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Designing SAG Mill Liners for Improving Performance and Life Time at the Sarcheshmeh Copper Complex

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Abstract

The structural characteristics of mill liners, such as lifter shape and mill speed, significantly influence the grinding process. At the Sarcheshmeh slag flotation plant, the 6×6 meters SAG mill was initially equipped with 48 rows of liners, designed in a Hi-Lo configuration for the first half and a Lo-Lo configuration for the second. Throughout the mill shell liner's 1700-hour operational period, monitoring identified 30 failures. Investigations revealed that defects in the liner design and improper charge motion were the main causes. This study proposes modifications and standardization of the shell liner design, tailored to the specific circuit conditions, to enhance performance and reliability. The redesign included several key changes: 1) Reducing the number of rows: The number of liner rows was decreased from 48 to 32. 2) Adjusting lifter angle: The lifter angle was increased from 23 to 30o to optimize performance. 3) Eliminating Hi-Lo design liners: The Hi-Lo design liners were changed to Hi-Hi, and 4) Reducing liner variety: The variety of liners was streamlined from 5 types to 2. The installation of the proposed liners optimized the charge trajectory for grinding, resulting in higher liner's lifetime. It extended the liner life by 30% and eliminated liner failures, reducing them from 30 to zero. The wear rate for the proposed design was 0.05 mm/hour, while the original design had a wear rate of 0.11 mm/hour. This difference corresponds to a factor of 2.3 times improvement.

1. Introduction

Comminution circuits within mineral processing circuits are the largest energy consuming section (up to 70%), and often account for a large component of the capital and operating costs associated with mineral production [1, 2]. The use of mills for grinding is a major contributor to the inefficient use of energy. This is because the nature of the particle breakage process is unconstrained and random [3, 4]. The inefficient nature of the comminution process coupled with ore reserves of declining head grade suggests that the long-term viability of the mineral processing industry depends on improvement of the efficiency of this process [5-7]. This could facilitate higher throughput rates at lower capital and operating costs. To address this issue, a vast number of research work aimed at studying various aspects of grinding with the objective of performance improvement [8-14]. Over the years, the primary functions of mill liners have remained consistent: protecting the mill shell, transferring energy to the charge, retaining grinding media, classifying products, and transporting material from the mill [15-18]. The mill liner profile is recognized for its potential to be optimized, enhancing mill throughput and extending liner longevity. Various studies have investigated the impact of mill shell liners on mill performance, highlighting their significant influence on operational efficiency [19-24]

In comminution processes, mills experience significant wear on their working surfaces due to

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the intense impacts and high shear forces required to break down particles. As the liners wear, the surfaces that come into contact with the particles often alter in shape. This can lead to modifications in the charge trajectory, variations in charge pressure, fluctuations in energy consumption, and, ultimately, changes in the mill's operational performance. The efficiency of a comminution device can vary greatly over the lifespan of its liners [25, 26]. The capability to adjust liner designs is highly advantageous for enhancing mill efficiencies, optimizing throughput, prolonging liner life, and reducing the duration required to exchange worn liners during maintenance. This flexibility not only improves operational performance but also contributes to cost-effectiveness and productivity in milling operations [27, 28].

Autogenous (AG) and semi-autogenous grinding (SAG) mills in concentration plants form a critical part in the process chain. The availability of these mills plays an important role in the economics of the operation [29-33]. The design of liners and lifter profiles significantly affects the movement of particles in AG and SAG mills, which in turn impacts the grinding process and the mills' power draw. However, optimizing liner profiles for durability often conflicts with the goal of enhancing the mill's grinding efficiency. This trade-off between extending liner life and maximizing the grinding rate is a key consideration in mill design [34-36]. Achieving a balance between liner lifetime and grinding efficiency is crucial. Toor et al. [37] demonstrated the advantages of shorter liner life cycles in enhancing performance. They calculated the increase in throughput and the decrease in power draw using historical data from a 32-foot operational mill, highlighting the potential improvements in mill operation. Yahyaei et al. [38] extended the method proposed to design liners for performance through investigating the effect of relining efficiency using such an approach in an industrial case.

Hi-Low lifters were an early innovation aimed at mitigating the effects of packing by alternating high lifter bars with lower ones. In conventional Hi-Low liner systems, worn "Low" lifters in alternate rows are replaced with new "Hi" lifters. This approach tends to be effective in smaller mills, under 24 feet, where packing levels can be managed effectively. However, in larger mills, particularly those subject to high impact, traditional Hi-Low systems often fail due to the difficulty in preventing the breakage of extensively worn lifters. Additionally, Hi-Low lifters present maintenance challenges, as precise timing of relining is essential to maintain the Hi-Low configuration. Consequently, many mills have transitioned to "Hi-Hi" shell lifter systems to circumvent the issue of liner breakage [23, 39-41]. Maleki Moghaddam et al. implemented a change in the SAG mill liners from a Hi-Low to a Hi-Hi configuration at the Sarcheshmeh Copper Complex. This modification led to significant improvements: the incidence of broken liners over the lifespan of the liners dropped from six to zero, the time required to replace a single liner was reduced from 21 to 16 minutes, and the mill's feed rate increased from 750 to 850 t/h [5].

Mishra and Rajamani pioneered the simulation of laboratory ball mill charge motion in two dimensions, marking the first reported use of the Discrete Element Method (DEM) in the field of mineral processing [42]. With the dawn of the 21st century, significant advancements in computing efficiency enabled other researchers to employ DEM, either solely or in combination with other methods, to simulate granular systems across various case studies [36, 43-45]. Kluge et al. introduced a groundbreaking framework designed to optimize operations of semi-autogenous grinding mills. This was achieved by evaluating liner stresses through the Impact Finder system, alongside simulations using both the discrete element method and the finite element method [46]. Panjipour and Barani studied the effect of ball size distribution on the mill power draw, charge motion regime and breakage mechanism in a laboratory ball mill using the discrete element method (DEM) simulation. They concluded that the effect of ball size distribution increased with increasing mill filling and for the mill filling of 35%, the ball size distribution had the maximum effect on the power draw [47]. The milling operation of pilot-scale SAG mills using the discrete element method (DEM) was investigated by Kolahi and Jahani Chegeni. Their results indicate that the optimum number of lifters for pilot-scale SAG mills was between 16 and 32 lifters with medium thicknessand liners with the number of lifters in this range requiring less mill speed to create cataract motions [48].

2. Grinding Circuit of The Slag Flotation Plant at The Sarcheshmeh Copper Complex

The Sarcheshmeh copper complex, situated in southeast Iran, is a significant producer of copper and molybdenum. Copper slag, a by-product of the smelting process, is formed when impurities separate from the molten metal and float to the surface. This slag has a solid density of 4 t/m^3 and is highly abrasive, making it suitable primarily for surface blast-cleaning applications. A notable component of copper slag is magnetite, constituting over 40% of its composition, with a copper (Cu) content ranging between 0.8% and 1.5%. Additionally, the Bond ball mill work index for the slag was measured at 21 kWh/t, indicating its grinding resistance. The slag flotation plant's SAG mill, measuring 6×6 meters, receives its feed from a jaw crusher, which reduces material to a top size of 20 cm for grinding to below 30 mm. This SAG mill is powered by a single 3600 kW synchronous motor with a Fixed-Frequency Drive, operating unidirectionally as depicted in Figure 1. Key specifications of this mill are detailed in Table 1. The mill's discharge passes through a vibrating screen to separate oversize material, recirculated back to the SAG mill. Meanwhile, the undersize material merges with discharges from two series ball mills, each measuring 5.03 × 8.3 meters and also powered by 3600 kW motors, before being directed to the cyclones. The designed processing capacity of the circuit is 166.6 t/h of fresh feed, with a total throughput of 200 t/h when including both fresh and recycled materials.

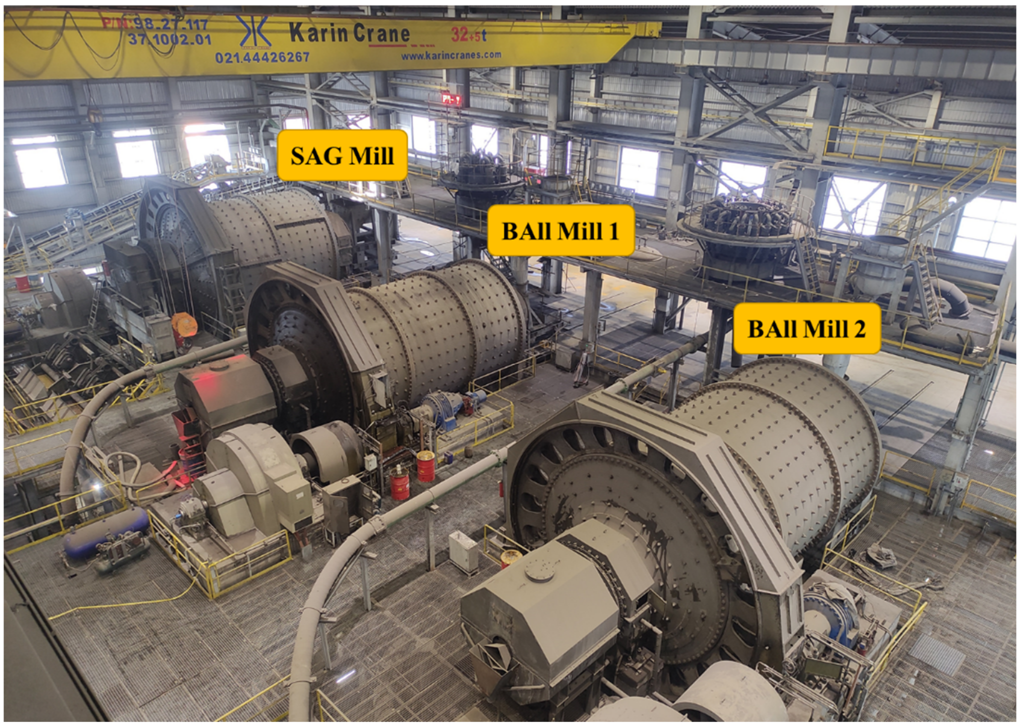

Figure 1. Grinding circuit of the slag flotation plant at the Sarcheshmeh copper complex

Table 1. Some major characteristics of the slag flotation SAG mill

Diameter (m)	Length (m)	Motor power (kW)	Mill filling (%)	Ball size (mm)	Ball filling (%)	Feed size (mm)	Product size (mm)	rpm
6	6	3600	35	125	15	-200	-20	13.3

The SAG mill's shell liners are categorized into four distinct sections, as depicted in Figure 2. The first half of the mill is equipped with 48 rows of Hi-Low type liners, featuring heights of 17 and 23 cm and a lifter face angle of 23 degrees. Conversely, the second half utilizes Low-Low type liners, all standing at 17 cm with the same lifter face angle. The liners, made from chrome-molybdenum steel casting, exhibit a Brinell hardness between 325 and 375. Despite their robustness, the replacement of both High and Low type liners has been fraught with challenges, including breakage and cold welding issues, making the process extremely laborious and time-consuming (as shown in Figure 3). For example, replacing a single liner affected by cold welding can take up to 24 hours. To enhance the efficiency of the liner design and prolong their service life while maintaining the required grind size, a comprehensive 3D scan of the current liners, along with a simulation of the charge trajectory, was performed.

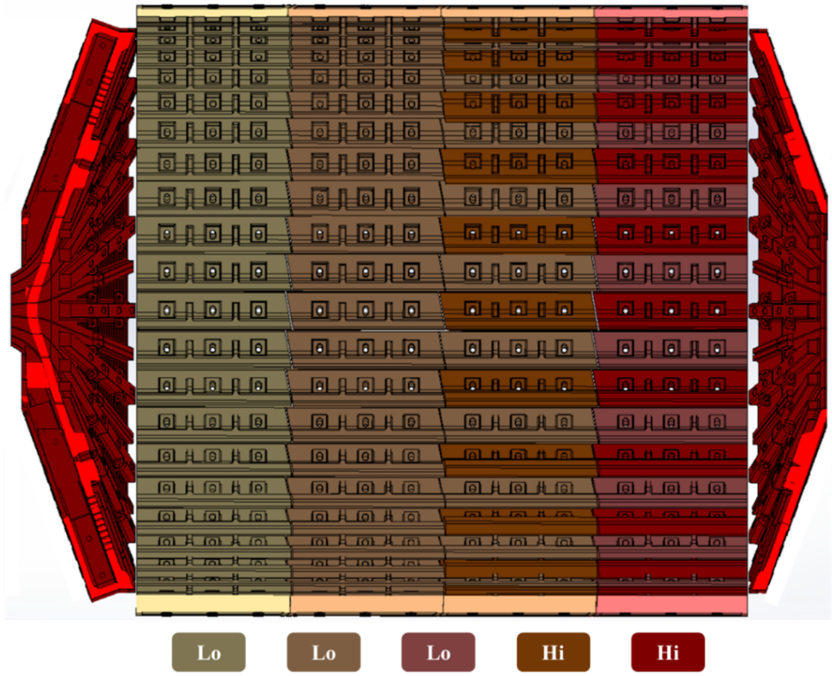

Figure 2. The interior mill liners of the SAG mill at the slag flotation plant

Figure 1. Broken liners in the SAG mill

3. Methodology

Liner design has become an increasingly important tool for optimizing AG/SAG mill performance. The integration of simulation with 3D scanning and modeling offers a unique opportunity to gain comprehensive knowledge during the development of new liner designs. Monitoring the status of current liners and the proposed plan is coducted using the Sence Pro 3D scanner, connected to the Latitude 12 Rugged handheld computer. The parameters of interest are examined and compared. The mentioned equipment and a view of the scanning process inside the mill are shown in Figure 4. To use the 3D scanner inside the mill, preparations such as ensuring suitable environmental conditions within the mill, like lighting and temperature, establishing a connection between the scanner device and the handheld computer with related software, and maintaining an appropriate distance for scanning the targeted piece are necessary.

Figure 4. Scanning using the Sence Pro scanner connected to the Latitude 12 Rugged handheld computer.

To accomplish this procedure, the liner profile is meticulously analyzed with SolidWorks© (2016 version) software (refer to Figure 5). This data is then utilized to engineer liners that not only last longer but also maintain the optimal charge trajectory. The performance of each liner design is carefully monitored by tracking the mill's throughput and liner wear, providing valuable insights into the impact of the liner design on the mill's grinding efficiency.

In this study, the development of a novel liner began with both analytical and numerical simulations to predict the charge trajectory. Subsequently, the liner's geometry is modified to achieve the optimal trajectory. The project introduced the Hi-Hi liner design, implemented with the aim of ensuring the correct charge trajectory. This design also aims to reduce liner breakage, minimize cold welding occurrences, and extend the overall lifespan of the liner.

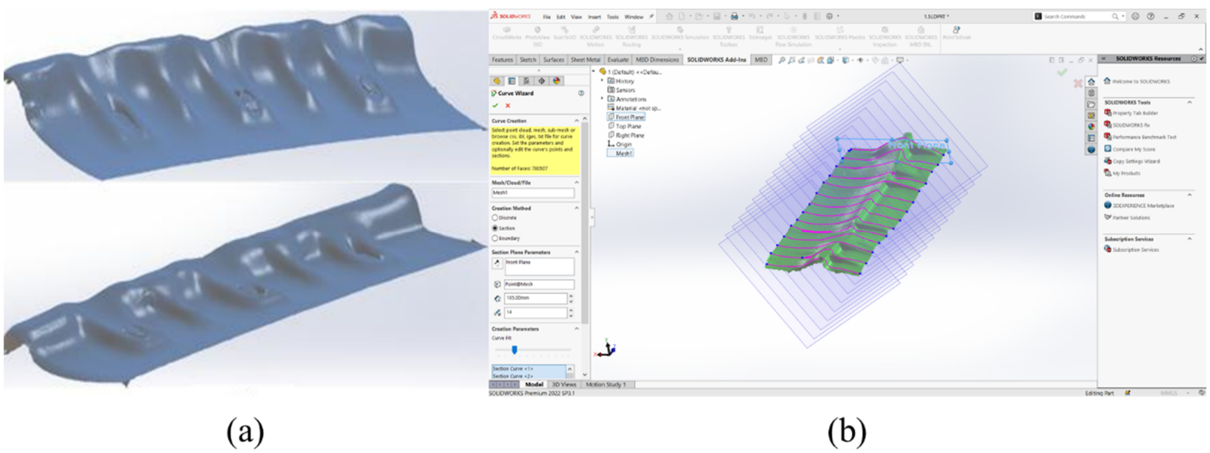

Figure 5. The liner profile scanned using 3D method (a) and the profile measured with SolidWorks software (b)

4. Charge motion simulation by discrete element method (DEM)

DEM modeling serves as a potent instrument for the comparative analysis of various mill liner designs and has become a staple in liner design methodology in recent years. This study employed three-dimensional DEM simulations via Altair © software, maintaining consistent operating conditions to evaluate the performance of both old and new liner designs by predicting the charge shape and impact points. The software's data entry process is divided into three primary sections: the first involves importing geometries designed in SolidWorks; the second requires defining the physical properties and velocities of these geometries, if applicable; and the third entails specifying the entry and exit points for particles. Additionally, this section is where users input particle characteristics, including size distribution and physical properties like density, elasticity modulus, and Poisson's ratio, as well as the equipment's throughput. The ball size distribution and the specific parameters applied in the DEM simulations for this research are detailed in Tables 2 and 3.

Table 2. Ball size distribution used for the DEM simulations.

Ball size (mm)	120	110	100	90	80	70	60
Distribution (%)	29	9	26	7	14	7	6

Table 3. Some major parameters used for the DEM simulations.

Number of balls per mill length unit	300,000
Ball density (kg/m^3)	7800
Ball sliding friction coefficient	0.25
Ball rolling friction coefficient	0.01
Ball elasticity modulus (MPa)	20
Poisons ratio	0.25
Ball restitution coefficient	0.3
Contact force model	Liner spring-dashpot

5. Results and discussion

5.1. Charge trajectory prediction

The Hi-Low and Low-Low liner types are crucial in influencing charge motion, and their simulation results are examined here in detail. Three-dimensional DEM simulations were conducted under identical operating conditions to assess the charge shape and impact points of both the original and modified liner designs using Altair software. The SAG mill and liner details were modeled in SolidWorks and then imported into Altair© software for simulation. Figure 6 illustrates the DEM simulation outcomes for the original Hi-Low and Low-Low liners. The significant gap between the toe angle and ball impact points (25 degrees) indicates that the original liner design might cause direct ball-to-liner contact, risking substantial damage. This could also explain the mill's low throughput and the coarse particle size of the output, likely due to an unsuitable trajectory where the charge toe fails to receive substantial direct impacts. Measurements were taken in degrees from the horizontal axis passing through the mill's center (the 3 o'clock position), proceeding counterclockwise.

A review of larger SAG mills that had changed to wider-spaced shell lifters and large face angles showed, in most cases, the changes were driven principally by (a) packing between lifters or (b) damage to liners and balls. As covered above, wider lifter spacing can eliminate packing and larger face angles can reduce damaging ball-on mill impacts. With the alleviation of these immediate issues, mill performance improved [51]. Therefore, modifications were made to the original liner design to improve the charge trajectory, including altering the height, release angle, and profile. The lifter face angle was increased from 23 degrees to 30 degrees to better direct the trajectory. The lifter height was also changed from 17 cm and 23 cm in the Hi-Low design to a uniform 22.5 cm in the Hi-Hi design. Additionally, the number of liner rows was reduced from 48 to 32, and the total liner count was cut from 192 to 128, aiming to enhance mill performance and reduce the risk of damage from ball impacts.

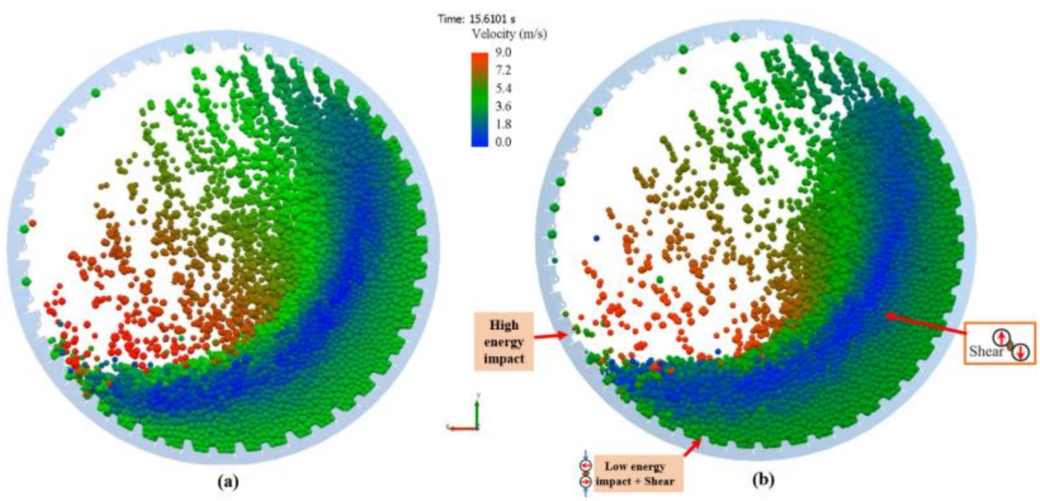

Figure 6. The typical images taken from the DEM simulations of (a) the Hi-Low and (b) Low-Low original liners in the model mill (25% filling, 75% of critical speed).

Figure 7 illustrates typical DEM simulations under identical operating conditions, specifically a 25% mill filling and a rotational speed at 75% of the critical value. The charge dynamics for both the original and the modified liner designs are visualized through a color gradient that indicates particle velocity, transitioning from blue for lower speeds to red for higher speeds. The original liner design presents a concern, as the proximity of the toe angle to the ball impact points suggests a risk of direct impacts on the liners at reduced mill fillings, potentially causing significant damage. Conversely, the modified design featuring Hi-Hi liners demonstrates a more confined cataracting region within the charge, which effectively channels impacts towards the toe region. This is further corroborated by the reduced distance between the impact points and the toe angle, now within a 10-15 degree range, when employing the proposed liners. The DEM simulations support the conclusion that the adoption of Hi-Hi liners over Hi-Low liners can lead to a more desirable charge trajectory.

The simulation results revealed that with the new liner design, an increase of 7 degrees in the lifter release angle is feasible. Details of the modified index parameters are shown in Table 4. Consequently, it became safe and practical to increase the ball filling and incorporate larger steel balls (125 mm). Encouraged by these promising outcomes, the new liners featuring a 30° lifter face angle and a lifter height of 22.5 cm were fabricated and installed in the SAG mill, as depicted in Figure 8. Additionally, Figure 9 provides a visual representation of the proposed liner layout designed in SolidWorks software, alongside the actual liners fitted in the mill.

The wear monitoring of the liners was conducted utilizing a 3D scanner, noted for its high precision, over the entire lifespan of the liner shell. An illustration of this design, following a duration of 500 hours within the mill, is depicted in Figure 10.

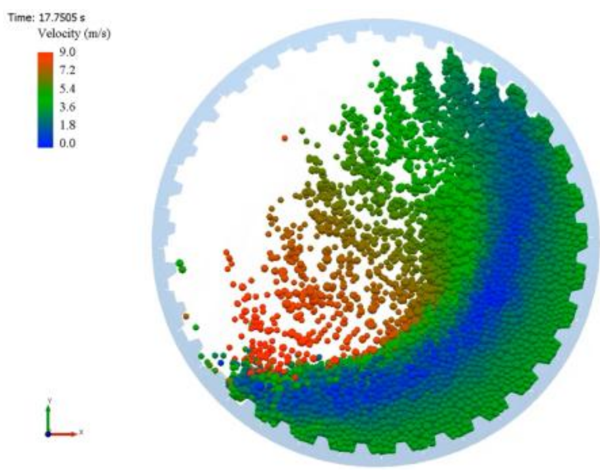

Figure 7. The typical images taken from the DEM simulations of the Hi-Hi proposed liners in the model mill (25% filling, 75% of critical speed).

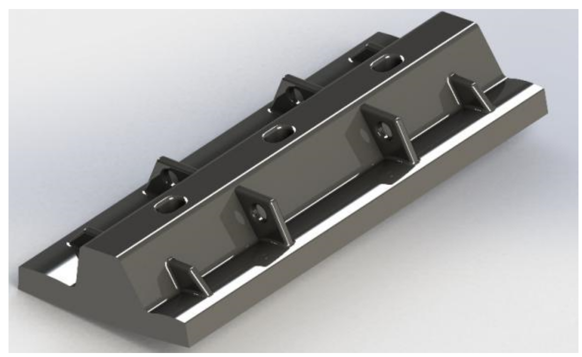

Figure 8. A snapshpt of the new liner

(a) (b)

Figure 9. The layout of the proposed liners in SolidWorks software (a) and installed liners in the SAG mill (b).

Figure 10. A view of the new liners after 500 hours of operation

After 500 hours of operation, the new liners have demonstrated remarkable performance and durability. Their innovative design has withstood the rigorous demands of continuous use, maintaining structural integrity and functional properties. This endurance is a testament to the advanced engineering and design principles applied during their development. The liners' resilience under such conditions suggests they will serve well beyond the standard operational timeframe, providing reliability and efficiency.

To evaluate the effects of the new liner design, the number of broken shell liners and some specific index of the SAG mill for a period of liner life before and after liner change were compared. The ability to increase throughput was prepared after the new liner's installation. The circulating charge decreased from 15 to 5 t/h. With the new liners, the number of broken liners over their lifespan was reduced from 30 to 0 pieces, and the total changing time for broken liners decreased from 50 to 0 hours. The lifetime of the liners increased from 1700 to 2200 hours. The total changing time for liners decreased from 190 to 120 hours, and no cold welding of shell liners was observed. A summary of the results obtained from this change is listed in Table 4. These significant results can be attributed to the change in the charge trajectory, which led to improved grinding efficiency. Due to the better charge trajectory, broken balls also decreased significantly, reducing grinding media consumption from 2 to 1.8 kg/t.

Table 4. Key Aspects Before and After Liner Design Modification

	The original liners	The new liners
Total configuration design	Hi-Low and Hi-Hi	Hi-Hi
Lifter face angle (°)	23	30
Lifter height (cm)	17 and 23	22.5
Number of liner rows	48	32
Total liner count	192	128
Broken liners	30	0
Broken liners replacement time (h)	50	0
Wear rate (mm/h)	0.11	0.05
Long life	1700	2200
Rows	48	32
Liners number	192	128
Liners replacement time	190	120

6. Conclusions

- The initial design's short lifetime and high failure rate were attributed to a non-standard charge path, which directly impacted the liners due to excessive rows and inappropriate lifting angles.
- The redesign addressed these issues by reducing the liner rows from 48 to 32, optimizing the lifting angle, standardizing the liner design to a uniform Hi-Hi configuration, and simplifying the liner variety from five to two types.
- The implementation of new liners has led to remarkable improvements in their performance and longevity. The incidence of liner breakage

has been completely eliminated, dropping from 30 instances to none, which has also reduced the total replacement time from 50 hours to zero.

- The lifetime of liners has seen a substantial increase, extending from 1700 to 2200 hours. The overall time spent changing liners has been reduced from 190 to 120 hours. Additionally, the issue of cold welding in shell liners was not observed post-implementation.
- The significant enhancements observed can be largely ascribed to the altered charge trajectory, which has resulted in increased grinding efficiency. This improved trajectory has also led to a considerable reduction in broken balls, further contributing to a decrease in grinding media consumption from 2 kg/t to 1.8 kg/t.

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طراحی آسترهای آسیای نیمه خودشکن برای بهبود کارایی و طول عمر در مجتمع مس سرچشمه

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چکیده

ویژگی های ساختاری آستر آسیا، مانند شکل بالابر و سرعت آسیا، به طور قابل توجهی بر فرآیند آسیا تأثیر می گذارد. در کارخانه فلوتاسیون سرباره مجتمع مس سرچشمه، از آسیای نیمه خودشکن ۶×۶ متری استفاده می شود که در ابتدا دارای ۴۸ ردیف آستر بود که در طرح آن در نیمه اول به صورت کوتاه-بلند و برای نیمه دوم به صورت کوتاه-کوتاه درنظر گرفته شده بود. در طول دوره عملیاتی ۱۷۰۰ ساعتی آسترهای بدنه آسیا، تعداد ۳۰ شکست آستر اتفاق افتاد. بررسی ها نشان داد که نقص در طراحی آستر و حرکت نامناسب بار عامل اصلی بوده است. این مطالعه اصلاحات و استانداردسازی طراحی آستر بدنه را، متناسب با شرایط مدار، برای افزایش کارایی و قابلیت اطمینان پیشنهاد کرد. طراحی مجدد شامل چندین تغییر کلیدی بود: ۱) کاهش تعداد ردیف ها: تعداد ردیف های آستر از ۴۸ به ۳۲ کاهش یافت. ۲) تنظیم زاویه بالابر: برای بهینه سازی عملکرد، زاویه بالابر از ۲۳ به ۳۰ درجه افزایش یافت. ۳) حذف آسترهای طراحی کوتاه-بلند: آسترهای طرح کوتاه-بلند به بلند-بلند تغییر یافتند، و ۴) کاهش تنوع آستر: تنوع آسترها از ۵ نوع به ۲ نوع ساده شد. نصب آسترهای پیشنهادی مسیر حرکت بار را بهینه کرد که منجر به طول عمر بالاتر آسترها شد. عمر آستر را ۳۰ درصد افزایش داد و شکست آستر را از بین برد و تعداد شکست را از ۳۰ به صفر کاهش داد. نرخ سایش برای طرح پیشنهادی ۰/۰۵میلی‌متر در ساعت بود، در حالی که طرح اولیه دارای نرخ سایش ۰/۱۱ میلی‌متر در ساعت بود و بهبود ۲/۳ برابری را نشان داد.

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