Research on the design of the working parts of vertical roller mills for grinding granulated slag

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Abstract. This research focuses on optimizing the design, parameters, and operational modes of vertical roller mills (VRMs) for grinding granulated slag, which are crucial in industries such as cement, mining, and energy. VRMs are widely recognized for their energy efficiency and ability to grind various materials with minimal energy consumption. However, the challenge lies in designing mills that can operate efficiently under harsh conditions of intense friction, impact loads, and abrasive particles, especially when processing hard materials like granulated slag. To address these challenges, advanced materials and protective coatings are being utilized to improve wear resistance. Additionally, the research explores the use of polymer-metal composites in the construction of mill components, which significantly reduce wear rates and extend the lifespan of the mill, ultimately leading to cost savings and reduced maintenance needs.

Furthermore, the study examines the integration of intelligent control systems that optimize operational parameters in real-time, thus enhancing grinding efficiency and minimizing energy consumption. The findings also emphasize the importance of reducing vibrations and improving the stability of equipment to ensure reliable performance. The research identifies the key parameters that affect VRM performance, such as roller pressure, material moisture content, and rotational speed, and proposes methods for optimizing these factors to achieve maximum efficiency.

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The development of VRMs is especially important in post-war Ukraine, where cement production has significantly declined due to infrastructure damage. Vertical roller mills are considered the only viable technological solution for new high-capacity cement plants, capable of enhancing cement quality and reducing CO_2 emissions. This research aims to further develop VRM technology, ensuring its ability to meet the demands of the cement, metallurgy, and coal industries by improving energy efficiency, wear resistance, and grinding quality, making it a vital tool for sustainable industrial production.

Keywords: vertical roller mills, granulated slag grinding, energy efficiency, advanced engineering solutions, operational characteristics.

INTRODUCTION

Vertical roller mills are currently essential equipment in the cement, mining, and energy industries, widely used for grinding raw materials, cement, granulated slag, coal, lime, gypsum, and more. In modern cement production, these mills set the technological standard for slag grinding, driven by the importance of slag cement (or blast-furnace slag additives) as a material with enhanced strength and resistance to aggressive environments.

A primary technical challenge in this field is the development of mill designs that deliver high productivity with minimal energy consumption. Energy efficiency is a critical parameter in construction industry processes, making research into energy optimization methods particularly relevant. These include improving drive systems, automating technological operations, and designing rollers and grinding tables with optimal geometry.

The demanding operating conditions, characterized by intense friction and impact loads, impose strict requirements on the wear resistance of mill components. Consequently, key directions involve implementing advanced materials and protective coatings to reduce wear. Moreover, the significant vibrational loads occurring during mill operation negatively affect equipment stability and durability. Addressing these issues necessitates designing structures that minimize vibrations and enhance reliability.

Another important aspect is achieving uniform grinding of materials, as variations in particle size distribution can significantly impact the quality of the final product. This underscores the need to establish parameters that ensure stable grinding while minimizing material losses. Since vertical roller mills are used to process a wide range of materials (cement, granulated slag, alkali-activated cements, etc.), developing universal designs suitable for efficient operation with diverse raw materials remains a critical task.

Equally important is the environmental aspect of mill operation, as grinding processes generate dust. To mitigate negative environmental impacts, it is necessary to implement effective dust collection systems and emission reduction technologies.

ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS

The design of vertical roller mills (VRM), as known today, became widely adopted starting from the early 1900s and has become a standard technology in the cement, energy, and mineral processing industries. Vertical roller mills are recognized as one of the most efficient devices currently available for grinding, capable of simultaneously grinding and drying materials such as limestone, quicklime, cement raw materials, talc, bauxite, magnesite, phosphate, feldspar, barite, graphite, and coal. The predominant use of VRMs is in cement raw material grinding and coal milling, though there are notable applications in the mining industry as well. Schaefer [1] describes the use of vertical roller mills for grinding phosphate, while other studies report VRM applications in grinding copper, iron, and lead slag. Bouchard J. [2] examined recent advancements in dry grinding technology in VRMs, as the construction materials industry faces challenges related to high energy costs, water scarcity, and stricter environmental regulations. His and other studies [3-5] demonstrate significant energy savings, at least 25-35% compared to ball mills, depending on the material type. In the study by Lucas R.D. Jensen, Erling Fundal, and Per Møller [6], the wear mechanisms of VRM wear-resistant parts during grinding of raw materials were investigated. The research included both macroscopic and microscopic analysis of worn parts, as well as laboratory experiments simulating wear processes. Using transparent rollers and tables, the researchers observed the movement of particles in the material layer during grinding, identifying areas with high stress and deformation. The primary wear mechanism was identified as two-body abrasive wear, leading to intense wear in high-pressure zones. Microscopic analysis revealed that cracks beneath the wear-resistant layer of the rollers cause delamination of these layers from the main material. Jung O. [7] investigated the wear characteristics of vertical roller mills used in cement production, noting that wear of friction surfaces could be minimized by selecting appropriate wear-resistant materials such as alloyed cast iron, optimizing the shape and size of worn parts, and reducing the proportion of highly abrasive components. These measures extend the service life of wear components and ensure effective grinding of very abrasive feed materials.

Kalyagina N. [8] assessed the performance of mills with smooth disc rollers, identifying the cause of failure in sectors of a mill manufactured by FLSmidth. The study revealed that under simultaneous operational loading and shifting of sectors, caused by intense wear, the resulting equivalent stresses exceed the endurance limit under cyclic loading, leading to fatigue failure, crack formation, and growth, which negatively impacts mill performance. Turkish researchers Altun Deniz and Aydogan Namik [9] evaluated the performance of VRMs in cement grinding, focusing on key aspects such as grinding efficiency, energy consumption, and product quality. Their experimental study compared VRM performance to traditional ball mills, providing data on operational parameters and results from production tests in cement plants. The findings demonstrate that VRMs outperform ball mills in terms of energy efficiency and the ability to produce finer particles, which is crucial for improving cement quality. Technological advancements enhancing these benefits were also discussed, emphasizing the potential for cost reduction in the cement industry through VRM technology.

Studies [10, 12-13] have analyzed and optimized VRM grinding efficiency based on experimental data. Key parameters such as pressure, rotational speed, and material moisture content were varied, and energy consumption models were developed using the response surface method (RSM). These models, validated through analysis of variance (ANOVA), demonstrated the significant impact of parameters on mill performance. The researchers used multi-criteria optimization to determine the optimal settings, reducing energy consumption and maximizing grinding efficiency. Optimal parameters were identified as 6 MPa pressure, 350 rpm speed, and 2% material moisture. The results confirmed that the predicted values matched experimental data, validating the model for optimizing mill operation.

Maruf Hasan and Sam Palaniandy [11] investigated the determination of breakage parameters in a laboratory vertical mill using a load balance model. The study aimed to understand the impact of experimental conditions on product particle size distribution and fine fraction generation. The model was used to assess particle selection and breakage functions under different operating conditions. It was found that particle selection and breakage functions vary with medium size, rotational speed, and solid concentration, with increased rotational speed leading to finer particles and smaller medium sizes improving breakage efficiency. These results demonstrate that the selection function depends on process conditions but remains linear for limestone.

THE PURPOSE OF THIS WORK

The aim of the research is to optimize the construction, parameters and operational modes of vertical roller mills to enhance energy efficiency, wear resistance, and grinding quality of granulated slags in industrial applications.

METHODS OF RESEARCH

As a result of the Russian Federation's military aggression against Ukraine, our country has suffered massive destruction of residential and industrial infrastructure, with recovery costs estimated at nearly $500 billion. Currently, over 4,000 reconstruction projects are being implemented in Ukraine, with a budget of $4.7 billion. However, for post-war recovery, our nation will critically lack many production capacities. The most critical will be the production of glass, electrical equipment, and cement. According to the latest publicly available data, approximately 35 million tons of cement will be needed to restore what was destroyed by Russia during the war. In 2022 prices, this amounts to almost $2 billion.

The pre-war development dynamics of the cement industry showed a gradual increase in production capacity, reaching 11 million tons in 2021 (Fig. 1).

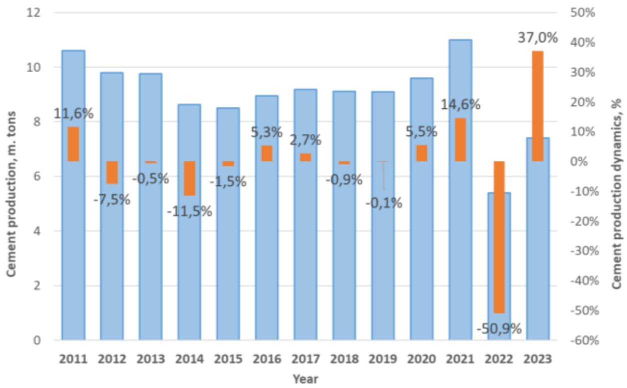

Figure. 1. Cement production in Ukraine

With the onset of the war, cement production experienced a significant decline due to a halving of demand and the loss of production facilities. Of the nine cement plants located in non-occupied territory, only eight remain, three of which were shut down due to damage or proximity to the frontline. By the end of 2022, cement production dropped to 5.4 million tons, losing half of its capacity. Despite a 37% increase in consumption in 2023, primarily driven by defense contracts, production remains below 8 million tons. The head of the Ukrainian Cement Producers Association "Ukrcement" optimistically forestalls increasing cement output to 15 million tons annually in the post-war period under favorable conditions. However, even if these estimates are realized, this volume will still fall significantly short, and rapid expansion of cement production will be unfeasible due to the lengthy timelines required to construct new cement manufacturing facilities.

Currently, ball mills used in the cement industry have reached their design limits. Further improvements in hourly productivity would necessitate larger dimensions, which are impractical due to the lack of sufficiently durable materials for their construction. Consequently, in constructing new, high-capacity cement plants, vertical roller mills (VRMs) are the only viable technological solution offered by machinery manufacturers.

Vertical roller mills are a leading technology in cement production and metallurgy, owing to their high efficiency in grinding materials. They can mill cement, slag, and other materials with minimal energy consumption. Incorporating slag in cement production not only enhances the strength of construction materials but also reduces CO_2 emissions, contributing to resource conservation and improving the industry's environmental sustainability.

The schematic diagram of a vertical roller mill is shown in Fig. 2. The material to be ground is fed into the center of the rotating grinding table (8) via a feed chute, where centrifugal forces push it under the rollers (5), forming a material bed for grinding. The grinding table is protected from wear by lining plates, and the rollers by bands. The milled material flows over the edge of the table. Hot air flows upward through openings (13) around the table's perimeter, carrying the material to the separator (2). Fine particles rise to the separator, pass through the rotating grid rotor (1), and exit the mill as the final product.

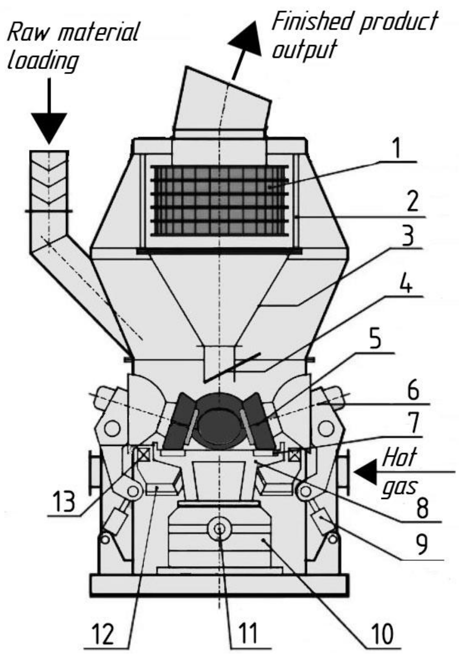

Figure. **2**. Construction of a vertical roller mill

Coarse particles settle downward and are recirculated into the mill for further grinding via a loading cone (3) equipped with a discharge gate (4). Oversized particles too heavy to be lifted by the air stream exit through the coarse product chute (12) and require mechanical transportation back to the mill. Once out of the mill, the fine product passes through a bag filter or a cyclone and bag filter system to separate solid particles from the airflow.

Thus, material grinding in vertical roller mills is achieved through compression and shear within the particle layer; the surface contact between particles distributes stress within the grinding material layer. When sufficient stress is reached, micro cracks form, and compressive grinding with a regulated proportion of shear forces leads to energy-efficient size reduction compared to drum mills.

Modern vertical roller mills are equipped with intelligent control systems that utilize artificial intelligence and machine learning technologies to optimize the grinding process. These systems analyze data in real time and automatically adjust operational parameters to achieve maximum performance. Contemporary mills are focused on sustainability, particularly minimizing energy consumption and reducing CO_2 emissions. The implementation of heat recovery technologies further enhances efficiency in industrial processes. To reduce noise and vibration levels, advanced designs are employed, making roller mills more suitable for use in environmentally sensitive areas. New designs feature modularity, allowing for quick replacement of parts and adaptation of the mill to various types of materials.

RESEARCH RESULTS

The need to increase the roller pressure force against the table surface led to a change in the design of the power elements: instead of a spring unit that pulled the opposing rollers together, hydraulic cylinders were used to apply the necessary pressure to each individual roller (fig. 3). At the same time, the transition from grinding relatively soft materials, such as coal, to hard slags resulted in significant wear on the surfaces of both the rollers and the grinding table. While for coal, a roller surface hardness of HRC52 with waviness no more than 3 mm and a thickness of at least 6.5 mm was sufficient, for slags, much stronger materials for linings were required.

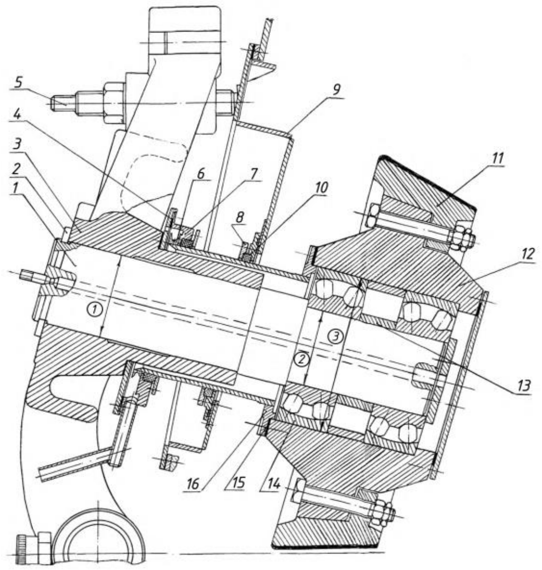

Figure 3. Design of the roller assembly:
1 – roller shaft; 2 – half-ring; 3 – lever; 4 – front disc; 5 – special bolt; 6 – ring; 7 – sealing housing; 8 – cover; 9 – casing; 10 – rear disc; 11 – roller bandage; 12 – roller housing; 13 – spacer bushing; 14 – bearing; 15 – sealing; 16 – bushing.

For materials of medium hardness, the installation of a bandage made of low-carbon steel with wear-resistant cladding is permitted, using at least powder strip PL-AN 101, powder wire PP AN-125, PP-Np350X10B8T2 according to EN 14700.

Regarding the most demanding operating conditions, when parts of the roller mill are subjected to significant wear (especially when grinding materials with a high content of silica and slags), this wear has a direct impact on the mill's performance: a worn roller decreases grinding efficiency, increasing energy consumption and crushing costs. Furthermore, excessive wear of the grinding table lining (Fig. 4) may also lead to increased vibrations, exacerbating the issue and risking equipment damage.

Figure. **4**. Wear pattern of the grinding table surface

The wear of the working elements of vertical roller mills, such as the rollers and grinding table, is a critical factor determining their operational efficiency and reliability. The working elements of mills operate under harsh conditions of intense friction, impact loads, and exposure to abrasive particles, which significantly complicates ensuring their durability. The use of polymer-metal composites for manufacturing these components (Fig. 5) demonstrates significant advantages in improving wear resistance compared to traditional materials such as alloyed steels or cast iron. Polymer-metal composites, thanks to their optimal combination of mechanical strength, impact toughness, and low friction coefficient, allow for a substantial reduction in wear rate. This, in turn, reduces the frequency of repairs and associated costs, providing economic benefits for production. Moreover, research indicates that the use of such materials ensures stable mill performance even during prolonged production cycles. Extending the service life of working elements without significant degradation of operational characteristics helps increase the reliability and continuity of equipment operation. It also minimizes the risks of unplanned downtime, which can lead to significant losses in production processes.

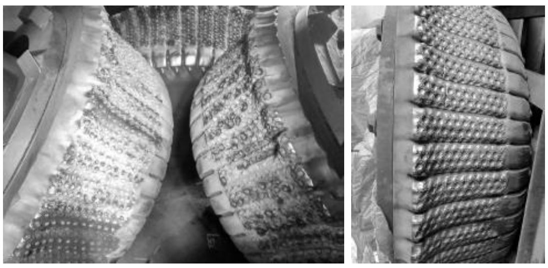

Figure 5. Roller design with a wear-resistant surface

CONCLUSIONS

Vertical roller mills have significant development prospects due to their energy efficiency, environmental friendliness, and adaptability to different materials. Further development of automation technologies and intelligent control systems will optimize the grinding process, reducing energy consumption and minimizing emissions. The use of modern materials and modular designs enhances reliability and reduces maintenance costs. Vertical roller mills also offer advantages in reducing operational costs and minimizing repair expenses due to the longer lifespan of components. They are becoming a key technology in the cement, metallurgy, and coal industries, providing stable and efficient grinding.

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Дослідження конструктивного виконання робочих органів вертикальних валкових млинів для помелу гранульованого шлаку

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Анотація. Дослідження зосереджено на оптимізації конструкції, параметрів і режимів експлуатації вертикальних валкових млинів для помелу гранульованих шлаків, які є критично важливими для таких галузей, як цементна, гірничодобувна та енергетична. Вертикальні валкові млини широко визнані за свою енергоефективність і здатність обробляти різні матеріали з мінімальними витратами енергії. Однак проблема полягає в проектуванні млинів, які можуть ефективно працювати за умов інтенсивного тертя, ударних навантажень і високої абразивності частинок, особливо при помелі твердих матеріалів, таких як гранульовані шлаки. Для вирішення цих проблем використовуються передові матеріали та захисні покриття, які покращують зносостійкість. Крім того, дослідження вивчає використання полімерно-металевих композитів у конструкції валків, що значно зменшує швидкість зношування та продовжує термін служби млина, що в підсумку призводить до економії витрат і зниження потреби в технічному обслуговуванні.

Дослідження також вивчає інтеграцію інтелектуальних систем управління, які оптимізують експлуатаційні параметри в реальному часі, що підвищує ефективність помелу та мінімізує енергоспоживання. Результати дослідження також підкреслюють важливість зниження вібрацій і покращення стабільності обладнання для забезпечення надійної роботи. У дослідженні визначено ключові параметри, що впливають на ефективність роботи млинів, такі як тиск на ролики, вологість матеріалу та обертова швидкість, і запропоновано методи оптимізації цих факторів для досягнення максимальної ефективності.

Розвиток вертикальних валкових млинів є особливо важливим у повоєнній Україні. Такі млини розглядаються єдиним життєздатним технологічним рішенням для нових цементних заводів великої та середньої потужності, здатних покращити якість цементу та зменшити викиди CO_2. Це дослідження має на меті подальший розвиток технології валкових млинів, забезпечуючи її здатність задовольняти вимоги цементної, металургійної та вугільної промисловості шляхом покращення енерго-ефективності, зносостійкості та якості помелу, що робить їх важливим інструментом для сталого промислового виробництва.

Ключові слова: вертикальні валкові млини, помел гранульованих шлаків, енергоефективність, новітні інженерні рішення, експлуатаційні характеристики