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Ball mill energy efficiency optimization: A lifter face angle optimization approach

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Abstract: On average, approximately 40% of the total energy consumed by grinding comminution industries is attributed to industrial ball mills, underscoring the urgent necessity to address this energy consumption challenge. This study investigates the influence of lifter face angle variations on the performance of ball mills in comminution processes. Through a combination of discrete element method (DEM) simulations and experimental design, the study explores the effects of lifter face angle on energy efficiency, wear rates, and comminution effectiveness. Findings reveal that smaller lifter face angles result in increased scattering of ore particles within the mill, while larger angles lead to reduced wear and improved grindability of materials. The optimal lifter face angle is identified as approximately 24.8°, falling within the typical range used by industrial ball mill accessories manufacturers. An overall energy saving of 5.89% is achieved by using the optimum ball mill lifter face angle of 24.8°. Recommendations for future research include further exploration of optimal parameters, experimental validation of the findings, and the development of advanced modelling techniques.

Keywords: Ball mill energy optimization, ball mill operational efficiency, discrete element modelling, response surface modelling, comminution processes

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1. Introduction

Achieving effective energy optimization in mining operations necessitates a central focus on the productivity of mining equipment (Maregedze, et al., 2022), such as ball mills, which consume at least 40% of the total energy used by comminution industries (Usman, 2018). Ball mill designs have been modified and refined numerous times over the past forty years, yet an optimum design has not been achieved. Ball mills still exhibit high energy consumption and operational inefficiencies. The energy efficiency of comminution processes is currently less than 1%, with over 80% being lost as heat energy in slurry and ambient heat (Radziszewski, 2013; Schmidt et al., 2016; Bouchard et al., 2017; Maregedze et al., 2023). Radziszewski suggested that through comprehensive insulation of the ball mill grinding circuit, energy efficiency could be enhanced by 10%. Additionally, the implementation of heat energy harvesting technologies, such as thermoelectric generation systems, could potentially save more than 7.3 GW (Radziszewski, 2013).

Usman et al. (2020) suggests that designing lifters with the same face angle but different configurations, along with wear rate analysis, is crucial for optimizing ball mill design. This underscores the significant role of liners and lifters in this optimization process. His research indicates that a spacing-to-height ratio of four at 75% of the critical speed yields optimal results.

Additionally, Hanumanthappa et al. (2020) conducted an experiment comparing a ball mill with and without lifters, and with and without a closed end. They found that incorporating lifters at the discharge end reduced recirculation compared to the discharge end without lifters. This experiment demonstrated that appropriate lifter design and placement result in better particle grade distribution and minimize recirculating load, thereby reducing the need for regrinding of ball mill ore. Consequently, lifter design and placement emerge as crucial aspects in optimizing ball mill design.

According to (Guzman & Garcia, 2011), achieving benefits in grinding efficiency hinges on an optimal grinding media charge, mill speed, and lifter profile optimization, particularly focusing on the face angle. They emphasize that lifter design optimization is critical, as it directly impacts mill power, charge motion, liner wear, and throughput.

Rosales-Marín et al. (2019) observed that mill power varied with lifter type and increased with ball mill rotational speed up to 75% of the critical speed (Nc). They found that lifters with a wider face angle of 22.5°, the largest angle used, exhibited the lowest wear rate and highest breakage rates except at 55% Nc. However, they noted an increase in power consumption between 65% and 75% Nc, followed by a decrease, attributed to the effect of centrifugal force beyond 75% of the critical speed.

Despite the effectiveness of helical lifters in enhancing ball mill comminution and energy efficiency, including reducing wear rates at high speeds like 90 to 100% of the critical speed, lifter face angle optimization remains a challenge (Safa & Aissat, 2023). Despite numerous research efforts and design innovations on ball mill liners and lifters, an optimum face angle has yet to be identified, and several inefficiencies persist. Studies have emphasized the need for ball mill designs that enhance operational efficiency, including energy utilization and grinding efficiency (Singh et al., 2021; Gao, et al., 2021; Slíva & Bra'zda, 2020; Ugwuegbu et al., 2017; Shahbazi et al., 2020).

Furthermore, (Kolev et al., 2021) assert that despite existing inefficiencies in comminution energy utilization, up to 90% of thermal energy losses have the potential to be recovered. Kolev's perspective underscores the possibility of optimizing ball mill energy use, despite the lack of significant efforts to harvest or minimize persistent energy losses.

The proposed research on optimizing the ball mill lifter face angle represents a critical endeavour to address persistent inefficiencies in comminution processes. Despite numerous previous efforts, an optimum face angle for ball mill liners and lifters remains elusive. By systematically exploring the lifter face angle's impact on ball mill energy efficiency through advanced modelling techniques such as discrete element modelling (DEM) and response surface modelling (RSM), this study aims to fill this gap. The novelty of this research lies in its holistic approach to improving operational efficiency in ball milling operations. By optimizing the lifter face angle, the study sought to enhance key performance metrics such as energy consumption, grinding efficiency, and overall process productivity. By harnessing wasted energy and improving overall energy efficiency, the outcomes of this study have the potential to drive significant advancements in mining operations, contributing to economic, environmental, and societal benefits on both local and global scales.

2. Methodology

2.1. Computer-aided design (CAD) drawing

A computer-aided Design (CAD) geometry of the ball mill was developed using SOLIDWORKS 2021, subsequently saving it as an STL file for compatibility with discrete element modelling (DEM) software. This approach is corroborated by Mhadhbi (2021), who emphasized the critical role of the discrete element method (DEM) in simulating comminution mills, beginning with the generation of CAD geometry for DEM simulations. A parametric design process was employed to create the ball mill model, allowing the modification of the design parameters for various lifter configurations and ball mill sizes. The external ball mill diameters utilized were 1m, 4m, and 7m, with face angle configurations set at 15°, 30°, and 45°. The data obtained from this study proved valuable for assessing energy loss and identifying optimal energy efficiency.

2.2. Modelling and simulation using DEM

As Mhadhbi stated Mhadhbi (2021), the utilization of the discrete element method (DEM) is crucial for simulating comminution mills. Consequently, the present study employed this method, beginning with the creation of a CAD geometry. The computer-aided design (CAD) geometry of the ball mill was saved as an STL file, which was then imported into ANSYS ROCKY modelling software for discrete element modelling (DEM) of the ore crushing process. ROCKY simulations were conducted to ascertain the power and energy dissipated during the comminution process across various virtual experimental ball mills and their lifter configurations.

According to (Hirosawa & Tomohiro, 2021), the design of an energy-efficient milling process relies on the variation of energy provision, along with the correct particle size and quantity. They emphasized that energy dissipation should be examined to understand ore or material particle breakage, as opposed to impact energy, since dissipated energy indicates energy losses while impact energy reflects the kinetic energy associated with collisions. Furthermore, they simulated the ball mill comminution process using the discrete element method (DEM) under dry milling conditions were done to determine the energy dissipated by the ball mill. In Carvalho et al. (2021) and Carlvalho et al. (2020), the authors argue that the use of DEM in the optimization of industrial grinding mills is essential for small-scale experimental laboratory trials, as plant experiments are risky, more costly, and time-consuming. A full factorial face-cantered central composite experimental design approach was employed in this study using Design Expert 2024 software. Two main parameters were varied, as shown in Table 1.

Table 1. Simulation parameters.

No	Ball Mill size (m)	Lifter face angle (degrees)
1	1	15
2	1	30
3	1	45
4	4	15
5	4	30
6	4	45
7	7	15
8	7	30
9	7	45

As noted by Gupta and Yan (2016), several ball mill design Equations (1) – (9) have been utilized in the design of ball mills. The Bond equation for specific energy for grinding or for size reduction, E_G, in a closed circuit is given by;

$$E_G = 10\, W_i \left[\frac{1}{\sqrt{P_{80}}} - \frac{1}{F_{80}}\right] (kWh/t) \quad (1)$$

Where W_i is Bond's work index and represents the energy required to reduce the ore from an infinite size to 100 microns (100 µm), P_{80} is the 80% passing size of the product in microns and F_{80} is the 80% passing size of the feed in microns. However, in order to be able to calculate the energy required for the comminution process, the work index has to be calculated using the Bond's work index, $W_{i\ TEST}$; the output power which is given by Equation (2) where D is the aperture in millimetres (mm) of the classification screen and G is the undersize wet mass in grams (g) product per unit revolution of the mill while W_i can be computed using the Equation (3) where F is the total correction factor, that is, $F_1 + F_2 + \cdots + F_8$. The correction factor, F_1which is the conversion factor from wet grinding to wet grinding is as given by Equation (4). The correction factor, F_2 for the conversion from dry to wet grinding circuits in a closed circuit given in table 2 (Gupta & Yan, 2016).

$$W_{i\ TEST} = \frac{48.95}{10\, D^{0.23}\, G^{0.82}\left[\frac{1}{\sqrt{P_{80}}} - \frac{1}{F_{80}}\right]} (kWh/t) \quad (2)$$

$$W_i = F(W_{i\ TEST}) \quad (3)$$

$$W_{(Dry)} = 1.3(W_{(Wet)}) \quad (4)$$

Table 2. Conversion factor from dry to wet grinding circuits.

Product size control (microns)	Multiplying factor
50	1.035
60	1.05
70	1.10
80	1.20
90	1.40
92	1.46
95	1.57
98	1.70

The correction factors F_3, F_4, F_6 and F_8 are not used in ball mill design, hence the study did not include them. For the ball mills lower reduction ratio correction factor, F_5, the equation is provided by Equation (5) or (6) where R is the reduction ratio, and the mill diameter correction factor, F_7 (Equation 7) is the changes in mill capacity in relation to change in diameter.

$$F_5 = \frac{2(R-1.35)+0.26}{2(R-1.35)} \quad (5)$$

$$F_5 = \frac{F_{80}+1.22P_{80}}{F_{80}-1.35P_{80}} \quad (6)$$

$$F_7 = \left[\frac{2.44}{D}\right]^{0.2} \quad (7)$$

For $D < 3.81\ m$, and $F_5 = 0.914$ for $D \geq 3.81\ m$, since Bond (1961) and Gupta and Yan (2016) asserts that the grinding energy reduction from the increase in mill diameter mills ceases for diameters above 3.81 m. After determining the energy requirement, the study considered this energy as the hourly power requirement, hence $E_G = P$. One of the crucial equations used to determine the rational velocity of the ball mill is the critical speed N_c, which is given by Equation (8), where N_c is the critical speed of the mill (in rpm), D is the inner diameter of the mill (in meters); and d is the size of the grinding balls (in meters).

$$N_c = \frac{42.3}{\sqrt{\mathrm{D-d}}}(rpm) \tag{8}$$

2.3. Optimization virtual experimental results

The virtual ball mill system developed in SOLIDWORKS and simulated using DEM software produced virtual experimental data, which was subsequently utilized in response surface modelling (RSM) to achieve optimal results. A similar methodology was employed by Liu et al. (2022), who conducted optimization research by using Design of Experiments to generate experimental data and then applying RSM for optimization. In this study, RSM was used to generate empirical formulas for power consumption and intensities, allowing them to assess the impact of the lifter face angle on energy consumption and grinding energy efficiency.

3. Results and discussion

3.1. Modelling and simulation using DEM model

The simulation process revealed that a smaller face angle of 15° is characterized by lower power and intensity dissipations. Intensity dissipation, defined as power dissipated per unit area, leads to higher ore particle scattering and shorter mill media trajectory paths compared to other lifter face angle configurations. This results in lighter ore particles being more scattered within the ball mill than the heavier grinding media, promoting high media-to-media interaction since the grinding media follow a shorter trajectory path than the ore particles, as depicted in Fig. 1. Consequently, this leads to increased wear rates of the grinding media and lining, primarily due to impact forces. The greater scattering of ore material ensures that the heavy grinding media reach the floor of the ball mill first, leading to minimal ore material coverage on the liners, which in turn results in higher liner wear and energy consumption due to the low breakage opportunities from ore particle-to-ore particle interactions. Overall, liner wear is moderate due to the effect of moderate-intensity dissipation.

The lifter face angle of 15° is characterized by lower power and intensity dissipations, which implies that as more charge or ore particles scatter within the ball mill, there is less trajectory of balls on the toe since most ore particles will remain in motion due to centrifugal forces. The medium angle of 30° for the lifter face is associated with medium power and intensity dissipation, translating to a balance in energy use and intensity dissipation that results in an improved comminution rate of the ore. According to (Rosales-Marína et al., 2019), the lowest power draw produces the finest grind grade ore product, whereas the coarsest grind results from the highest power draw. This can be attributed to the increased sliding, crushing, and abrasion wear caused by a shorter ball and media trajectory distance when a larger lifter face angle is employed. A 45° lifter face angle led to high power and intensity dissipation, indicating that for optimal comminution results, it is essential to balance the lifter face angle and the intensity to ensure better energy utilization.

When the lighter ore particles are more scattered in the ball mill than the heavier grinding media, due to a smaller lifter face angle at 75% of critical speed or high rotational speed, high media-to-media interaction predominantly occurs in suspension. This is because the ball mill grinding media have a shorter trajectory path than the ore particles due to their weight. Consequently, this leads to high wear rates of both the grinding media and the liners, primarily due to the impact of the balls on the liners and lifters. The increased scattering of ore material ensures that the heavy grinding media reach the floor of the ball mill first, with minimal ore material covering the liners, leading to increased liner wear and energy consumption since more particle-to-ore interactions yield very low breakage opportunities. Liner wear is moderate due to the effect of moderate-intensity dissipation.

The falling particle trajectory observed in this study is consistent with the findings in literature (Hanumanthappa, et al., 2020; Rosales-Marín et al., 2019; Royston et al., 2007), which showed that particle streams are clear and dense when a very small lifter face angle is used, resulting in ineffective production of fine-grade ore particles from the ball mills. By using a wider lifter face angle, there is a higher applied force per unit area as particles fail to travel longer distances and predominantly slide over each other.

The utilization of a 30° lifter face angle design facilitates high interaction between the ball mill grinding media and particles, enhancing impact among the balls and the particles, including the compression of particles by the mill balls. This results in a predominantly high-intensity dissipation and moderate power dissipation during the grinding process, accompanied by a moderate spreading of both the grinding media and the ore. Consequently, there are high impact forces per unit area, leading to significant impact and partial crushing and abrasion. This configuration exhibits a high sorting rate of materials compared to other configurations; the media-to-ore particle mixture is substantial. Therefore, although the intensity is very high, it is predominantly directed towards the ore particles, thus facilitating a more effective comminution process.

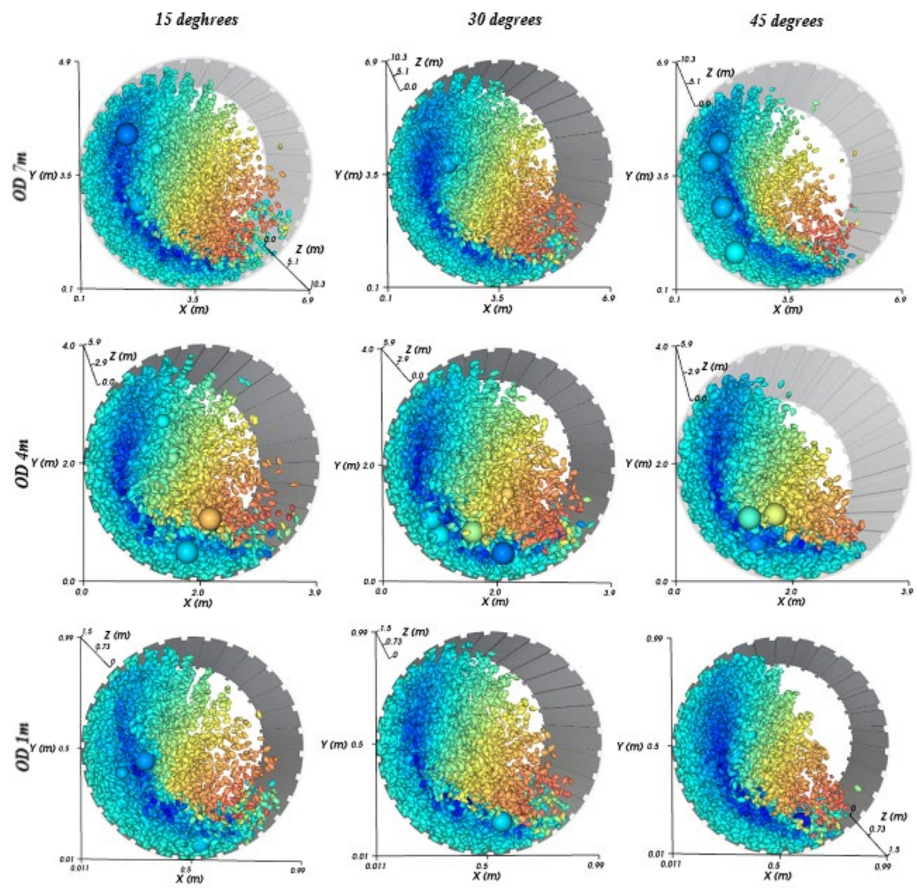

Figure 1. Ball mill grinding simulation results.

A larger face angle of 45° results in lower power and intensity dissipation, which in turn reduces energy dissipation and wear of the liners and balls. Additionally, this configuration is characterized by a lower trajectory of both the heavier materials, i.e., the grinding media, and the lighter ore particles, which are further away from their falling position, leading to increased cascading of the grinding media. This fosters more compression of fewer ore particles between the mill balls, causing the comminution process to be predominantly characterized by crushing and abrasion reduction, while the bulk of the action in the ball mill involves ball-to-ball abrasion and high ball mill lining abrasion wear.

The utilization of a wider lifter face angle results in less applied force per unit area of the material in the ball mill, due to minimal impact forces, thereby leading to lower wear and improved grindability of material in the ball mill.

3.2. Optimization using response surface modelling (RSM)

The power dissipation in the ball mill demonstrates a direct proportionality to the square of the increase in both the lifter face angle and the ball mill diameter (refer to Fig. 2). Consequently, the energy dissipated by the ball mill exhibits a similar direct proportionality to the square of the increase in the lifter face angle, as energy dissipation is intricately linked to power dissipation over time. Moreover, increasing the face angle results in increased energy usage, thus optimizing energy efficiency necessitates an optimally smaller angle for the lifter face.

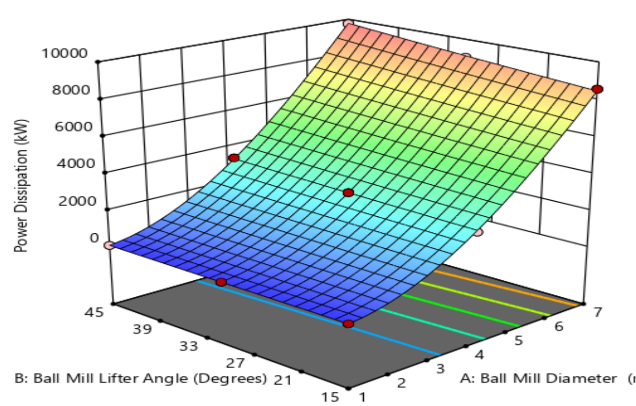

Figure 2. Power dissipation relationship graph.

By denoting the power dissipated as P_d, the ball mill diameter as x, and the lifter face angle as y, the empirical formula for determining the power dissipation, which corresponds to energy dissipation to five decimal places, is expressed as:

$$P_d = (-12.28736 + 17.59262x + 0.00439y + 0.02729xy - 0.44471x^2 + 0.00048y^2)^2 \quad (9)$$

$$I_d = e^{(-2.62622+1.92312x+0.06232y-0.00661xy-0.09548x^2-0.00015y^2)} \quad (10)$$

By considering the intensity dissipated as I_d, the mathematical model for intensity dissipation is given by Equation (10) Fig. 3 shows the relationship between intensity dissipation, the ball mill lifter face angle and the ball mill diameter. Intensity dissipation demonstrates a direct proportionality to the exponential increase in both the lifter face angle and the ball mill size. This emphasizes that an increase in the lifter face angle enhances the efficiency of the grinding process. Consequently, by optimizing the lifter face angle, the optimization of the comminution process is also achieved. The researchers determined the optimum ball mill lifter face angle to be 24.8°. This optimal solution yields a total energy saving, represented by a power saving of 5.89%, which correlates well with other ball mill diameter sizes. In terms of operational efficiency, the ball mill will operate at 5.78%, considering the maximum intensity of the ball mill.

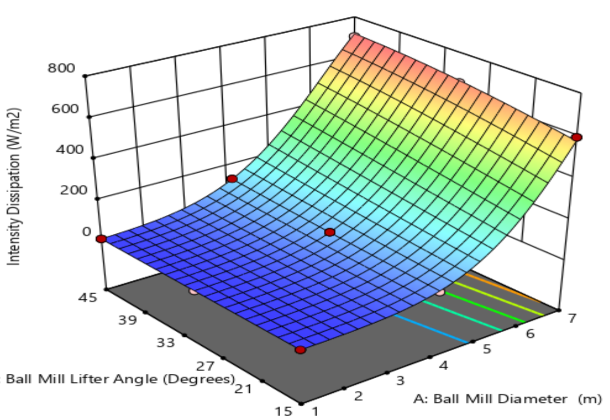

Figure 3. Intensity dissipation relationship graph.

The lifter face angle falls within the typical range for industrial ball mill lifter face angles, as asserted by Royston et al. (2007), who noted that the market standard for lifter face angles ranges between 22° and 35°. Therefore, an angle of 24.8° falls within the range of lifter face angles commonly used by ball mill accessories manufacturers. Moreover, the optimum angle obtained in this research closely aligns with the 22.5° angle (Rosales-Marín et al., 2019) to produce better fines, although without optimization, compared to angles of 7.5° and 30°.

Intensity dissipation is directly proportional to the exponential increase in the lifter face angle, with the optimum intensity dissipation value realized at 24.8°. This intensity dissipation correlates with the power exerted on the charge during the grinding process; thus, higher intensity results in a greater number of fines produced by the comminution process. Consequently, the operational efficiency of the ball mill is directly related to the exponential increase in the lifter face angle.

At lower face angles, the balls or grinding media strike the wall, creating a significant impact zone that generates centrifugal motion and results in the failure of most grinding media or balls to participate in the comminution process (Royston et al., 2007). This implies that while aiming to reduce energy costs, it is crucial to ensure some charge cataracting and avoid centrifugal motion by charge particles due to high speed and smaller lifter face angles, which can impede the grinding process.

4. Conclusions

This study revealed that smaller lifter face angles, such as 15°, are associated with lower power and intensity dissipations, leading to increased scattering of ore particles within the ball mill. Conversely, larger lifter face angles, such as 45°, result in reduced power and intensity dissipations, fostering lower wear and grindability of materials. Optimization efforts identified the optimal lifter face angle to be approximately 24.8°, falling within the typical range used by industrial ball mill accessories manufacturers. This angle demonstrated a balance between energy efficiency and comminution effectiveness, resulting in significant energy savings without compromising operational performance. Furthermore, our study highlights the importance of considering lifter face angle variations in ball mill design and operation. While smaller angles may lead to reduced energy costs, they also pose challenges such as charge cataracting and centrifugal motion, which can impede the grinding process.

In light of the findings and insights gained from this study on ball mill performance optimization, several key recommendations emerge to guide future research endeavours and industrial practices.

- Further research is warranted to advance the design of liners and lifters with improved abrasive resistance, aiming to extend their lifespan and enhance durability in ball mill operations.
- Investigating the impact of lifter wear on energy consumption and operational efficiency is crucial to ensuring sustained optimal performance of the lifter

angle solution identified in this study. This research will help maintain efficient ball mill operation over time by addressing potential degradation due to lifter wear.

- Further research could explore additional parameters and their effects on ball mill performance, paving the way for enhanced efficiency and sustainability in mineral processing operations.

Overall, these findings contribute to a better understanding of the factors influencing ball mill performance and provide valuable insights for optimizing the design and operation of comminution processes in industrial settings.

Conflict of interest

The authors have no conflict of interest to declare.

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