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RESEARCH

# Design, Implementation, and Performance Evaluation of an Automatic Lubrication System for Open Gears in a Ball Mill

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A B S T R A C T

*Open gear drives in ball mills are exposed to severe operating and tribological conditions that demand reliable and consistent lubrication. This study presents the design, implementation, and industrial performance evaluation of an automatic lubrication system developed for the open gear drive of a ball mill. A structured selection procedure based on the VDI 2225 methodology was applied to integrate technical and economic criteria in the system design. The proposed solution was evaluated under real operating conditions using infrared thermographic analysis of the pinion gear, vibration monitoring of the countershaft bearings, and spray pattern verification tests. Comparative measurements conducted before and after installation show a significant reduction in the pinion temperature gradient, from approximately 20 °C to 6.4 °C, along with noticeable decreases in vibration amplitudes. These results demonstrate that the automatic lubrication system improves lubricant distribution, enhances tribological performance, and increases the operational reliability of ball mill open gear drives.*



## 1. INTRODUCTION

Open gear drives used in ball mills are critical components in mining and mineral processing operations because they transmit high torque under severe operating conditions. These systems are continuously exposed to high contact stresses, cyclic loading, contamination, misalignment, and thermal fluctuations, making lubrication essential for controlling friction, wear, and surface degradation [1–6]. Inadequate lubricant distribution may result in localized lubricant starvation, elevated temperatures, increased vibration, accelerated wear, and ultimately reduced equipment reliability [5, 7–11].

In many small and medium-sized mining operations, open gear lubrication is still performed manually or through semi-automatic systems with limited control capabilities. Such practices often depend on operator experience and maintenance routines, leading to inconsistent lubricant application and non-uniform coverage of the tooth flanks. Besides increasing tribological risks, manual lubrication exposes personnel to rotating machinery and potentially hazardous operating environments [7–11].

Automatic lubrication systems have been increasingly adopted in industrial equipment to improve lubricant delivery consistency, reduce maintenance requirements, and enhance operational reliability [12–18]. Previous studies have reported successful applications of automatic lubrication technologies in manufacturing systems, machine tools, construction machinery, vehicle components, and bearing systems [13–18]. These investigations demonstrate that automated lubrication can improve lubrication efficiency, reduce friction-related problems, and contribute to longer component service life.

Despite these advances, relatively few studies have addressed automatic lubrication systems specifically for open gear drives in ball mills operating under real industrial conditions. Furthermore, most published works focus either on lubrication technology itself or on general industrial implementation, while limited attention has been given to integrated studies that combine systematic system selection, industrial implementation, and quantitative performance evaluation using operational indicators relevant to tribological performance and equipment reliability [5,13,17].

Another aspect that remains insufficiently discussed in the literature is the structured selection of lubrication system architectures for open gear applications. The choice of pumping technology, lubricant distribution method, and spray configuration directly influences lubrication reliability, maintainability, operating costs, and long-term performance. Therefore, objective methodologies capable of integrating technical and economic criteria can support more effective decision-making during system design and modernization projects [13,18].

The present study addresses these gaps through the design, implementation, and industrial evaluation of an automatic lubrication system for the open gear drive of a ball mill. Unlike previous studies that primarily report lubrication system applications in industrial equipment, this work integrates a systematic VDI 2225-based selection methodology with industrial implementation and quantitative performance evaluation under real operating conditions. The selected system was installed and evaluated through thermographic measurements, vibration monitoring, and spray pattern verification tests. The objective is to assess the influence of automated lubricant application on lubricant distribution effectiveness, thermal behavior, and drivetrain dynamic response, while providing a practical framework for the selection and implementation of automatic lubrication systems in ball mill open gear drives.

## 2. METHODOLOGY

### 2.1 Evaluation of the optimal lubrication system

To define the most suitable configuration of an automatic lubrication system for the open gears of the ball mill, the VDI 2225 methodology was applied to evaluate and compare alternative subsystem configurations within fully automatic lubrication technologies [19-21]. The evaluation focuses on identifying the optimal combination of system components rather than comparing different levels of automation, considering technical and economic requirements such as operational reliability, controllability, maintenance demands, adaptability to harsh industrial environments, and integration with existing mill infrastructure. Table 1 presents a comparison matrix of the most suitable lubrication system variants for this application. The delivery unit may be pneumatically or electrically driven, with pneumatic pumps generally preferred due to their rapid pressure buildup, lower cost, and reduced maintenance requirements, despite the need for an electro-pneumatic control pan-el. Metering device selection is primarily governed by system reliability: progressive systems provide fault detection through system shutdown and alarm signaling in the event of clogging, whereas single-line and dual-line systems may continue operating despite partial blockages, requiring visual inspection. Finally, spray technology selection depends largely on the gear guard arrangement, with independently mounted spray nozzles preferred to facilitate maintenance and component replacement.

**Table 1.** Combination of solutions to achieve variants.

| Subsystem | Delivery unit | Metering devices | Spray technology |
|---|---|---|---|
| V1 | Pneumatic | Single line | Lance |
| V2 | Pneumatic | Dual line | Individual |
| V3 | Pneumatic | Progressive | Individual |
| V4 | Electric | Dual line | Individual |
| V5 | Electric | Progressive | Lance |

According to the VDI 2225 standard, each evaluation criterion is assigned a score ranging from 0 to 4, where 0 denotes non-compliance with the requirement, 1 minimal adequacy, 2 acceptable performance, 3 good performance, and 4 ideal performance. To reflect the relative importance of the selected criteria, weighting factors are introduced, with the symbol g representing the weighting assigned to each technical or economic criterion and p denoting the score attributed to each subsystem variant. The overall degree of appreciation for each configuration is calculated as the ratio between the total weighted score achieved by a given variant and its corresponding ideal score. This structured evaluation enables an objective comparison of alternative automatic lubrication system configurations and supports the selection of the most appropriate solution for subsequent system design and implementation.

The technical evaluation of automatic lubrication systems for ball mill open gear drives is based on four main criteria summarized in Table 2. Lubrication reliability and delivery consistency (T1) are essential to ensure stable tribological conditions under severe operating environments, where uneven or interrupted, lubricant supply can rapidly lead to wear and thermal instability. Operational robustness and fault tolerance (T2) reflect the system's ability to withstand harsh conditions and to detect or mitigate failures that could otherwise result in lubrication starvation. Controllability and system integration (T3) enable lubrication parameters to be adapted to actual operating conditions and allow seamless interaction with plant automation systems for monitoring and diagnostics. Finally, maintainability and serviceability (T4) address the ease of inspection, cleaning, and component replacement, directly influencing system availability and long-term reliability.

**Table 2.** Technical evaluation.

| Variants | | V1 | | V2 | | V3 | | V4 | | V5 | | Ideal | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Technical criteria** | g | p | gp | p | gp | p | gp | p | gp | p | gp | p | gp |
| T1 | 4 | 2 | 8 | 3 | 12 | 4 | 16 | 3 | 12 | 2 | 8 | 4 | 16 |
| T2 | 3 | 2 | 6 | 3 | 9 | 3 | 9 | 3 | 9 | 2 | 6 | 4 | 12 |
| T3 | 3 | 2 | 6 | 3 | 9 | 3 | 9 | 4 | 12 | 2 | 6 | 4 | 12 |
| T4 | 2 | 2 | 4 | 3 | 6 | 3 | 6 | 2 | 4 | 2 | 4 | 4 | 8 |
| Score | 12 | 8 | 24 | 12 | 36 | 13 | 40 | 12 | 37 | 8 | 24 | 16 | 48 |
| Technical Value (gp) | | 0.50 | | 0.75 | | 0.83 | | 0.77 | | 0.50 | | 1.00 | |

The technical evaluation of the proposed alternatives was performed following the VDI 2225 methodology. Each criterion was assigned a weighting factor (g) according to its relative importance, while a performance rating (p) was assigned to each alternative. The weighted score (gp) was calculated as the product of the weighting factor and the performance rating. The overall Technical Value was obtained by normalizing the total weighted score of each alternative with respect to the ideal solution. The same procedure was subsequently applied for the economic evaluation presented in Table 3.

**Table 3.** Economic evaluation.

| Variants | | V1 | | V2 | | V3 | | V4 | | V5 | | Ideal | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Economic criteria** | g | p | gp | p | gp | p | gp | p | gp | p | gp | p | gp |
| E1 | 2 | 4 | 8 | 3 | 6 | 3 | 6 | 2 | 4 | 3 | 6 | 4 | 8 |
| E2 | 3 | 2 | 6 | 3 | 9 | 3 | 9 | 2 | 6 | 2 | 6 | 4 | 12 |
| E3 | 4 | 2 | 8 | 3 | 12 | 4 | 16 | 3 | 12 | 2 | 8 | 4 | 16 |
| E4 | 3 | 2 | 6 | 3 | 9 | 4 | 12 | 3 | 9 | 2 | 6 | 4 | 12 |
| Score | 12 | 10 | 28 | 12 | 36 | 14 | 43 | 10 | 31 | 9 | 26 | 16 | 48 |
| Economic Value (gp) | | 0.58 | | 0.75 | | 0.90 | | 0.65 | | 0.54 | | 1.00 | |

The economic evaluation of automatic lubrication systems for ball mill open gear drives is summarized in Table 2 and considers several complementary cost-related aspects. Initial investment cost (E1) reflects the capital expenditure required for system components, integration, and commissioning, which must be balanced against functional performance. Operating and maintenance cost (E2) accounts for energy consumption, lubricant usage efficiency, and routine maintenance requirements that influence long-term operating expenses. The economic impact of downtime and failure risk (E3) addresses potential losses associated with lubrication-related failures, unplanned shutdowns, and component damage. Finally, lifecycle cost and return on investment (E4) integrate capital and operating costs with the economic benefits derived from improved reliability, reduced lubricant consumption, and extended component service life.

Based on the combined technical and economic evaluation conducted using the VDI 2225 methodology, Variant V3—comprising a pneumatic delivery unit, a progressive metering system, and individual spray application—was selected as the most suitable automatic lubrication configuration for the ball mill open gears. This variant achieved the highest technical value (0.83) and economic value (0.90), indicating superior overall performance among the evaluated solutions. From a technical standpoint, the progressive metering system ensures consistent lubricant delivery, while the pneumatic pump provides reliable pressure generation under harsh industrial conditions. The use of individual spray elements improves maintainability and enables localized intervention. Economically, Variant V3 offers a favorable balance between initial investment and long-term operating costs while reducing the risk and financial impact of lubrication-related failures. Consequently, this variant was selected for detailed design, implementation, and performance evaluation.

## 2.2 The proposed lubrication system

The proposed automatic lubrication system is based on a centralized pneumatic delivery architecture combined with progressive metering and individual spray application, as schematically illustrated in Fig. 1. The system employs a pneumatic pump supplied by a high-capacity lubricant container to deliver high-viscosity open gear lubricant, while an electro-pneumatic control panel and a PLC-based control system manage air supply, sequencing, and safety functions. Lubricant distribution is achieved through a progressive metering valve with integrated cycle monitoring, ensuring sequential and complete delivery to individual spray nozzles and enabling fault detection in the event of flow interruption. This configuration emphasizes robustness, controllability, and ease of maintenance under industrial operating conditions.

System operation is governed by a programmable logic controller that executes lubrication cycles at predefined time intervals and coordinates the actuation of the pneumatic pump and spray air supply. Lubricant flow is divided into fixed and repeatable volumes by the progressive metering valve, providing inherent verification of correct lubricant delivery through cycle feedback. A post-blow air phase is applied after each lubrication cycle to clean spray nozzles and prevent grease accumulation, contributing to stable spray patterns and reduced maintenance. The selected lubrication frequency follows lubricant manufacturer recommendations and international standards, ensuring adequate lubricant film formation and wear protection for high-viscosity open gear lubricants.

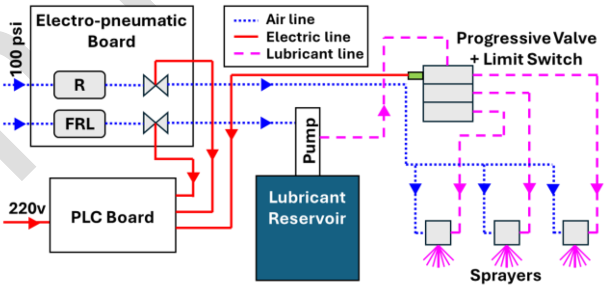


**Fig. 1.** A scheme of the proposed lubrication system.

Installation of the system was carried out with careful con-sideration of accessibility, protection, and long-term maintain-ability in an industrial mining environment. Control panels and system components were positioned to minimize exposure to dust, vibration, and mechanical damage while allowing straightforward inspection and servicing. The modular layout enables localized maintenance without full system shutdown, reducing operational disruption. Preventive internal cleaning using a dedicated flushing lubricant is recommended at regular intervals to mitigate blockage risks associated with high-viscosity lubricants, thereby maintaining stable lubricant delivery and extending system service life.

The selected lubrication system was designed for use with a high-viscosity asphaltic open gear lubricant commonly employed in ball mill applications. The lubricant exhibits a kinematic viscosity greater than 55,000 cSt at 40 °C in its undiluted form and approximately 6,000 cSt at 40 °C in its sprayable formulation, while maintaining a viscosity above 1,600 cSt at 100 °C, exceeding the minimum requirements established by AGMA 9005-E02 for open gear lubrication. The lubrication interval was established according to AGMA 9005-E02 recommendations for single-pinion ball mills, resulting in one lubrication cycle every 20 minutes [22]. Each cycle delivers approximately 9.30 $cm^3$ of lubricant through a progressive metering valve that distributes the lubricant uniformly among the three spray nozzles. The spray bar was positioned at an angle of approximately 30° toward the loaded side of the gear tooth flank to ensure lubricant application directly within the primary load-carrying contact zone.

### 2.3 System and mill performance analysis

The performance of the proposed automatic lubrication system was evaluated through operational verification tests and comparative measurements conducted before and after system installation. System functionality was verified by forced lubrication cycles initiated from the PLC control panel, confirming proper actuation of the pneumatic pump, solenoid valves, and spray nozzles. Visual inspections were performed to identify leaks, blockages, or synchronization issues, and lubricant atomization at the spray nozzles was directly observed during controlled test cycles.

Thermal performance of the open gear drive was assessed using a FLIR C9 infrared thermographic camera, which was employed to measure surface temperature distribution and thermal gradients on the pinion gear during normal operation. Dynamic performance was evaluated through vibration measurements taken at the countershaft bearings using a SMART SENSOR AS63B vibration meter, with data collected at the drive and non-drive ends in the vertical, horizontal, and axial directions. Measurements were performed under comparable operating conditions before and after system installation. In addition, a spray pattern test using a white plastic film placed on the gear tooth surface was conducted with the mill stopped to verify correct nozzle positioning and uniform lubricant coverage of the active tooth flanks.

To improve measurement reliability, thermographic and vibration measurements were repeated three consecutive times under comparable operating conditions, and the reported values correspond to the representative measurements obtained during these tests. Measurements were performed during normal mill operation at steady-state conditions. However, it should be noted that ball mills are inherently dynamic systems, and operating conditions may vary due to changes in ore feed characteristics, ball charge distribution, and material flow within the mill. Consequently, some variability in temperature and vibration measurements is expected. The uncertainty of the results is also influenced by the accuracy of the measuring instruments and by operational fluctuations of the process. Nevertheless, the magnitude of the observed reductions in temperature gradient and vibration levels after system implementation was substantially greater than the expected measurement uncertainty, supporting the validity of the observed performance improvements.

## 3. RESULTS

### 3.1 Technical characteristics of the lubrication system

The implemented automatic lubrication system corresponds to the configuration selected through the VDI 2225 evaluation and reflects the technical requirements defined for reliable open gear lubrication in industrial ball mill applications. The system is composed of independent electro-pneumatic and control units, a centralized lubricant delivery assembly, and a progressive metering and spray application subsystem in-stalled directly at the gear guard.

Figure 2 presents the general arrangement of the electro-pneumatic control panel and the PLC control panel installed adjacent to the lubricant drum. The pneumatic pump is mounted directly on the lubricant container, minimizing suction losses and ensuring stable lubricant supply. Electrical power at 220 V is supplied to the PLC control panel, which manages the control logic and system sequencing, while compressed air at 100 psi is supplied to the electro-pneumatic control panel. This physical separation between power/control and pneumatic actuation improves system safety, simplifies troubleshooting, and facilitates maintenance access.

**Fig. 2.** The electro-pneumatic panel and PLC panel installed next to the drum.

The valve and spray panel installed on the mill gear guard is shown in Figure 3. This assembly includes the progressive metering valve, spray nozzles, limit switch, and a lubricant strainer. The progressive valve ensures sequential and volumetrically controlled lubricant distribution to the spray nozzles, while the integrated limit switch provides cycle completion feedback to the PLC. The strainer protects downstream components from contamination. The spray nozzles were carefully positioned to direct lubricant exclusively toward the working face of the gear teeth, avoiding application on the passive flank and ensuring effective lubrication at the load-carrying contact zone.

**Fig. 3.** Valve and sprays panel installed in the gear guard of the mill.

A detailed view of the electro-pneumatic control panel interior is shown in Figure 4. Inside the panel, a filter–regulator–lubricator (FRL) unit conditions the compressed air supply and is regulated at 80 psi to ensure clean and stable air delivery. A secondary pressure regulator, set at 60 psi, controls the operating pressure supplied to the pneumatic pump. The panel also houses two 2/2 solenoid valves that independently control pump actuation and blower air supply to the spray nozzles. Metallic tubing is used for internal pneumatic connections to provide mechanical robustness and resistance to vibration and temperature variations.

**Fig. 4.** The electro-pneumatic panel (inside).

Figure 5 illustrates the interior of the PLC control panel, which contains the programmable logic controller responsible for executing the lubrication sequence, along with protective and auxiliary electrical components. These include a thermo-magnetic circuit breaker, fuse holder, terminal blocks, selector switch, and pilot lights for system status indication. This configuration allows precise control of lubrication timing, reliable signal processing from the progressive valve limit switch, and clear visual feedback for operators during normal operation and fault conditions.

**Fig. 5.** The PLC panel (inside).

## 3.2 Economic details of the implementation

The economic evaluation of the implemented automatic lubrication system was based on actual costs incurred during procurement, installation, and commissioning, using data compiled from the project economic datasheet. This dataset includes expenses related to major system components, minor components and auxiliary accessories, as well as labor associated with on-site installation and integration, providing a realistic estimate of the total investment required for industrial deployment. Major components—including the pneumatic pump assembly, progressive metering valve, spray nozzles, electro-pneumatic elements, and PLC-based control panel—accounted for approximately 45% of the total project cost, while minor components and accessories represented about 30%, and installation and commissioning labor comprised the remaining 25%. The total installed cost of the system was USD 9,220, which represents a relatively small fraction of the overall cost of ball mill open gear drives. This investment is justified by the expected benefits in terms of improved gear protection, reduced maintenance requirements, and minimized risk of unplanned downtime, supporting the economic feasibility of the proposed solution for similar industrial applications.

## 3.3 Performance analysis results

The performance of the proposed automatic lubrication system was evaluated through operational tests and comparative measurements conducted before and after system installation. The analysis focused on the thermal behavior of the open gear drive, the dynamic response of the mill drivetrain, and the effectiveness of lubricant application under controlled conditions.

Thermographic measurements of the pinion gear were per-formed during normal milling operation to assess temperature distribution and thermal balance. Figure 6 presents the thermographic image obtained before installation of the automatic lubrication system, where a temperature difference (ΔT) of approximately 20.0 °C was observed between opposite sides of the pinion. This elevated thermal gradient indicates non-uniform lubrication and localized heat generation at the gear mesh. After system commissioning, the thermographic image shown in Figure 7 reveals a substantially more homogeneous temperature distribution, with the measured ΔT reduced to approximately 6.4 °C, which is within acceptable operating limits for open gear applications. This reduction demonstrates the improved lubricant distribution achieved by the automatic system. Continued monitoring is recommended, as further stabilization is expected due to the periodic lubricant application every 20 minutes, in accordance with the use of high-viscosity asphaltic open gear lubricants.

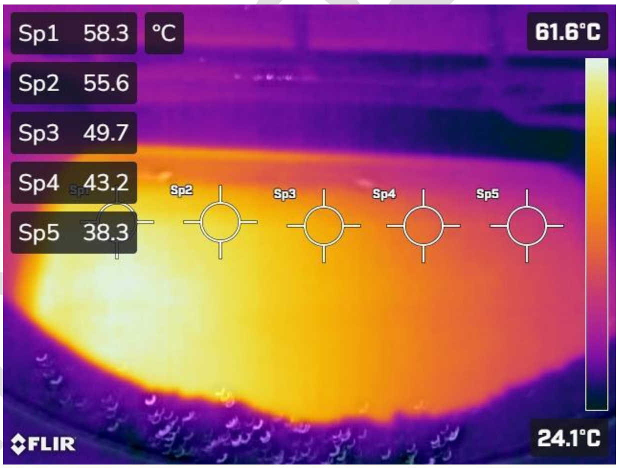


**Fig. 6.** Thermographic image obtained before the installation of the system.

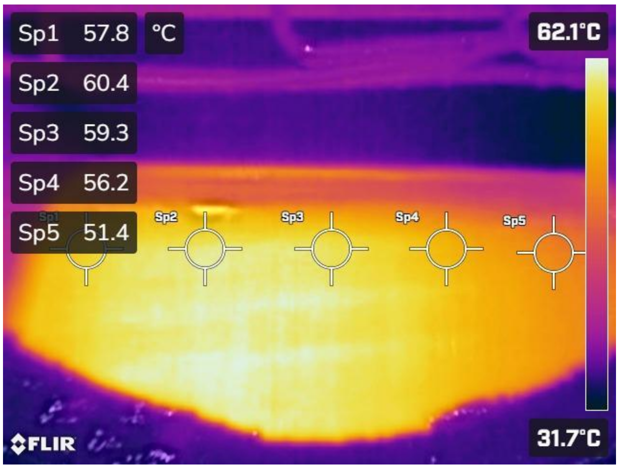


**Fig. 7.** Thermographic image obtained after the installation of the system.

From a tribological perspective, the reduction in temperature gradient suggests a more uniform lubricant film distribution along the tooth flanks and a decrease in localized boundary lubrication conditions. More homogeneous lubrication reduces frictional heat generation at the gear mesh and promotes more stable load sharing between mating teeth. Consequently, the risk of lubricant starvation, adhesive wear, and surface distress mechanisms such as scuffing is expected to decrease, contributing to improved gear reliability and service life.

The improved thermal uniformity observed after system implementation also suggests more favorable tribological conditions at the gear tooth interface. Under open gear operating conditions, inadequate lubrication may promote boundary lubrication regimes, increasing the likelihood of adhesive wear, abrasive wear caused by contaminants, and surface distress phenomena such as scuffing. The more uniform lubricant distribution achieved by the automatic system is expected to improve lubricant film continuity and reduce direct asperity contact between mating surfaces. Although no direct wear measurements or surface inspections were performed in this study, the observed reductions in temperature gradients and vibration levels are consistent with improved lubrication effectiveness and potentially lower wear severity.

The observed reduction in temperature gradient was consistently verified during repeated measurements conducted under comparable operating conditions. The magnitude of the reduction (20.0 °C to 6.4 °C) was substantially greater than the expected variability associated with normal process fluctuations and measurement uncertainty, supporting the repeatability of the observed thermal improvement. According to ANSI/AGMA 6114-A06 guidelines [23] and common industrial practice for open gear drives, temperature differentials below 8 °C are generally considered indicative of satisfactory operating conditions, whereas values above 16 °C may indicate lubrication deficiencies, misalignment, or abnormal load distribution. Therefore, the measured temperature differential of 6.4 °C after system implementation can be considered acceptable for this application.

Vibration measurements were conducted on the counter-shaft bearings of the ball mill at both the drive end and non-drive end, with data collected in the vertical, horizontal, and axial directions. The vibration levels measured before system installation are summarized in Table 4, where values reached up to 12.2 mm/s, indicating elevated mechanical excitation of the drivetrain. After installation of the automatic lubrication system, the vibration levels reported in Table 5 show a marked reduction across all measurement directions, with maximum values reduced to approximately 4.5 mm/s. This decrease in vibration amplitudes reflects improved gear meshing conditions, reduced frictional forces, and enhanced dynamic stability resulting from the consistent and controlled lubrication pro-vided by the proposed system.

**Table 4.** Vibration in mm/s for the drive and non-drive end of the bearings on the countershaft of the ball mill before the installation of the lubrication system.

| Drive End | | | Non-Drive End | | |
|---|---|---|---|---|---|
| V | H | A | V | H | A |
| 8.4 | 9.7 | 12.2 | 7.9 | 9.2 | 9.0 |

**Table 5.** Vibration in mm/s for the drive and non-drive end of the bearings on the countershaft of the ball mill after the installation of the lubrication system.

| Drive End | | | Non-Drive End | | |
|---|---|---|---|---|---|
| V | H | A | V | H | A |
| 4.1 | 3.2 | 2.6 | 2.8 | 4.5 | 3.7 |

The observed vibration reduction may also be associated with improved tribological conditions at the tooth contact interface. More consistent lubricant supply promotes stable film formation and reduces fluctuations in friction forces during meshing. Lower friction variability can reduce dynamic excitation of the transmission system, leading to smoother gear engagement and decreased vibration transmission to the countershaft bearings. These results are consistent with the thermal measurements, which indicate improved lubrication effectiveness after system implementation.

A comparison of the measured values shows that the maximum vibration amplitude decreased from 12.2 mm/s to 4.5 mm/s, corresponding to a reduction of approximately 63%. Similar reductions were observed in the remaining measurement directions at both bearing locations. This improvement indicates a substantial decrease in drivetrain dynamic excitation after the implementation of the automatic lubrication system. The results suggest that more uniform lubricant distribution contributed to smoother gear meshing conditions, reducing friction-induced vibration and improving the overall dynamic behavior of the transmission system.

Similar trends were observed during repeated vibration measurements, with reduced vibration levels consistently recorded after system implementation. The observed reductions were considerably larger than the expected variability associated with normal operating fluctuations of the ball mill, indicating that the improvement was not attributable solely to measurement scatter.
The effectiveness of lubricant application was further verified through a spray pattern test conducted with the mill stopped. A white plastic film was placed on the working face of the gear to visually evaluate lubricant distribution. Figure 8 shows the resulting spray pattern, confirming that all three spray nozzles delivered lubricant uniformly to the active tooth flank without overspray onto the non-working surface. This result validates the correct positioning of the spray nozzles, proper synchronization between lubricant and air delivery, and reliable operation of the progressive metering and control system.

**Fig. 8.** Spray pattern of the lubricant in the gear.

From a tribological standpoint, uniform lubricant coverage of the active tooth flank is essential to ensure continuous replenishment of the lubricant film within the contact zone. Adequate coverage minimizes the occurrence of starved lubrication regions and promotes effective separation between mating surfaces, thereby reducing friction and wear. The observed spray pattern therefore supports the improved thermal and vibration performance obtained after system installation.

A quantitative comparison of lubricant consumption before and after system implementation was not possible because the previous manual lubrication practice relied on operator-dependent lubricant application without systematic consumption records. Future studies could incorporate lubricant consumption monitoring to quantify the economic and operational benefits of automatic lubrication systems.

## 4. CONCLUSION

This study presented the design, implementation, and performance evaluation of an automatic lubrication system for open gears in a ball mill operating under industrial conditions. The system was developed using a structured technical and economic selection methodology and integrated a pneumatic pumping unit, progressive metering valve, spray nozzles, and PLC-based control architecture to ensure reliable and repeat-able lubrication. Operational testing and performance measurements demonstrated that the proposed system significantly improved the thermal and dynamic behavior of the mill drivetrain. Thermographic analysis revealed a substantial reduction in the pinion temperature gradient after system installation, indicating more uniform lubricant distribution and improved load sharing at the gear mesh. Vibration measurements showed a marked decrease in vibration levels at the countershaft bearings, reflecting enhanced meshing stability and reduced mechanical excitation. Spray pattern verification further confirmed accurate lubricant application to the active gear tooth surface. From an economic perspective, the total installed cost of the system represents a modest investment relative to the critical role of open gear drives in ball mill operation. The cost structure, combined with reduced vibration, improved thermal performance, and enhanced lubrication reliability, supports the feasibility of the proposed solution as an effective strategy to mitigate wear, reduce maintenance effort, and lower the risk of unplanned downtime. Overall, the results confirm that a properly designed automatic lubrication system can substantially enhance the operational reliability and performance of open gear drives in ball mills. The proposed approach offers a practical and scalable solution for industrial applications where consistent lubrication and condition control are essential for long-term equipment integrity. A limitation of the present study is that direct gear wear measurements, lubricant condition analysis, and surface characterization were not performed. Future work should incorporate these techniques to further quantify the tribological benefits of the proposed lubrication system.

## REFERENCES


[1] G. Ngandu Kalala, X. Chiementin, L. Rasolofondraibe, A. Boujelben, and B. Kilundu, "Modeling Impulsive Ball Mill Forces Effects on the Dynamic Behavior of a Single-Stage Gearbox," *Machines*, vol. 10, no. 4, p. 226, Mar. 2022, doi: 10.3390/machines10040226.

[2] A. Suresh, K. V. V. Sai Kalyan, K. S. Sibin Kumar, K. Vinod Kumar, V. Tanishka Varma, and B. Sravan Kumar, "Design and simulation of gear box for stone crushing ball mill," *Materials Today: Proceedings*, vol. 64, pp. 239–245, 2022, doi: 10.1016/j.matpr.2022.04.456.

[3] D. K. Pandey and H.-C. Lim, "Pinion Failure Analysis of a Helical Reduction Gearbox in a Kraft Process," *Applied Sciences*, vol. 10, no. 8, p. 2935, Apr. 2020, doi: 10.3390/app10082935.

[4] G. Saracoglu and A. Yapici, "Fatigue analysis of girth gear of a rotary dryer," *Engineering Failure Analysis*, vol. 68, pp. 187–196, Oct. 2016, doi: 10.1016/j.engfailanal.2016.05.024.

[5] H. Liu, H. Liu, C. Zhu, and R. G. Parker, "Effects of lubrication on gear performance: A review," *Mechanism and Machine Theory*, vol. 145, p. 103701, Mar. 2020, doi: 10.1016/j.mechmachtheory.2019.103701.

[6] P. L. de Vaal, "Open-gear lubrication: Meeting industrial requirements using laboratory techniques," *Tribotest*, vol. 5, no. 1, pp. 79–91, Sep. 1998, doi: 10.1002/tt.3020050108.

[7] J. Pei, Y. Tian, H. Hou, Y. Tao, M. Wu, and L. Wang, "Lubrication Reliability and Evolution Laws of Gear Transmission Considering Uncertainty Parameters," *Lubricants*, vol. 13, no. 9, p. 392, Sep. 2025, doi: 10.3390/lubricants13090392.

[8] H. Liu, C. Zhu, Z. Sun, and C. Song, "Starved lubrication of a spur gear pair," *Tribology International*, vol. 94, pp. 52–60, Feb. 2016, doi: 10.1016/j.triboint.2015.07.030.

[9] L. Braumann, V. S. de Viteri, B. Morhard, T. Lohner, J. Ochoa, and H. Amri, "Tribology technologies for gears in loss of lubrication conditions: a review," *Journal of Materials Science: Materials in Engineering*., vol. 20, no. 1, Feb. 2025, doi: 10.1186/s40712-024-00204-5.

[10] D. Croccolo, M. De Agostinis, G. Olmi, and N. Vincenzi, "A Practical Approach to Gear Design and Lubrication: A Review," *Lubricants*, vol. 8, no. 9, p. 84, Aug. 2020, doi: 10.3390/lubricants8090084.

[11] B. Morhard, T. Lohner, and K. Stahl, "Influence of surface and material technologies on the loss of lubrication performance of gears," *Journal of Materials Science: Materials in Engineering*, vol. 19, no. 1, Jun. 2024, doi: 10.1186/s40712-024-00143-1.

[12] M. H. Farhat, L. Gelman, G. Conaghan, W. Kluis, and A. Ball, "Novel Diagnosis Technologies for a Lack of Oil Lubrication in Gearmotor Systems, Based on Motor Current Signature Analysis," *Sensors*, vol. 22, no. 23, p. 9507, Dec. 2022, doi: 10.3390/s22239507.

[13] H. Peng, Y. Chen, L. Shangguan, R. Cheng, Y. Li, and C. Yang, "Multi-Objective-Based Intelligent Lubrication System Performance Evaluation Technology for Construction Machinery," *Applied Sciences*, vol. 13, no. 21, p. 11768, Oct. 2023, doi: 10.3390/app132111768.

[14] M. Piechowski, R. Wyczółkowski, W. Paszkowski, and A. Meller, "Improving the efficiency of greasing operations with the lubrication management support system - a case study," *IFAC-PapersOnLine*, vol. 58, no. 8, pp. 228–233, 2024, doi: 10.1016/j.ifacol.2024.08.125.

[15] T. Sardhara and K. Tamboli, "Design and Development of Automatic Lubrication system for ATC of CNC," *Materials Today: Proceedings*, vol. 5, no. 2, pp. 3959–3964, 2018, doi: 10.1016/j.matpr.2017.11.653.

[16] S. H. Lee, M. H. Kim, S. Lee, and K. C. Lee, "Automatic Lubrication System for Minimizing Friction of Driving Parts for Large-Sized Commercial Vehicle," *Advanced Materials Research*, vol. 909, pp. 198–203, Mar. 2014, doi: 10.4028/www.scientific.net/amr.909.198.

[17] S. Yildiz, M. Apakhan, and M. H. Aksoy, "Cost-Effectiveness of an Automatic Lubrication System for Bearings," *Lecture Notes in Networks and Systems*. Springer Nature Switzerland, pp. 199–209, 2024. doi: 10.1007/978-3-031-51494-4_18.

[18] M. Sparham, A. A. D. Sarhan, N. A. Mardi, and M. Hamdi, “Designing and manufacturing an automated lubrication control system in CNC machine tool guideways for more precise machining and less oil consumption,” *International Journal of Advanced Manufacturing Technology*, vol. 70, no. 5–8, pp. 1081–1090, Oct. 2013, doi: 10.1007/s00170-013-5325-y.

[19] VDI 2225 Blatt 2:1998-07, Design engineering methodics - Tables for engineering design at optimum cost, 1998

[20] T. G. V. Llave, L. A. L. Huaman, B. P. R. Torres, J. C. Rodríguez, and Y. L. S. Vidal, “Conceptual Design of a Trash Collecting Machine for Highways in Arequipa, Peru,” *International Journal of Mechanical Engineering and Robotics Research*, vol. 13, no. 4, pp. 477–488, 2024, doi: 10.18178/ijmerr.13.4.477-488.

[21] C. A. Castillo Roque, W. C. Yupanqui Leon, T. G. Vasquez Llave, J. C. Canazas Rodriguez, Y. L. Silva Vidal, and J. F. Garate Delgado, “Ergonomic optimization of a manual wheeled furrowing implement (IMRS) using user-centered design methodologies: a case study in Peruvian smallholder agriculture,” *Eastern-European Journal of Enterprise Technologies*, vol. 2, no. 1 (140), pp. 42–56, Apr. 2026, doi: 10.15587/1729-4061.2026.352159.

[22] ANSI/AGMA 9005-E02, American National Standard – Industrial Gear Lubrication, 2003.

[23] ANSI/AGMA 6114-A06, American National Standard – Gear Power Rating for Cylindrical Shell and Trunnion Supported Equipment , 2006.