MCIT Modeling, control & information technologies

Rationale for selecting the type of grinding balls in energy-efficient invariant control of ore comminution

https://doi.org/10.31713/MCIT.2025.112

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Abstract — **This publication is devoted to the rationale of the choice of high-hardness grinding balls and the implementation of energy-efficient invariant control measures for ore comminution processes in the first-stage ball mills, ensuring reduced energy consumption and increased mill productivity.**

Keywords — ball mill; ore comminution; 6th hardness group

I. INTRODUCTION

Ukraine is one of the world's leading producers of iron ore raw materials: in 2023 it ranked sixth globally in terms of production volume [1]. The depletion of rich ore reserves since the second half of the 20th century has led to an increased role of beneficiation of low-grade ores, where material sized 0–25 mm is ground to liberate valuable mineral inclusions.

One of the ways to optimize this process is the development of staged crushing and the use of steel grinding balls and liners. This is important because comminution processes consume 7–10% of global energy and about 2% of the world's metal production, with a specific energy consumption of 20–60 kWh/t [2]. At mining and beneficiation plants, energy consumption for grinding reaches up to 20% of the global level.

Ball mills remain the main equipment used for grinding – they are productive, reliable, and simple to operate. However, their main disadvantage is the high specific energy consumption and the low efficiency of surface formation [2]. As a result, total capital and operating costs in beneficiation plants reach 50–70%. This issue remains relevant today, especially for the first grinding stage, which consumes the most energy resources.

II. TYPES AND COMPOSITION OF GRINDING BALLS

Analysis has shown that in the first stages of grinding at modern beneficiation plants, it is advisable to use balls with a diameter of 80 mm or smaller. This ensures finer grinding (better mineral liberation), increases the content of the valuable component in the product, and prevents excessive power consumption in mills with a diameter exceeding 3.6 m. Another advantage of smaller balls is the reduced wear of the liner and the preservation of ball integrity.

Enhancing the durability of grinding balls remains a key issue worldwide. High-hardness balls are recommended since they increase process efficiency. Cast iron balls can be more effective under certain conditions compared to steel ones, but their use in the first stages of grinding is currently impractical, prompting the search for alternatives. One solution is chromium steel balls, whose loading and replenishment rates are twice as low as those of cast iron balls.

The wear rate of balls is directly proportional to the mill drum diameter – the larger it is, the faster the wear. Since harder grinding bodies abrade softer ones, balls within a charge must have uniform hardness. The use of 5th hardness group balls does not increase the wear of various types of armor plates or rubber liners. They also retain their spherical shape throughout the service period.

The quality of the produced balls must be controlled at the consumer's site, and they should be used in mills grinding ore of the same technological type. Currently, the most effective are the 6th hardness group steel balls produced in Ukraine by the company "Energosteel". These steel balls are optimal even under wet grinding conditions, where corrosion wear is significant. They demonstrate equally high hardness from the surface to the core, which minimizes wear and reduces costs [3].

According to DSTU 8538:2015, grinding balls of the 5th and 6th hardness groups produced by Energosteel are made from high-carbon alloy steels with a high content of alloying elements [4]. The best results, however, can only be achieved when both balls and liners are of uniform hardness and quality is continuously monitored directly at the consumer's site.

Indirect benefits of using high-quality balls include increased mill productivity and reduced specific energy consumption. The use of high-hardness balls does not require additional operational or capital costs, while the cost of concentrate changes only due to ball consumption. As a result of using 6th hardness group balls, a reduction in specific consumption (compared to 5th group balls) of 10–30% was achieved, depending on the grinding conditions [5].

III. Quality control of grinding balls

An important component of improving production efficiency is the introduction of modern information and technical solutions for quality control of grinding media. Selective inspection is no longer sufficient – continuous control must be implemented, where all operations are automated with full documentation of results at both the manufacturer and the consumer. This approach is economically justified, as it ensures consistent product quality, reduces production costs in ferrous metallurgy, and enables higher-grade output.

Energosteel continuously improves its laboratory base for ball quality control. Recent upgrades include the introduction of an automated hardness tester capable of storing all measurement results, calculating average values automatically, and generating detailed reports [6].

Additionally, a wire-cut electrical discharge machine was installed, significantly accelerating sample preparation for volumetric hardness testing. Previously, cutting a 120 mm ball on a surface grinding machine took about two days, whereas now the process takes only six hours. This allows for faster results and prompt detection of possible deviations.

Furthermore, surface hardness and general product quality are inspected every two hours during the rolling of each new batch. Such a system guarantees full compliance with established standards and consistent quality characteristics.

IV. Factors affecting ball mill operation

Grinding of a single technological ore type or a mixture thereof in a separate ball mill using high-hardness balls (5th and especially 6th groups) allows the technological unit to operate close to its optimal mode. At the same time, its performance is influenced by numerous factors considered in the system analysis of the grinding process as an object of energy-efficient invariant control using predictive parameter estimation.

According to the literature, in the first stage of grinding in a closed circuit with a hydrocyclone, the decisive parameters include the ratio of ball and ore sizes, their quantity, density, and hardness, as well as the drum diameter and its rotation speed. Optimal ball loading must be maintained constantly, which requires a clear methodology. Although size segregation of balls in the drum is often considered negative, it can also have positive effects: smaller balls work efficiently at the feed end, while larger ones operate effectively at the discharge end.

The analysis shows that mill operation deviates from optimal conditions under the influence of several factors, which can be divided into three groups:

- variable factors – caused by mill operation (ball segregation and wear, liner wear, changes in pulp density and ore particle size);
- constant or conditionally variable factors – such as rotation speed, material and manufacturing technology of balls and liners, ore type;
- controllable factors – such as ore feed rate and pulp dilution at the inlet.

The study of ball mill operation reveals the particular impact of ball segregation. During grinding, balls are distributed along the drum, forming zones of nearly constant size, especially near the liner. The use of uniform balls allows for direct evaluation of grinding energy efficiency. Smaller balls efficiently pass ore through the low-density pulp near the feed end, acting collectively to create significant impact forces. Larger balls, operating at the discharge end, effectively overcome dense pulp and fine particles, breaking them by impact, compression, and abrasion. At a solid content of about 80%, undesired ball "packing" may occur, although dense pulp generally promotes better ore breakage.

Modern research indicates that specially shaped grinding bodies increase the packing density and productivity of the mill. When using uniform balls, their volume fraction reaches 74% (compared to 26% of voids filled with ore), whereas with multi-sized loading, the voids reach 38%, reducing mill efficiency. Thus, segregation has both negative and potentially beneficial effects that can be accounted for in practice.

Operational data from beneficiation plants show that, in practice, ball replacement according to wear is rarely performed. The use of variable-speed drives is economically unjustified, as costs outweigh benefits. Productivity loss due to liner wear can be partially offset by additional ball feeding, but automatic grinding media control systems have yet to be implemented. Optimization requires accounting for changes in pulp density and viscosity along the drum, while simultaneous ore discharge from three bunkers onto one conveyor does not ensure proper size homogenization.

In closed circuits with hydrocyclones, the main disturbing factors are the particle sizes of the feed and sand, while the ore feed rate serves as a control variable. The classifier sand flow may act as either a regulated or disturbing parameter, depending on the control scheme. Process economy is achieved only under full grinding media loading, which can be monitored via indicators of grinding energy efficiency. Since a method has been developed for determining the weighted average particle size of single-spiral classifier sands, it is possible to implement the control characteristic of the closed grinding circuit proposed by O. M. Maryuta.

V. Conclusions and prospects for further research

Thus, the fundamental principles of first-stage ore grinding are well developed and widely applied. To raise the performance of ball mills to a new qualitative level, a set of measures must be implemented. These include the substantiation of new approaches, automated regulation of key parameters, and organizational as well as technical improvements. The most challenging tasks are those aimed at enhancing overall production culture – namely, the transition to specific types of balls and liners, adaptation of mills to particular ore types, and the implementation of advanced monitoring and control systems.

References

[1] U.S. Geological Survey, "Iron ore statistics and information," National Minerals Information Center. [Online]. Available: https://www.usgs.gov/centers/national-minerals-information-center/iron-ore-statistics-and-information. Accessed: Sep. 29, 2025.

[2] Y. V. Naumenko, "*Fundamentals of the theory of operating modes of rotary mills"*, Rivne: SPD Zelept, 2009, pp.282

[3] Energosteel, "Meeting with a European partner within Energosteel company walls," [Online]. Available: https://energosteel.com/uk/zustrich-z-ievropejskim-partnerom-v-stinah-kompanii-energostil/. Accessed: Sep. 29, 2025.

[4] Energosteel, "How alloying elements affect the wear of grinding balls," [Online]. Available: https://energosteel.com/kak-vliyajut-legirujushhie-elementy-na-stepen-iznosa-meljushhih-sharov/. Accessed: Sep. 29, 2025.

[5] Energosteel, "How GZK choose steel grinding balls," [Online]. Available: https://energosteel.com/uk/gzk-vibirajut-stalevi-pomolni-kuli/. Accessed: Sep. 29, 2025.

[6] Energosteel, "New automated equipment in Energosteel laboratory," [Online]. Available: https://energosteel.com/uk/nove-avtomatizovane-obladnannya-v-laboratorii-energostil/. Accessed: Sep. 29, 2025.