relative energy of impact crushing for one revolution of the drum E_{ibrt} from ψ_ω is shown in Fig. 8. The E_{ibrt} values were determined from expression (13) taking into account (8) and (12).

The plot of change of the analog of the relative performance of impact grinding Q_{ibr} from ψ_ω is shown in Fig. 9. The Q_{ibr} values were determined from expression (15) taking into account (8) and (12).

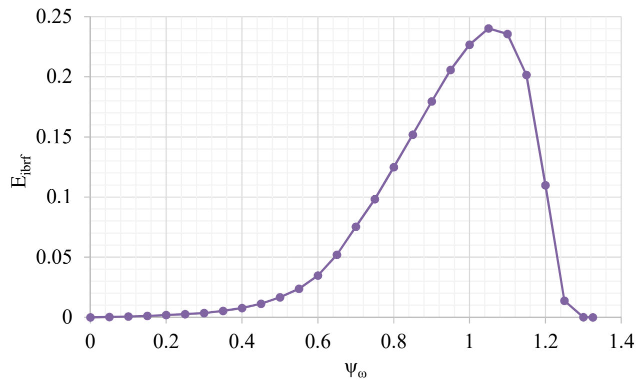

Fig. 6. Experimental dependence of the change in the relative impact crushing energy during one cycle of loading circulation in the chamber of the rotating drum E_{ibrs} on the relative speed of rotation ψ_ω

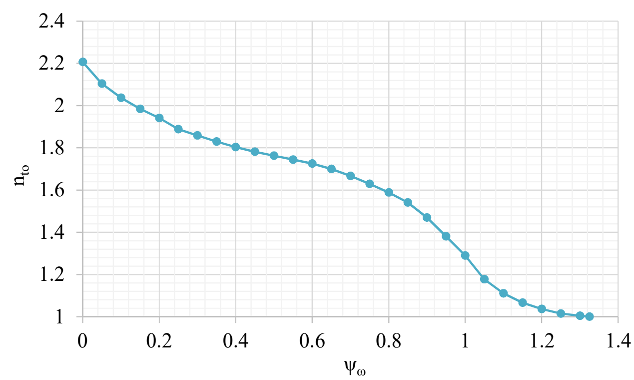

Fig. 7. Experimental dependence of the change in the reversibility of the loading movement n_{to} on the relative speed of rotation ψ_ω

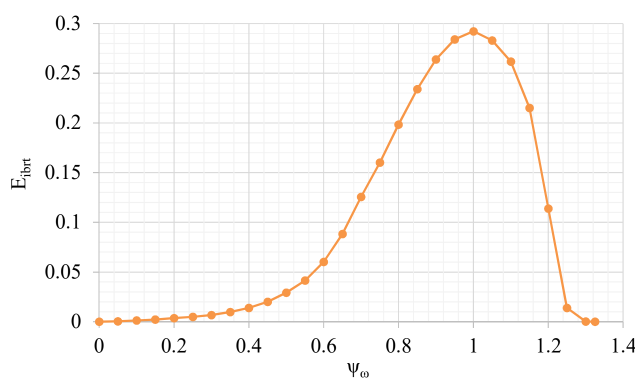

Fig. 8. Experimental dependence of the change in the relative impact crushing energy for one revolution of the drum E_{ibrt} on the relative speed of rotation ψ_ω

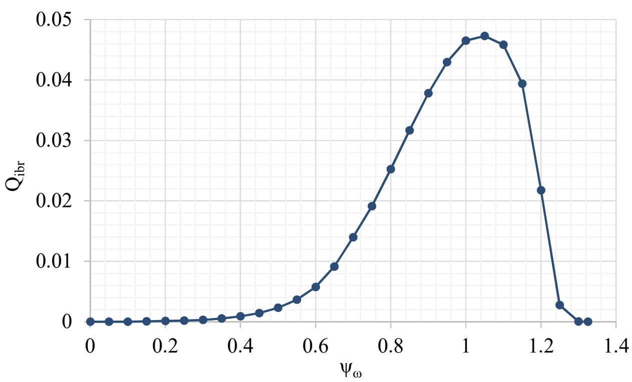

Fig. 9. Experimental dependence of the change of the analog of the relative productivity of impact grinding Q_{ibr} on the relative speed of rotation ψ_ω

The obtained experimental dependences of the numerical values of the shock interaction parameters of loading characterize the quantitative influence of the rotation speed on the impact grinding process in a tumbling mill.

6. Discussion of results of investigating the grinding process in a tumbling mill with impact action

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

The initial characteristic, which approximately determines the magnitude of the impact action, has been revealed. This is the averaged value of the vertical component of the speed of movement of the loading flight zone before the impact interaction on the contact surface (1). This contact is realized at the border of the transition of the flight zone into the shear layer.

It was established that the value of the analog of grinding performance in a tumbling mill by impact action (16) is proportional to the square of the initial characteristic (1). In addition, the performance is proportional to the mass fraction of the flight zone (8), load reversibility (12), and drum rotation speed. The defining characteristic of impact interaction is the speed of rotation, which determines the values of parameters (1), (8), and (12).

It was established that the impulse, work, mass fraction, energy (Fig. 3–6, 8) and productivity (Fig. 9) of impact action acquire maximum values at the value of the relative speed ψ_ω=1–1.05. This is caused by the velocity (Fig. 3) and mass fraction (Fig. 5), which are the determining parameters of impact interaction, reaching their maximum values precisely in this narrow range of ψ_ω.

It was found that the values of the parameters (Fig. 4–6, 8, 9) acquire half or more of the maximum possible values at the value of the relative velocity ψ_ω in the range from 0.7–0.8 to 1.2–1.25. This is due to the velocity (Fig. 3) and mass fraction (Fig. 5), which are defining characteristics, reaching large values in the range ψ_ω=0.7–1.25.

It was established that the energy (Fig. 8) and productivity (Fig. 9) of impact grinding acquire half or more of the maximum values at the value of the relative speed ψ_ω from 0.75–0.8 to 1.2. Moreover, it was found that when ψ_ω>0.9, the loading flight zone makes unproductive contact with the cylindrical surface of the chamber (Fig. 2, *i*), which reduces the effectiveness of the impact grinding process. Therefore, ψ_ω=0.75–0.9 can be considered a rational range of values of the relative speed of rotation for grinding in a tumbling mill with impact action.

The results obtained in the work regarding the rational range of ψ_ω coincide well with the data according to GOST 10141-91 "Rod and ball mills. General technical requirements". This technical standard regulates grinding processes in ball mills for coarse grinding, which are carried out mainly by impact action. According to the standard, at the degree of filling the chamber with a milling load of κ=0.42–45, the recommended value of the relative speed of rotation is ψ_ω=0.75–0.85.

The applicability of the established dynamic characteristics of the shock action of loading and the results of forecasting the parameters of the coarse grinding process by implementing the impact mechanism is limited by the discrete values of the initial parameters. The value of the degree of filling of the drum chamber with loading was κ=0.45. 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 use of the obtained results, which can be interpreted as shortcomings of this study. Therefore, identifying the characteristics of the impulse interaction with a different, in particular, a smaller filling of the chamber with loading seems to be a potentially interesting direction of further research. This will reveal new dynamic effects of the impact grinding mechanism.

The shortcomings of the applied approach to assessing the impact of dynamic loading on the grinding process include the failure to take into account crushing and abrasion grinding mechanisms.

In the future, it is advisable to find out the qualitative and quantitative influence on the dynamic and technological parameters of the process of crushing and abrasive interaction of grinding bodies with the particles of the crushed material. This will make it possible to establish rational conditions for creating a crushing and abrasive loading action on the material during the implementation of medium and fine grinding processes in drum-type mills.

7. Conclusions

1. Modeling of the impact action of the intra-chamber loading of the tumbling mill is based on taking into account the jump-like final change in the speed of movement of the flight zone on the surface of the impulse contact. The inelastic shock interaction occurs at the border of the transition of the loading flight zone to the shear layer zone. The impact factor is the averaged value of the vertical component of the speed of the flight zone before the interaction. Analogs of the dynamic parameters of impact interaction are momentum, work, and power of impact forces. As an analog of the relative productivity of the impact grinding process, the relative strength of the impact forces can be taken. The applied relative dynamic parameters of impact interaction are criteria for the similarity of the loading movement and the grinding process in the tumbling mill by impact action.

The speed and mass fraction of the flight zone, the reversibility of the charge circulation in the chamber, and its rotation speed are the determining parameters of the impact on the analog of the grinding productivity by impact action.

2. It was established that the energy and the analog of the productivity of grinding by impact action reach their maximum values at the value of the relative speed of rotation

of the drum chamber ψ_ω=1–1.05. Half and more, from the maximum possible values, the energy and the analogue of impact grinding productivity are obtained within the range of ψ_ω from 0.75–0.8 to 1.2. It was found that the rational range of values of the relative speed of rotation during grinding in a tumbling mill by impact action is ψ_ω=0.75–0.9.

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.

Funding

The study was conducted without financial support.

Data availability

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

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