UDC 622.7

ANALYSIS OF THE MATERIAL GRINDING PROCESS IN A BALL MILL WITH MULTI-FREQUENCY VIBRO-IMPACT EXCITATION

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Abstract. This article presents the results of a study on the parameters of the grinding process in a vibratory mill with multi-frequency vibro-impact excitation. The objective of the study is to determine the influence of technological parameters, such as the level of the grinding chamber filling with material, the physical and mechanical properties of the raw material, and the gaps between the striker and the mill's driving frame on the efficiency of the grinding process. Two materials with different characteristics — basalt and ilmenite — were used in the experiments. The dependencies of the degree of grinding and mill productivity on the percentage of chamber filling with material were established, and the influence of the material's physical and mechanical properties on the final grinding outcome was demonstrated. The results show that for both materials, an optimal chamber filling level of approximately 15–25% achieves the maximum degree of grinding, with a mill productivity of Q = 3–5 t·h/m³. Exceeding this level leads to reduced efficiency due to decreased intensity of grinding media movement. The influence of grinding time was determined, revealing that the most intensive grinding occurs within the first five minutes, with the degree of grinding ranging from 5 to 7. The initial particle size of the material (within the tested range of basalt particle sizes from 0.3 mm to 3 mm) has a minimal impact on the degree of grinding. The effect of gaps, which directly influence the chamber's acceleration, was analyzed separately. It was shown that increasing the gaps (from 1 mm to 3 mm) enhances the degree of grinding due to increased impact energy. This fact was experimentally confirmed for both brittle basalt with a degree of grinding around 6 and more viscous ilmenite, with a degree of grinding around 4. The obtained dependencies can be used to optimize the operating modes of vibro-impact mills of a new type operating in a vibratory-impact regime, laying the foundation for further research in mathematical modeling and control of grinding processes in next-generation mills. The practical results of the study are important for advancing fine grinding technologies for minerals and improving the quality of the final product in the mining, metallurgical, and construction industries.

Keywords: vibratory mill, multi-frequency vibro-impact excitation, degree of grinding, material particle size, gaps between striker and driving frame.

1. Introduction

Fine grinding of mineral raw materials is a critical stage in the technological process, determining the subsequent efficiency of extracting target components from ore using screens, separators, and other beneficiation equipment [1–16]. One of the promising methods is vibratory grinding, which enables a high degree of grinding in a relatively short time [17]. However, traditional vibratory mills have limitations due to the dominance of particle destruction by friction over impact and the difficulty in achieving significant acceleration of grinding media, which overall reduces process efficiency. To ensure the dominance of impact-based destruction and achieve the maximum degree of grinding with minimal energy consumption, specialized drives capable of generating high accelerations and controlling the dynamic parameters of the grinding chamber's oscillations are required.

The use of a multi-frequency vibro-impact drive developed at the M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine opens new opportunities for intensifying the grinding process by generating high-intensity impact loads. Such drives have already been successfully applied in screens and feeders developed at the Institute and have demonstrated their good effectiveness [18, 19]. This drive enables significant accelerations of the grinding chamber with the technological medium (limited only by the chamber's durability and reliability),

Received: 07.05.2025 Accepted: 27.06.2025 Available online: ________

allows for dynamic adjustments to the grinding process, improves the quality of the final product, and reduces energy consumption [20].

The enhanced grinding efficiency in a vibro-impact ball mill is driven not only by significant accelerations but also by the complex oscillatory movements generated in its structure, which are transmitted to the grinding chamber with the technological load. These movements and accelerations result from the interaction of masses, unilateral and bilateral elastic and viscous bonds, and the exciting force from unbalanced vibration exciters.

The calculated oscillogram of mass accelerations derived from computations based on the developed mathematical model of the vibro-impact mill [20], is presented in Figure 1.

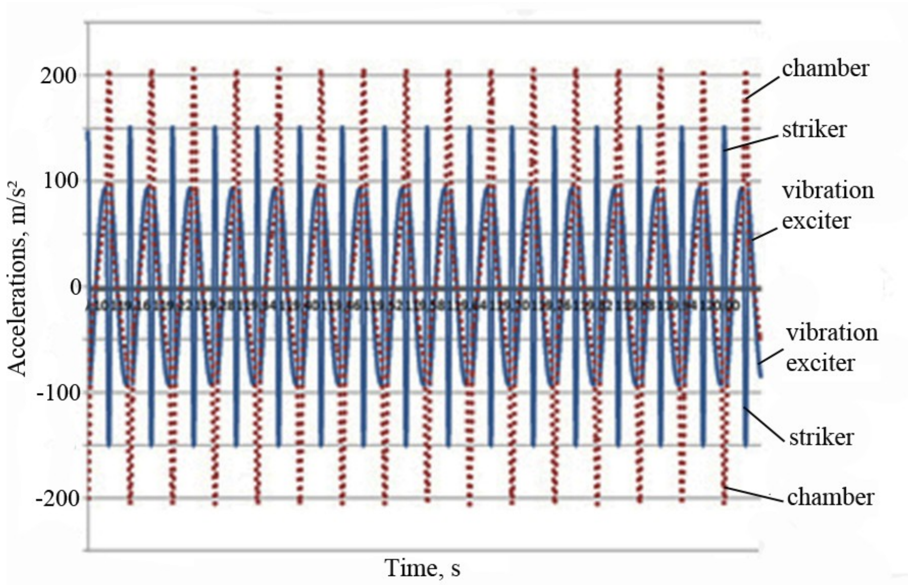

Figure 1 – Calculated oscillogram of accelerations in a vibratory mill with vibro-impact excitation

Analysis of the oscillogram clearly shows that the acceleration of the unbalanced masses of the mill's vibration exciters, which rotate and generate a periodic variable force transmitted to the striker and subsequently to the grinding chamber, is significantly lower than the chamber's acceleration. This is because the chamber's acceleration has an impulsive, impact-driven nature – when the force reaches a value that triggers unilateral bonds, a sharp acceleration occurs. This regime generates impact accelerations (short-duration high-intensity pulses) that are effectively transferred to the grinding media and the material being ground.

Due to the achieved significant grinding media accelerations, vibro-impact mills provide higher energy efficiency and better quality of fine grinding due to the intense influence of vibrations and impacts. However, they have lower productivity and higher wear of working parts compared to drum ball mills, which are more versatile and reliable for processing large material volumes but less effective for achieving fine-dispersed grinding, especially for obtaining a final product smaller than 100 µm.

Therefore, the purpose of this study is to conduct a practical analysis of the fine grinding process in a mill with multi-frequency vibro-impact excitation and to identify the patterns of influence of key mill operating parameters on the efficiency of material grinding, as well as to substantiate optimal operating conditions.

2. Methods

During the experimental studies of the patterns of changes in the grinding process parameters in a vibro-impact ball mill, an experimental setup was used with the ability to adjust the grinding chamber's acceleration by varying the gap size. The grinding chamber is a vertical cylinder with a diameter of 150 mm, a height of 155 mm, and a weight of 5 kg, with a total mass of grinding media (steel balls 10–40 mm) of 11.4 kg. Ilmenite and basalt, which have different hardness and internal structures, were selected as test materials.

The main variable parameters of the experiments were:

- Grinding time (from 1 minute to 15 minutes);
- Initial particle size of the raw material (0.3–3 mm);
- Size of grinding steel balls (10–40 mm);
- Percentage of the working chamber filling with material (up to 40%) and balls (up to 60%);
- Acceleration of the working chamber (100–300 m/s^2).

The final particle size of the material was studied using sieve analysis. All experimental stages, parameters, and results were documented for further reproducibility and analysis.

3. Results and discussion

Before the main cycle of experiments, the grinding efficiency of basalt was studies and evaluate at different initial particle sizes and grinding times. The physical and mechanical properties of basalt include a density of 2800–3100 kg/m^3 and a compressive strength of 300–400 MPa. Basalt is a relatively hard material due to its fine-grained structure formed during rapid lava cooling, which prevents crystal growth, making it dense and uniform but highly brittle, as intercrystalline bonds break down under impact loading with minimal plastic deformation. The initial particle size of basalt was: Variant 1 – average fraction 3 mm, Variant 2 – average fraction 0.5 mm. The grinding chamber was filled with material at 20% and steel balls at 55%, enabling grinding modes with the technological medium impacting the chamber lid. In this mode, during vibration, the grinding media not only move along the bottom or walls of the chamber but are also thrown upward, striking the chamber lid (its upper part) with force. This impact serves two main functions: it transfers significant impulsive energy to the material, promoting its destruction, and ensures more intensive grinding due to multi-vector impacts. The striker gap was set at 3 mm, providing free striker movement before colliding with the chamber, generating high-intensity impact pulses.

The experimental methodology involved grinding the initial basalt (3 mm and 0.5 mm) to the required fractions and sieving it to ensure uniformity. The filling volume of the chamber remained constant at 20% to ensure accurate comparison of results. Experiments were conducted at fixed time intervals (1–15 minutes) to analyze grinding dynamics. After each cycle, the material was extracted, and granulometric sieve analysis was performed to determine the degree of grinding, which is an indicator of process efficiency and is defined as the ratio of the initial particle size to the final particle size.

The results of these studies are presented in Figure 2.

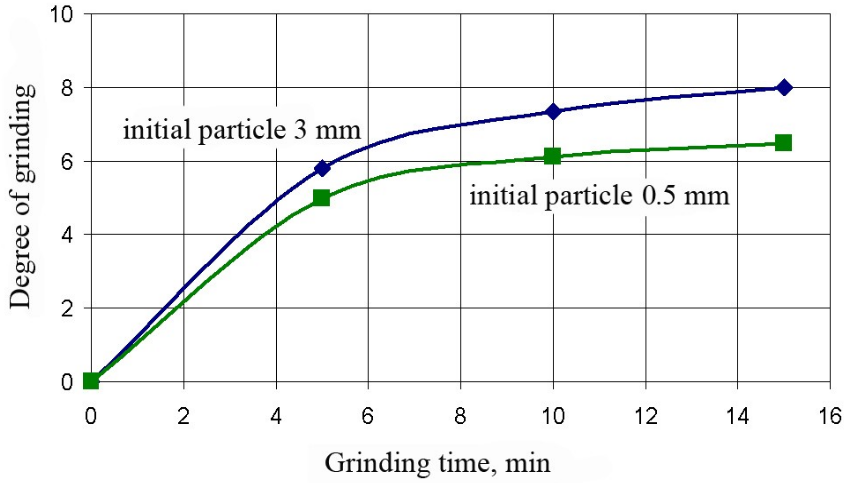

Figure 2 – Degree of grinding of basalt with different initial particle sizes versus time

Based on the nature of the obtained dependencies of the degree of grinding on grinding time for different initial particle sizes, it can be concluded that the most intensive grinding occurs within the first five minutes, with the degree of grinding ranging from 5 to 7. Additionally, the initial particle size (0.5–3 mm) has a minimal impact on the degree of grinding, as with a six-fold difference in initial particle sizes, the change in the degree of grinding is within 20%.

This is explained by the fact that at the beginning of the grinding process, the material has a large number of cracks, defects, and contact surfaces, facilitating effective destruction under the action of impacts and vibrations. In a vibro-impact mill, where impulsive loads are generated, the highest energy efficiency is observed at the initial stage when particles are actively destroyed due to impact interactions with grinding media and chamber walls. Thus, energy is primarily expended on overcoming intercrystalline bonds rather than on friction or repeated abrasion.

Moreover, the vibro-impact mill with multi-frequency excitation generates high-intensity impact force pulses and accelerations, which are almost equally effective in destroying particles of different sizes, especially for hard, brittle materials like basalt. Due to the impact-driven nature of the interaction and the dynamic uniformity of the force pulse field, the initial particle size has less influence than in grinding devices where destruction primarily occurs through contact friction. The fact that the change in the degree of grinding with a six-fold difference in initial particle size (within the tested range) is only ~20% indicates the high adaptability of the grinding regime to the size of the initial fractions.

The next stage of the study involved determining the dependence of the degree of grinding and mill productivity on the percentage of the chamber filling with the material being ground. For this purpose, a material with different physical and mechanical properties–ilmenite–was selected, with a density of 4000 kg/m³ and a compressive strength of 100 MPa. Although ilmenite has lower compressive strength than basalt, it is more resistant to mechanical impact due to its high cleavage or strong interatomic bonds in certain directions, which complicates destruction. Additionally, it can be partially deformed without breaking, unlike brittle basalt. The average initial particle size of ilmenite was 0.316 mm. The gaps between vibro-impact pairs were 3 mm, the grinding time was 5 minutes, and the chamber was filled with grinding media at 55%. The results of these studies are presented in Figure 3.

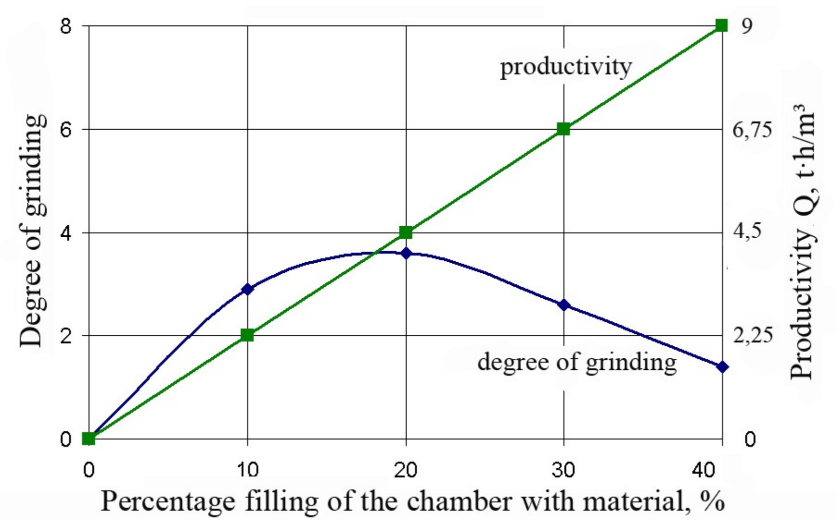

Figure 3 – Dependence of the degree of ilmenite grinding and mill productivity on the percentage of the chamber filling with material

The obtained results show that as the chamber filling with ilmenite increases, the degree of grinding changes, reaching a maximum within the range of 15–25% chamber filling, after which efficiency decreases. This is explained by the following:

- At a chamber filling of up to 15%, the number of ilmenite particles is insufficient for productive grinding, and a significant portion of the impact energy is dissipated in interactions between the grinding media without grinding the ilmenite particles. Thus, the number of collisions between particles and grinding media is insufficient for productive grinding, leading to a low degree of grinding and low productivity.
- In the range of 15–25% filling, optimal conditions are created for intensive interaction between particles and grinding media. The grinding media continue to move intensively within the chamber, ensuring sufficient energy for impact interactions. This promotes effective material grinding, resulting in maximum efficiency in this range, with a mill productivity of Q = 3–5 t·h/m³.

- With further increases in filling more than 25%, the intensity of grinding media movement decreases due to reduced mobility, internal friction between particles of the technological medium in the chamber increases, and the number and energy of impact interactions decrease. This leads to reduced energy efficiency of grinding—despite the mill's operation, grinding efficiency decreases.

These results highlight the importance of selecting the appropriate filling volume to achieve maximum grinding efficiency. As the chamber filling increases, mill productivity is directly correlated and limited by the chamber's internal volume when fully filled with the technological medium. Compared to basalt, ilmenite exhibited a slightly lower degree of grinding under similar conditions explained by its greater resistance to impact destruction.

The final stage of the study involved determining the influence of varying the gap between the striker and the driving frame in the range of 1–3 mm, which directly affects the magnitude of the grinding chamber's acceleration and the intensity of impact interactions between the technological medium bodies, as shown in Figure 1. The experiments were conducted for basalt and ilmenite, with a grinding time of 5 minutes, the chamber filled with grinding media at 55% and material at 20%. The initial particle size of basalt was 0.5 mm, and that of ilmenite was 0.316 mm. The results of these studies are presented in Figure 4.

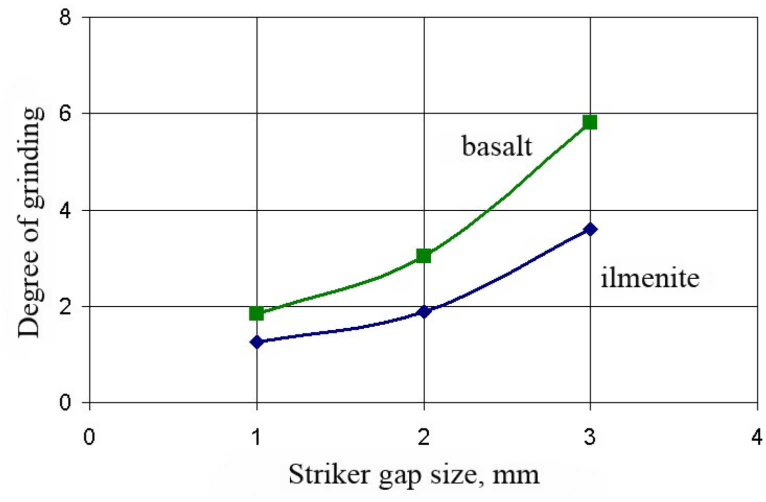

Figure 4 – Dependence of the degree of grinding on the striker gap size for different materials

The results in Figure 4 demonstrate a clear dependence of the degree of grinding on the striker gap size. As the gap increases from 1 mm to 3 mm, the grinding chamber's acceleration becomes more intense, leading to increased impact forces and, consequently, improved grinding efficiency. This is particularly noticeable for basalt, which is more brittle and sensitive to increased impact loads, achieving a degree of grinding of 6 at a 3 mm gap. For ilmenite, despite its smaller initial particle size, an increase in efficiency with larger gaps is also observed, though it is less pronounced due to its higher resistance to mechanical destruction, reaching a degree of grinding of around 4. Thus, increasing the striker gap to the maximum value within the experiment (3 mm) enables the highest degree of grinding for both materials tested, indicating the advisability of using larger gaps for intensive grinding modes. However, this should be applied considering the mechanical strength of the mill's structure, as increased accelerations and impact forces significantly increase the load on the mechanism's components.

4. Conclusions

The conducted studies established for the first time that the optimal range for filling the grinding chamber with material in a vibratory mill with multi-frequency vibro-impact excitation is 15–25%, ensuring the maximum degree of grinding while maintaining equipment stability, with a mill productivity of Q=3–5 t·h/m³. The dependence of grinding efficiency on the gap between the striker and the driving frame is directly correlated: as the gap increases to 3 mm, the degree of grinding improves due to increased chamber acceleration and the force of impact interactions between the grinding media and the chamber's internal surfaces, ranging from 6 for basalt to 4 for ilmenite.

The influence of grinding time was determined: the most intensive grinding occurs within the first five minutes, and within the tested range of initial particle sizes, the initial particle size has a minimal impact on the degree of grinding. With a six-fold difference in particle sizes, the change in the degree of grinding is within 20%, ranging from 5 to 7 for basalt.

The practical significance of the study lies in the fact that the obtained results will be used to optimize the design and operating modes of vibratory mills with multi-frequency vibro-impact excitation. The findings contribute to improving the energy efficiency of grinding technologies, reducing wear on grinding media, and enhancing the quality of the final product.

The scientific value of the work lies in identifying new patterns in the grinding process within a complex field of vibro-impact oscillations, expanding scientific understanding of the relationship between material mechanical properties, machine parameters, and the final grinding outcome, and laying the foundation for further research in mathematical modeling and control of grinding processes in next-generation mills.

Conflict of interest

Authors state no conflict of interest.

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АНАЛІЗ ПРОЦЕСУ ПОДРІБНЕННЯ МАТЕРІАЛІВ У КУЛЬОВОМУ МЛИНІ З ПОЛІЧАСТОТНИМ ВІБРОУДАРНИМ ПРИВОДОМ

Шевченко Г., Шевченко В., Сухарєв В., Тітов О., Самодрига О.

Анотація. У статті представлено результати дослідження параметрів процесу подрібнення у вібраційному млині з віброударним полічастотним збудженням. Метою роботи є визначення впливу технологічних параметрів, таких як заповнення камери подрібнюваним матеріалом, фізико-механічні властивості вихідної сировини, а також зазорів між ударником і приводною рамою млина, на ефективність процесу подрібнення. У дослідженнях використано два матеріали з різними характеристиками – базальт і ільменіт. Визначено залежності ступеня подрібнення та продуктивності млина від відсоткового заповнення камери матеріалом, показано вплив фізико-механічних властивостей матеріалу на кінцевий результат подрібнення. Результати досліджень демонструють, що для обох матеріалів існує раціональний рівень заповнення камери матеріалом (приблизно 15–25%), за якого досягається максимальний ступінь подрібнення, при продуктивності млина Q=3–5 т·год /м^3, перевищення цього рівня призводить до зниження ефективності через зменшення інтенсивності руху помольних тіл. Визначено вплив часу подрібнення, встановлено, що найбільш інтенсивне подрібнення відбувається в перші п'ять хвилин і коливається в межах 5–7, та на зміну ступеня подрібнення суттєво не впливає вихідна крупність матеріалу (в заданому діапазоні крупності часток вихідного матеріалу базальту від 0,3 мм до 3 мм). Окремо проаналізовано вплив зазорів, які безпосередньо впливають на прискорення камери. Показано, що збільшення зазорів (від 1 мм до 3 мм) спричиняє зростання ступеня подрібнення, оскільки супроводжується підвищенням енергії ударів. Це підтверджено експериментально як для крихкого базальту, значення ступеня подрібнення якого коливаєтеся в межах 6, так і для більш в'язкого ільменіту зі ступнем подрібнення 4. В результаті отримані залежності можуть бути використані для оптимізації режимів роботи віброударних млинів нового типу, що функціонують у вібраційно-ударному режимі, закладенні основи для подальших досліджень в області математичного моделювання і керування процесами подрібнення в млинах нового покоління. Практичні результати досліджень мають значення для подальшого розвитку технологій тонкого подрібнення мінералів та підвищення якості кінцевого продукту у гірничій, металургійній та будівельній галузях.

Ключові слова: вібраційний млин, віброударне полічастотне збудження, ступінь подрібнення, крупність матеріалу, зазори між ударником і приводною рамою.