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DYNAMICS OF THE INTERACTION BETWEEN THE CHARGE AND THE PROTECTIVE LINING INSIDE THE DRUM BALL MILLS

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Abstract. The article is focused on the study of a process of interaction between the charge and the rubber lining inside the drum ball mills, which are used for the disintegration of mineral raw materials in the mining, metallurgical, and cement industries. Special attention is paid to the study of the dynamics of the interaction between the charge and the protective rubber linings inside the mill, wear of the linings and their influence on the productivity of the mills during operation. An important aspect of the research is the analysis of various lining designs and their behavior under dynamic loads.

The study was conducted with the help of numerical modeling with the Rocky DEM software complex, which enables the researches to simulate the interaction between the particles of the charge and the lining surface and to study the dynamics of the motion of the charge segments inside the mill. Two types of linings were modeled: "Plate - Lifter - Plate" and "Plate - Plate". The model took into account parameters such as impact loads, abrasive wear, mill rotation speed and type of material to be charged. A series of experiments was conducted on a laboratory mill to verify the results of numerical modelling. The tests confirmed high accuracy of the obtained data.

The study results showed that the greatest loads on the lining occur in the area of the rollback heel, which is critical in terms of the lining wear. In particular, the "Plate-Plate" lining shows a lower level of wear compared to the "Plate-Lifter-Plate" due to the better dynamic interaction with the charge and reduced impact forces. It was established that correct choice of a lining type can significantly influence the efficiency of material grinding because of reduced rubber aging at the abrasive-fatigue wear and extended service life of the mill linings. The experimental results align with the simulation and industrial test data, hence, confirming the effectiveness of the numerical approach.

The obtained data can be used to improve designs of rubber linings for drum ball mills, which will increase the grinding efficiency and reduce the maintenance costs of the equipment. In particular, the results of the research can applied in the mining, metallurgical and cement industries, where the service life of linings and the reduction of their wear are the key factors for lowering operational costs and improving performance of enterprises.

Keywords: disintegration, grinding, drum mill, rubber lining, modeling, wear.

1. Introduction

Drum ball mills are one of the most widely-used material grinding equipment in various industries. Their use is particularly important in the mining and metallurgical complex, construction, chemical and other industries, where it is necessary to obtain the fine-dispersed products [1, 2]. Nowadays, more and more attention is given to the use of rubber protective linings in these mills as they have a number of advantages compared to traditional metal ones [3, 4]. These advantages include reduced noise level, better operating conditions, increased service life of equipment, and improved economic performance of the process of disintegration of mineral raw materials [1, 3, 4]. It is also known that the rubber lining not only protects the drum from wear, damage and dynamic loads, but also directly participates in the disintegration process influencing the efficiency of material grinding [1].

Despite the widespread implementation of ball mills with rubber linings, the processes occurred inside the mill during its operation remain poorly understood. This is especially true for the dynamics of the interaction between the charge and the protective lining inside the mill, which directly influence the mill productivity and its economic performance. Despite significant progress in the development of modern mill designs, the influence of variable factors on grinding efficiency, such as geometric parameters, materials and layout of the rubber lining, has not been fully investigated yet. These issues require additional study in order to improve the operational characteristics of the equipment, to reduce its maintenance costs, and to improve the quality of material grinding.

Therefore, further study of dynamics of interaction between the charge and the lining is a promising direction that will enable to optimize the drum ball mill operation, increase their productivity and reduce operating costs.

The problem of the interaction between the charge and the lining is insufficiently covered in the existing literature. The cited sources contain just disembodied data concerning the charge distribution across the mill section, the charge sliding relative to the lining and frictional fluctuations of the center of the charge mass [5, 6]. The researchers mainly focused on studying the process of material grinding, determining mill productivity, constructing diagrams of the filling of drum cross section, and calculating the strength of the drums.

However, none the less is the issue of studying the motion of the charge segments at the boundary between the "charge-lining" phases, which has never been addressed. One of the main reasons for this is the complexity of experimental research. Therefore, the processes occurred in the contact zone are usually assessed by kinetics of wear of the lining and the nature of its destruction, and the morphology of the damaged surface.

Some aspects of the process are possible to simulate in laboratory mills or by analyzing the dynamics of two-phase materials (pulp and coarse material) in concentrators, hydrodynamic trays, or in natural conditions such as channel flows [7].

At the early stage of the rubber linings use in mills, ore pits, bunkers and sluices, it was stated [1] that the flow of abrasive material leaves traces on the lining surface in the form of a river-like pattern, while their wear in ball mills has a wave-like nature [8].

Designers took this pattern into account and gave the lining working surface a wave shape: in some designs, it is trapezoidal plates, and in others - a plate and lifters of different heights [5]. The long-term practice of using rubber linings gave a possibility to accumulate a significant amount of experimental data on the nature of their wear during the processing of various materials.

These data became the basis for creating more durable lining designs. Thus, a trapezoidal "Plate - Plate" type of lining was designed with no lifters [9]. This lining demonstrated long service life and high technological efficiency and is successfully used in ball mills of various types [1, 4, 10]. Another lining of the "Plate - Lifter - Plate" type with optimally chosen parameters is effectively used in wet self-grinding mills [1, 4, 10]. However, the mechanism of the charge-lining interaction is studied only in terms of the lining wear, and assumptions about the influence of the design on the mill performance require further investigation.

The purpose of the work is to determine the shape of a charge segment cross-section in the drum mill and to study its motion and interaction with the lining.

2. Methods

Mechanism of interaction between the charge and the linings is accompanied by a number of regularities and effects that can manifest both individually and in the form of collective-functional interaction. In this case, the principle of emergence applies: a joint action of various effects leads to the emergence of new patterns that cannot be obtained in case of separate action of each of these effects. However, for a more accurate understanding of the mechanism of action of each effect and to clarify its physical and mechanical essence, it is advisable to consider them individually.

The lining destruction process has a spatial structure and develops over time lasting from several hours to several years. This destruction is a part of a more general process of interaction between the lining and the technological charge of the mill, making it dependent on many factors such as:

- dimensions of the drum,
- speed of its rotation,
- properties of the processed material (abrasiveness, fragment size, presence of solid particles in the pulp),
- rubber lining form and physical and mechanical characteristics of rubber.

Therefore, the destruction process is multi-vector, stochastic and non-linear. A change in one of the parameters of the system, for example, the diameter of the drum or its rotation speed, can significantly change the character of the lining destruction.

Due to the specific nature of mill operation, modeling of these processes faces certain experimental difficulties that are sometimes difficult to overcome. Therefore, study often relies on indirect indicators, such as morphology of the destruction surface or the degree of wear of lining elements. As it has already mentioned, the main processes of technological charge disintegration occur in the loading zone, while destruction of the lining, its service life and the peculiarities of this process are manifested at the boundary of the interaction of the pulp with the lining surface.

3. Theoretical part

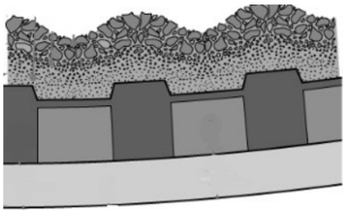
In a rotating drum, the stochastic motion of the charge has a complex hierarchical distribution of particles by size and zones. Many researchers [1, 3, 4, 8, 9, 10] have agreed that this distribution has the form shown in Figure 1a. Large pieces of material and metal balls are concentrated mainly in the upper part of the charge segment, while at the boundary between the "charge-lining" phases, a hydro-air cushion is formed in the form of a pulp with a high content solid particles.

It should be emphasized that such a hydrocushion can be considered as a kind of a "third body" formed by pulp and solid particles of different sizes and origins such as:

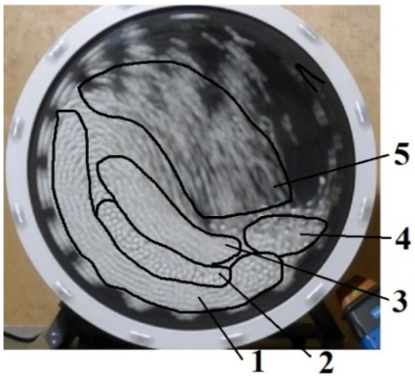
- material to be processed
- particles from the wear of metal balls and
- fragments of rubber lining

Due to the complex surface relief of the lining, the motion of the pulp is exceptionally turbulent, forming complex structures of a vortex-like and spiral-like character. In such a turbulent flow, pulsating fields of speeds and pressures are always present. Among the numerous structural formations, only those that ensure minimal energy dissipation are stably realized.

In the boundary layer (in this case, in the pulp layer at the contact boundary between the charge and the lining), vortices are formed with characteristic sizes corresponding to the thickness of this layer (Fig. 1b). Within this same layer, hydrodynamic and acoustic waves simultaneously interact, creating complex processes of phase interaction.



a



b

1 – dynamic zone, 2 – monodispersoid (low-motion zone), 3 – zone of turbulent motion of balls, 4 – rollback heel, 5 – zone of ball flight

Figure 1 - Distribution of cross-sectional areas of the mill

Let's consider an infinite medium described by the Euler equations and the continuity equation [11, 12]. We assume that the medium moves in the direction of the x axis with the speed U0. Then

$$
\begin{aligned}
&\frac{\partial U}{\partial t}+\left(U_0+U\right)\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}=-\frac{1}{\rho_0+\rho}\frac{\partial p}{\partial x};\\
&\frac{\partial V}{\partial t}+\left(U_0+U\right)\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}=-\frac{1}{\rho_0+\rho}\frac{\partial p}{\partial x};\\
&\frac{\partial p}{\partial t}+\left(U_0+U\right)\frac{\partial p}{\partial x}+\left(\rho_0+\rho\right)\frac{\partial U}{\partial x}+V\frac{\partial p}{\partial y}+\left(\rho_0+\rho\right)\frac{\partial V}{\partial y}=0,
\end{aligned}
\tag{1}
$$

where p_0 and ρ_0 are the pressure and density in the steady state; U, V, p and ρ are deviations of speed, pressure, and density components from stationary values, respectively

If the variables p and ρ are related by the adiabatic equation, then the relationship of U, V, p and ρ is valid

$$
p=p_0\left[\left(\frac{\rho}{\rho_0}+1\right)^{\gamma}-1\right]. \tag{2}
$$

By substituting (2) into (1) and restricting to a linear approximation in terms of deviations from steady states, we obtain

$$\frac{\partial U}{\partial t}+U_0\frac{\partial U}{\partial x}+\frac{a^2}{\rho_0}\frac{\partial p}{\partial x}=0;\quad \frac{\partial V}{\partial t}+U_0\frac{\partial V}{\partial x}=0;$$
$$\frac{\partial p}{\partial t}+U_0\frac{\partial p}{\partial x}+\rho_0\frac{\partial U}{\partial x}=0, \tag{3}$$

where $a=\sqrt{\frac{\gamma p_0}{\rho_0}}$ is the speed of sound in a stationary medium.

We will look for the solution of equation (3) in the form of waves traveling with frequency ω, which propagate along the x axis:

$$U=A\cos(\omega t-kx);\qquad \rho=C\cos(\omega t-kx);\qquad V=B\cos(\omega t-kx), \tag{4}$$

where k is the wave number; A, B, C – are unknown amplitudes.

By substituting (4) into (3), we get the following equation

$$(\omega-kU_0)\left[\left(a^2-U_0^2\right)k^2+2\omega U_0k-\omega^2\right]=0. \tag{5}$$

Equation (5) describes two types of waves: a hydrodynamic wave and two acoustic waves. For a hydrodynamic wave that always propagates in the direction of flow

$$k=\frac{\omega}{U_0}. \tag{6}$$

A hydrodynamic wave is usually associated with the motion of vortices in the boundary layer: it is commonly assumed that the speed of this wave is about 0.5-0.7 of the flow speed.

For counter-propagating acoustic waves

$$k_{1,2}=\pm\frac{\omega}{a\pm U_0}. \tag{7}$$

The difference in speeds of two oppositely directed acoustic waves is explained by the Doppler effect. As it follows from equation (7), the speed of a wave propagating in the direction of the flow can significantly exceed the speed of a wave moving in the opposite direction [8]

It is worth noting that the hydrodynamic wave differs from the acoustic wave: it is transverse – for it, the amplitudes of the longitudinal component of speed and density (A and C) are equal to zero. At the same time, in a longitudinal acoustic wave, the amplitudes of the transverse components of speed are also zero.

Basing on the existing theories of turbulent motion, it is difficult to draw practically significant conclusions for the use of rubber linings in drum mills. However, a promising direction is the control of turbulence through feedback using acoustic waves.

For this, it is advisable to install a special screen on the path of the flow, which will generate powerful acoustic waves by interacting with the flow. These waves will induce stochastic self-oscillations caused by the development of global instability. Since these self-oscillations and vortex pairing are nonlinear processes, they can excite turbulent motion in the flow. In addition, the feedback through the acoustic wave makes it possible to amplify or dampen the turbulence.

Rubber lining elements with a morphometrically complex surface, such as lifters or trapezoidal plates, can serve as a screen for exciting acoustic waves. If the differences in the height of cavities and ridges (surface relief) and the distance between them align with the structure and speed of the charge motion, a global equilibrium can be established in the drum mill. In this state, the material grinding will require minimal energy consumption.

In the absence of such aligning, the process of self-organization of monodisperse charge obeys the second law of thermodynamics: only those states of motion will be realized that provide minimum energy consumption. This will lead to random, short-lived stochastic states in the flow. Such dynamics will cause:

- increased abrasive and fatigue wear of the rubber lining.
- risk of catastrophic destruction of individual elements.

Over time (sometimes this can happen immediately before the failure of the lining), a certain quasi-static equilibrium can be established between the charge and the rubber surface; visually, this manifests in a river pattern and sometimes in an incomplete and not entirely clearly-defined wave pattern of natural wear on the working surface of the rubber.

That is, during the operation of all possible forms of linings, the charge motion will tend to some steady state with forming a flow channel on the surface of the lining in such a way that the principle of minimum energy consumption is realized. Therefore, the task for designers and technologists, as it is already mentioned above, is precisely that using analytical calculations and accumulated experience in the industrial use of linings to design rubber linings with such morphometric and geometric parameters that right from the initial stage of mill operation a stable state of equilibrium is established between the charge and the lining, which will contribute to minimal wear of the lining, subject to the optimality of the technological process.

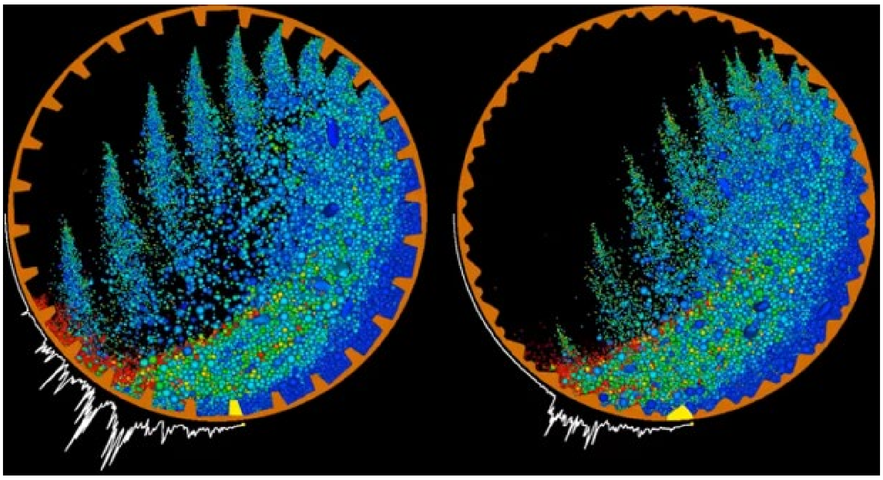
In the dynamic zone 1 (Figure 1b), there is constant moving of balls and material, their speed almost does not change, the destruction of the material occurs mainly through grinding. As material moves deeper into the grinding chamber, a slow-moving zone 2 is formed, which is called a monodispersoid; its dimensions change depending on the percentage of the drum loading and its operating mode. At cascade mode, size of the monodispersoid is larger, and in the waterfall mode, it is somewhat smaller. However in a real grinding chamber, a mixed mode is mainly realized, and the size of the monodispersoid will depend on the percentage of mill loading. In the second zone, the speed of balls and rock is constant.

The charge, moving from zones 1 and 2 into the zone of turbulent motion 3, is significantly accelerated and mixed. Here the material is crushed and destroyed by impact due to the difference in the motion of the charge layers: the upper layers move at maximum speed, and the lower layers, those on the boundary between zones 2 and 3, have a minimum speed.

Zone 4 is the rollback heel, in which there is a chaotic high-speed motion of balls and mineral raw materials; in this zone, crushing happens through impact and grinding. Zone 5 is the ball flight zone. The flight of the balls occurs at the waterfall mode of the mill operation, that is, when the drum rotational speed is increased, and when the "Plate-Lifter-Plate" lining is used; no grinding takes place in this zone.

Having studied the dynamics of the charge motion inside the mill, it can be stated that it significantly influence the quality and speed of grinding, the service life of the lining, the economic performance of the mill (power consumption, ball consumption, etc.). Besides, works [1, 2, 3, 8, 10] proposed the hypothesis that it is possible to control dynamics of the charge motion, and that it influences the performance indicators.

Modeling with the help of the Rocky DEM software complex makes it possible to study dynamics of the mill charge motion and the process of interaction between the charge and the lining. Figure 2 shows a mill model with "Plate-Lifter-Plate" and "Plate-Plate" linings. The conducted modeling of the process of disintegration of mineral raw materials made it possible to investigate the modes of charge motion and its influence on the lining, namely, to specify the areas with the greatest load and wear occurrence.



a b

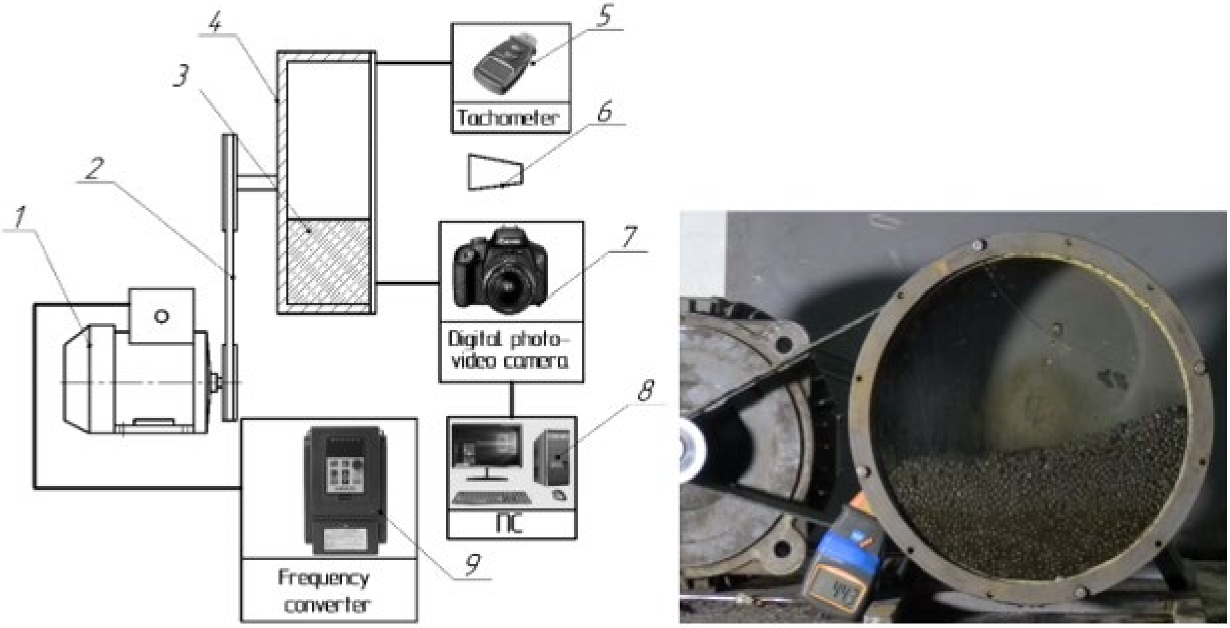
a – rubber lining of the “Plate – Lifter – Plate” type, b – rubber lining of the “Plate – Plate” type

Figure 2 – Model of the interaction between the charge and the rubber lining in the drum

As it can be seen in Figure 2, the greatest load on the lining occurs in the area of the rollback heel. It should be emphasized that the lining with lifters experiences a much greater load compared to the "Plate-Plate" lining. The simulation results are in line with the hypotheses regarding the influence of the charge motion dynamics on the lining wear resistance [1, 2, 3, 8, 10], and with laboratory studies conducted on a laboratory model of the mill (Figure 3).

The research (Figure 3) was conducted on the laboratory mill with linings of two types: "Plate - Lifter - Plate" and "Plate - Plate". The frequency of the drum rotation was regulated by a laboratory frequency converter SAKO SKI780; in parallel, the rotation frequency was fixed with a portable non-contact laser tachometer DT-2234C+. The dynamics of the charge motion was recorded by a digital photo-video camera through the Plexiglas window in the drum, and then the images and videos were transmitted to the PC for further processing and using for simulation.

Steel balls of different diameters and sand with added water were used as the mill charge, thus simulating the mill's operating conditions as close to production conditions as possible.



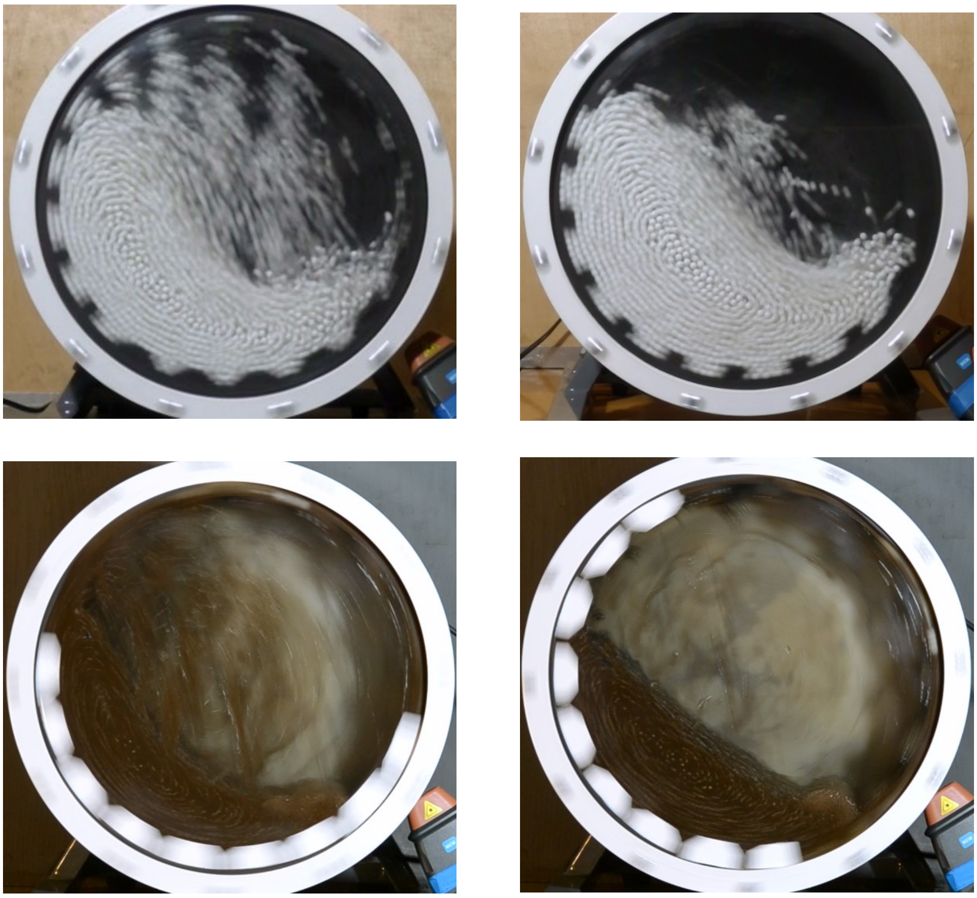
1 – electric motor, 2 – belt transmission, 3 – mill charge, 4 – drum, 5 – tachometer, 6 – illuminator, 7 digital photo-video camera, 8 – personal computer (PC), 9 – frequency converter

Figure 3 - Experimental laboratory mill

3. Results and discussion

The conducted research gave a possibility to establish a dynamic influence of different loading zones on the lining wear. Thus, according to Figures 1 and 4, dynamic zone 1 features steady motion and, consequently, gradual lining wear. Zone 1 can be conditionally divided into two areas: the lifting area and the sliding area, because a charge rises up to a certain lifting angle and then part of the charge slides back along the lining surface.

In the lifting area, the abrasive effect of the charge particles on the lining mainly dominates leading to the lining abrasive wear due to the friction of material particles and balls against its surface. The mechanism of wear is the abrasion of the rubber coating by fine particles, especially in areas of rubber contact with solid elements (ore, balls).



a b

a – rubber lining of the "Plate – Lifter – Plate" type, b – rubber lining of the "Plate – Plate" type

Figure 4 - Charge motion dynamics: modeling with balls and sand, balls and water

In the section of charge sliding, the material and balls, having reached the upper point of the trajectory, begin to fall freely or slide back. In this zone, the lining experiences less intensive wear, but short-term impacts are possible when balls and large pieces of material fall onto its surface. This type of wear is characterized as shock-abrasive.

Zones of ball flight and zone of turbulent motion pass into the rollback heel zone, where balls and ore fall freely from a height, and their turbulent chaotic motion occurs. This creates significant impact loads on the lining. Wear in this area is mostly impact-driven: balls and large pieces of material fall onto the lining with great force, resulting in micro-cracks and deformations of the rubber. Gradually, this causes delamination or destruction of the lining material.

Zone of minimum activity or monodispersoid is an area near the axis of the mill rotation where the material practically does not move. In this zone, the wear is minimal, since the low speeds of the material and the balls motion do not create significant loads on the lining and almost do not cause contact with it.

Mechanisms of the rubber lining wear are:

1. Abrasive friction - is the main mechanism in the lifting zones. Ore particles and small balls rub against the lining, which gradually leads to its wear by abrasion.

2. Impact effect – is characteristic for the falling zone and zone of the rollback heel. Falling balls and large pieces of ore cause local deformations and cracks in the rubber.

3. Combined wear – is observed at the boundaries between the lifting and falling zones, where the lining is subjected to both abrasive and impact loads. This leads to complex forms of wear, in particular to hydroabrasive-fatigue wear due to rubber aging [13].

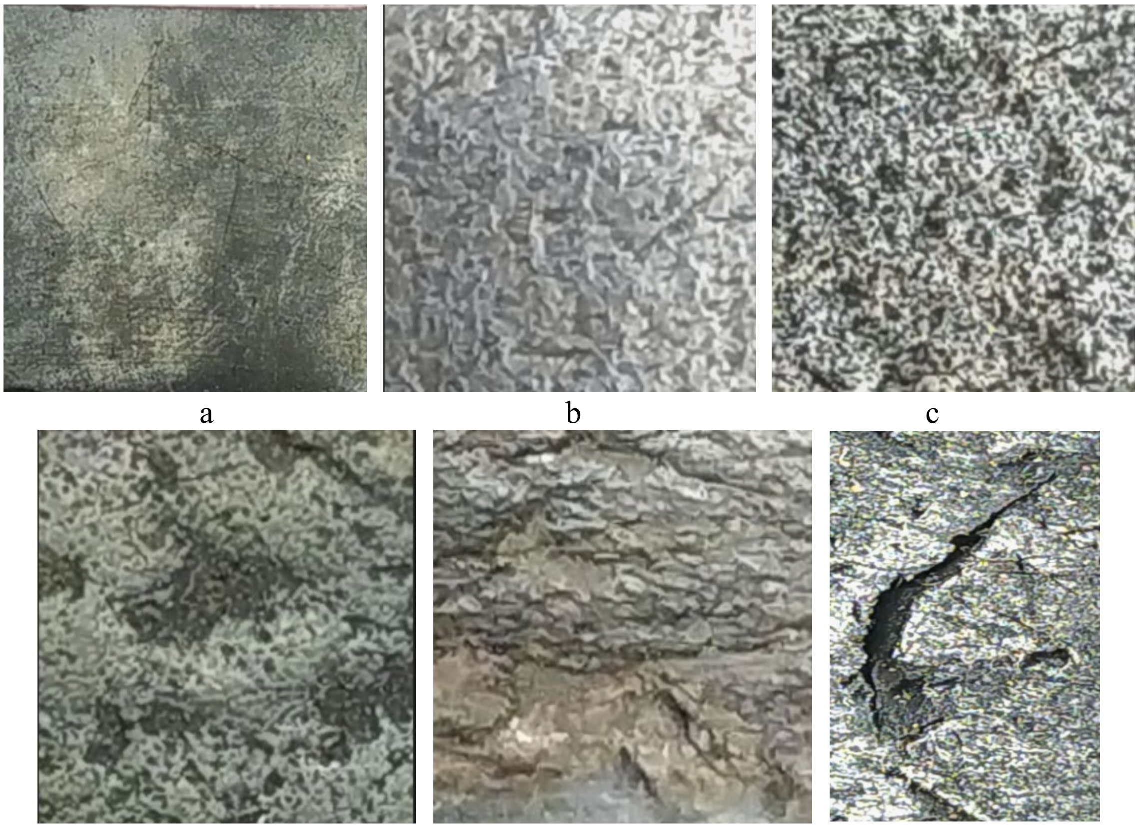
As a result of the impact effect from ore and balls and the scratching effect from particles in the upper layers of rubber, fatigue occurs, which causes the destruction and aging of the lining surface layer and its destruction. The research shows that the depth of rubber destruction due to the fatigue wear can reach 30 mm, after which the remaining part of the material retains physical and mechanical properties of a new rubber.

Other types of wear, such as cavitation and erosion, can also occur in the lining, but these processes are long-lasting and insignificant compared to abrasive wear. Therefore, they can be ignored.

The analysis of rubber samples (Figure 5) obtained during the shutdown of the MSHR 3.6×4.0 mill at the private joint stock company “Northern iron ore enrichment works” for maintenance and control inspection confirms the results of modeling and laboratory studies.

In the dynamics, it is clearly visible that the rubber gradually loses its strength characteristics and receives more and more damages over time. As it is noted above, all transformations occur in the upper layer, which gradually wears away, and the surface damage varies significantly. This is due to a decrease in the thickness of the lining and its resistance to fatigue. Figure 5a shows the surface of the new lining, the thickness of which is 270 mm. Figure 5f shows the critical lining thickness of 45–50 mm, which is almost incapable to damp and absorb the impact or compression energy caused by balls and charge fragments. As a result, the damage has a torn shape manifested in cracks and deep caverns.

On the basis of the conducted research, a new structure of the lining was designed for mills of the first grinding stage. This innovative design combines the original rubber grade, which is produced with nanotechnology and provides increased energy dissipation, increased plate thickness and morphometric characteristics that take into account the dynamics of the interaction between the mill charge and the lining. This is a lining of the "Plate-H-Wave" type with increased thickness (270 mm and 240 mm), which has an asymmetrical trapezoidal shape, that is, it has cuts at an angle of 15...17° and 50...60° to the horizontal from the point of connection with the upper working part of the plate (Figure 6) [14].

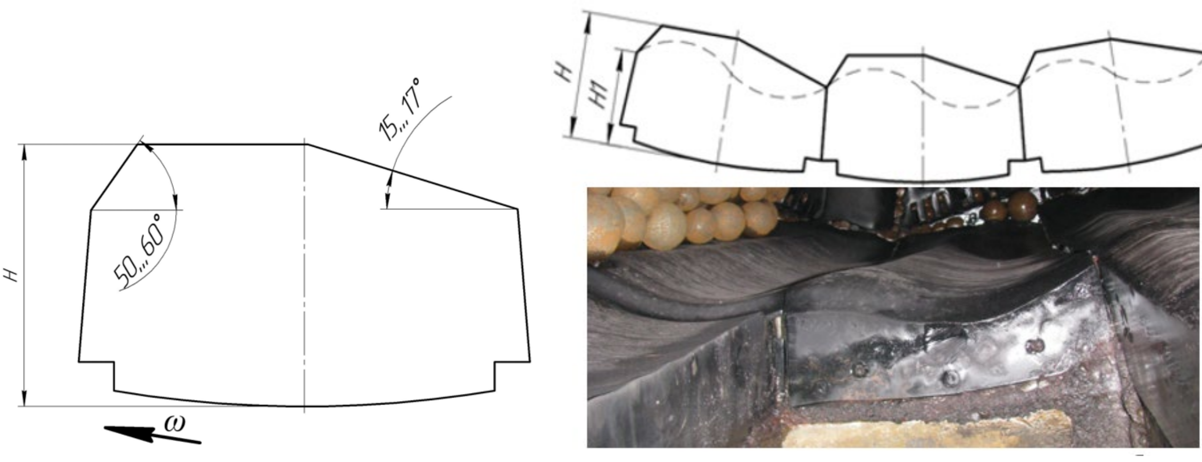


a b c

d e f

a – new, b – 1300 hours, c – 2650 hours, d – 4320 hours, e – 5454 hours, f – 6850 hours

Figure 5 - Views of linings with different running time



a b

a - lining plate of the drum mill (cross section), b - the plate surface with a wave-like shape formed after the mill has worked for 3780 hours

Figure 6 – Non-symmetrical trapezoidal lining of the "Plate-H-Wave" type

This lining produced by "Valsa GTV" LLC, (Ukraine, Bila Tserkva), was tested at the private joint stock company “Northern iron ore enrichment works” in the city of Kryvyi Rih on the first-stage grinding mill, MSHR 3.6×4.0 with a ball diameter of

100 mm and showed good results. Thus, in the first 10–15 days of operation, the mill reached the designated mode of operation in terms of productivity, which indicates a harmonious interaction between the new lining and internal mill charge and the formation of a wave-like surface with a specified step.

The test results: electricity consumption reduced by 5%; specific consumption of grinding bodies decreased by 5%; the growth of the finished product class increased by 10–12%; service life before failure is more than 9000 hours.

4. Conclusions

1. Mechanism of interaction between the charge and the lining is a complex and non-linear process accompanied by the mechanisms of abrasive, impact and combined abrasive-fatigue wear due to rubber aging. A key factor is the stochastic motion of the charge, which creates different types of loads on the lining in different areas of the mill.

2. The turbulent nature of the pulp and material motion in the mills leads to constantly changing operating conditions for the lining. These changes depend on many factors: rotation speed, drum size and abrasiveness of the materials. This causes the lining wear due to a combination of abrasive and impact effects.

3. The studies of the charge motion dynamics using simulations and experiments made it possible to identify the areas of the highest load on the lining and the type and nature of wear occurred under different conditions. This helps to predict the service life of the lining and to manage the process of disintegration of mineral raw materials more effectively.

4. The harmonious combination of geometric parameters and material of the lining with dynamic indicators of mill loading enables to reduce electricity consumption by 5%; to reduce specific consumption of grinding bodies by 5%; to increase the output of the finished product class by 10–12%; to ensure service life before failure to more than 9000 hours.

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ДИНАМІКА ВЗАЄМОДІЇ ВНУТРІШНЬОМЛИННОГО ЗАВАНТАЖЕННЯ З ЗАХИСНОЮ ФУТЕРІВКОЮ КУЛЬОВИХ БАРАБАННИХ МЛИНІВ

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Анотація. Стаття досліджує процес взаємодії внутрішньомлинного завантаження з гумовими футерівками кульових барабанних млинів, що використовуються для дезінтеграції мінеральної сировини у гірничодобувній, металургійній та цементній промисловості. Особливу увагу приділено вивченню динаміки взаємодії внутрішньомлинного завантаження і захисної гумової футерівки, а також зношуваності футерівок та їхнього впливу на продуктивність млинів під час експлуатації. Важливим аспектом дослідження є аналіз різних конструкцій футерівок та їхньої поведінки за умов динамічних навантажень.

Дослідження проведено за допомогою чисельного моделювання з використанням програмного комплексу *Rocky DEM*, що дозволяє імітувати взаємодію частинок завантаження з поверхнею футерівки та досліджувати динаміку руху сегментів внутрішньомлинного завантаження. Було змодельовано два типи футерівок: «Плита – Ліфтер – Плита» та «Плита – Плита». Під час моделювання враховувалися такі параметри, як ударні навантаження, абразивний знос, швидкість обертання млина та тип завантажуваного матеріалу. Для верифікації результатів чисельного моделювання також було проведено серію експериментів на лабораторному млині, що забезпечило високу точність отриманих даних.

Результати дослідження показали, що найбільші навантаження на футерівку виникають у зоні п'яти відкату, яка є критичною для її зношування. Зокрема, футерівка типу «Плита – Плита» демонструє менший рівень зносу порівняно з «Плита – Ліфтер – Плита» завдяки кращій динамічній взаємодії з завантаженням та зниженій ударній дії. Встановлено, що правильний вибір типу футерівки може суттєво вплинути на ефективність подрібнення матеріалів, зменшуючи старіння гуми під час абразивно-втомного зносу та подовжуючи термін служби футерівок млинів. Експериментальні результати узгоджуються з даними моделювання та промислових випробувань, що підтверджує ефективність чисельного підходу.

Отримані дані можуть бути використані для вдосконалення конструкцій гумових футерівок барабанних кульових млинів, що дозволить підвищити ефективність подрібнення та зменшити витрати на обслуговування обладнання. Зокрема, результати дослідження можуть знайти застосування в гірничодобувній, металургійній та цементній промисловості, де тривалість служби футерівок і зменшення їхнього зношування є ключовими факторами для зниження експлуатаційних витрат та підвищення продуктивності підприємств.

Ключові слова: дезінтеграція, подрібнення, барабанний млин, гумова футерівка, моделювання, знос.