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Changing sag mill liners type from Hi-Low to Hi-Hi at Sarcheshmeh copper complex based on physical and numerical modeling

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Abstract

Liner design has become an increasingly more important tool for the AG/SAG mill performance optimization. The Sarcheshmeh copper complex concentration plant uses a SAG mill lined with 48 rows of Hi-Low type liners. Because of breakage of Low type liners and cold welding, the liner replacement task of Low with new Hi type liners has become very difficult and time-consuming. With the objective of finding a new design for liners, numerical (3D DEM; discrete element method) simulation and physical modelling in a laboratory mill were used. It was found that changing the liner type from Hi-Low to Hi-Hi could provide an appropriate charge trajectory. The new Hi-Hi type shell liners were designed, manufactured, and installed. With the new liners, the number of broken liners over liner life reduced from 6 to 0 piece, the total changing time for one liner decreased from 21 to 16 minutes, and no cold welding of shell liners was observed. Comparison of the feed rate before and after installation of the new liners for a period of liner life showed an increase from 750 to 850 t/h, which was indicative of a higher flexibility of the mill in encountering ore hardness variations.

1. Introduction

The use of large AG (autogenous)/SAG (semi-autogenous) mills in mineral processing plants has been on rise due to a significant reduction in capital, operating costs, and increase in the plant throughputs [1]. The internal AG/SAG mill surfaces are covered with steel or rubber liners, which have two essential functions. The first is to protect the structural outer shell from the aggressive environment inside the mill. The aggressive environment required for size reduction also causes the shell liners to wear, and subsequently, the need for them to be periodically replaced by new liners. The second is to impart rotary motion to the charge. The structural characteristics of liners, lifter shape, and mill speed substantially influence particle motion in tumbling mills and dramatically influence the grinding process and power draw of these mills. These functions of the liners tend to conflict, as designing the liner profiles to maximize liner life inevitably reduces the grinding rate in the mill [2, 3]. It is, therefore, necessary to develop a balance between the liner life time and the grinding performance. Toor et al. (2013) quantified the benefit of having shorter liner life cycles for an improved performance by calculating the increase in the throughput and reduction in the power draw based on the historical data for an operational 32 foot mill [4]. Yahyaei et al. (2015) extended the method proposed by Toor et al. (2013) to design liners for performance through investigating the effect of relining efficiency using such an approach in an industrial case [3]. The charge motion is strongly influenced by the liner design and the subsequent liner profile changes due to the wear of the liners, while the charge motion influences the energy environment within the mill and the grinding rates within the mill [3-7].

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The availability of SAG mills plays an important role in the economics of the operation. One of the main reasons for mills down time is the time required to change the worn or broken liners [1]. It has been observed that downtime of mills for the replacement of worn liners with new liners is the main reason for loss of production. The liner profile will change over its life due to the aggressive environment inside the mill, which, in turn, affects the charge trajectory resulting in the mill throughput and grinding performance variations. Usually by monitoring the wear profile over few liner lives and identifying the areas of high and low wear, the design of liner is accordingly adjusted to provide a uniform profile at the end of the liner life, while maintaining the charge trajectory within the desirable regime [8-12].

Hi-Low lifters were an early attempt to reduce the effects of packing by replacing every second-high lifter with a low lifter bar. In traditional Hi-Low liner systems, alternate rows of worn “Low” lifters are replaced with new “Hi”. This system appears to work well in some smaller mills (below 24 ft), especially where packing can be controlled to the level of the “Low” lifters. Traditional Hi-Low systems, especially in high impact environments, fail in larger mills, where it is difficult to avoid breakage of highly worn lifters. Hi-Low lifters are also problematic from a maintenance perspective as the timing of the reline is crucial to ensure that the Hi-Low arrangement is retained. Usually such mills have been forced into “Hi-Hi” shell lifter systems to avoid liner breakage [13, 14].

It has been well-established that a change in the lifter face angle on SAG mill shell lifters results in a change in the motion of the charge. With the development of trajectory-generating computer programs, the effects of operational conditions, face angle, packing, and lifter height have been incorporated in the shell lifter design. Increasing the shell liner face angles does reduce the impact point of thrown balls, and can reduce shell liner damage [5, 6, 15, 16].

In the recent years, DEM (Discrete Element Method) has been used successfully for modelling and analyzing the internal dynamics of grinding mill motion. With this computational technique, the motion and interactions of individual bodies are calculated using a set of equations referred to as the Newton's laws and the contact model. DEM helps understand charge motion in SAG mills for the given liner designs and lifters, ball size and rock properties, and mill operating conditions. Based on the success of the 2-D model of the SAG mill, the 3-D model in DEM was developed. These types of models could help study charge motion, power draw, liners wear, and energy draft more accurately [5, 7, 11, 12, 17-22].

The charge trajectory is the main concern in liner designing issues because the direct impact of balls to the shell liners could result in liner damage and breakage. The charge trajectory can be optimized by the modification of the liner design [6]. Yahyaei and Banisi (2010) designed a spreadsheet-based software (GMT; Grinding Media Trajectory) to model charge trajectory in tumbling mills [16]. Charge shape and charge motion, predicted by the GMT program, was based only on a single ball trajectory. Maleki-Moghaddam et al. (2013) proposed new relationships to modify the GMT results to take into consideration the effect of charge. By applying the corrections to the charge shape and motion, the GMT software outputs became more realistic [23].

2. Sarcheshmeh copper complex SAG mill

This work was carried out at the Sarcheshmeh copper complex located in SE Iran. At the new concentration plant of the Sarcheshmeh copper complex, which comprises two parallel phases, two (9.75 × 4.87 and 9.15 × 4.87 m) SAG mills are used to grind a feed all under 17.5 cm that is the product of a gyratory crusher. The discharge of the SAG mill is transferred onto a vibrating screen. The oversize material is crushed in a pebble crusher, and the undersize is combined with the ball mill (6.71 × 9.91 m) discharge and sent to the cyclones. The SAG mill in phase 1 uses two 4100 kW synchronous motors and works with a constant 10.5 rpm rotational speed in two directions, and SAG mill of phase 2 uses two 3700 kW synchronous motors and works with variable speed in two directions. Since this research work was carried out with the objective of changing shell liners of the SAG mill of phase 2, some important characteristics of this mill are summarized in Table 1.

The mill shell is lined with 48 rows of Hi-Low type liners with 10 and 20 cm height and a lifter face angle of 22 degrees. The mill liners are of a chrome–molybdenum steel casting type with a Brinnell hardness between 325 and 375. According to the liner manufacturer's recommendation, the liners should be changed when the lifter height reaches one third of its initial height. The main objective of the operation was to increase the plant throughput while maintaining the grind size. Because of the breakage of Low type liners and cold welding, the replacement of Low with new Hi type liners became very difficult and time-consuming. With the objective of finding a new design for liners, the charge trajectory was determined by simulation and physical modelling in a laboratory mill. In this project, Hi-Hi liner design was proposed and installed with the objective of providing appropriate charge trajectory and increasing the liner life. To fulfil this task, the liner profile was measured over the liner life, and the data was then used to design new liners that could last longer while maintaining the desired charge trajectory. For each liner design, the performance of the mill was monitored by recording the throughput and liners breakage to evaluate the effect of the new liner design on the grinding performance.

Table 1. Some major characteristics of the Sarcheshmeh SAG mill.

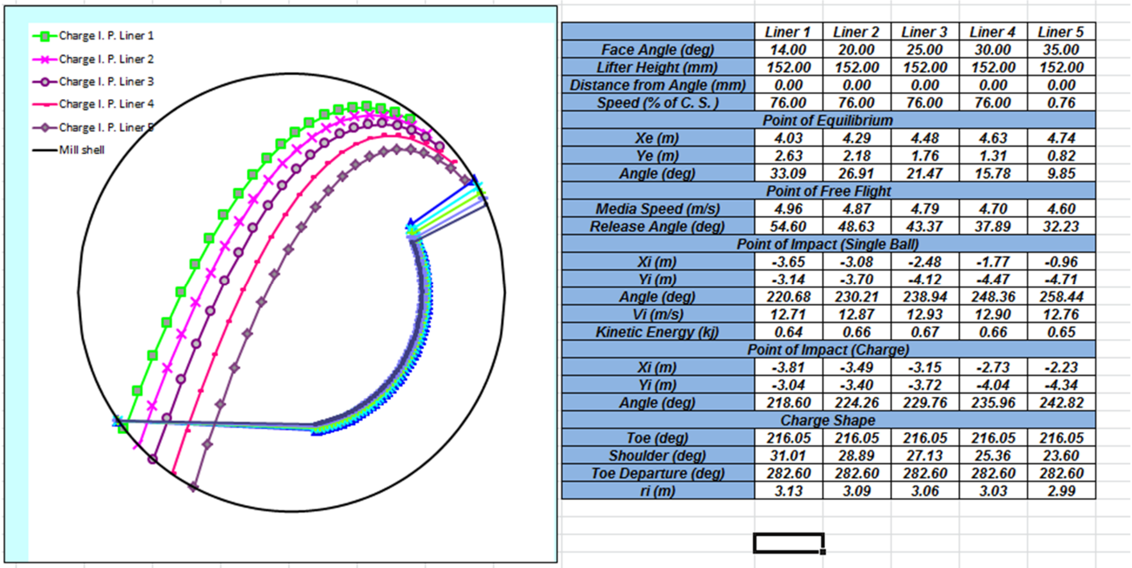
Diameter (m)	Length (m)	Motor power (kW)	Mill filling (%)	Ball size (mm)	Ball filling (%)	Feed size (mm)	Product size (mm)
9.15	4.87	2*3700	35	125	15	-250	-3

3. Methodology

Liner design has become an increasingly more important tool for the AG/SAG performance optimization. In this research work, the process of designing a new liner starts with the analytical and numerical simulation of the charge trajectory and modification of the liner geometry to arrive at the desired trajectory. This paper presents the results of using the GMT software and 3D simulation of the Sarcheshmeh SAG mill by the KMPC$_{DEM}$ software package to predict the charge motion. Based on the simulation results, a scale downed version of liners is then manufactured and installed in a laboratory mill to investigate whether the charge motion matches that of the simulation. The comparison of the current and the proposed liner shape on the charge trajectory was the key step in arriving at the final liner shape. A combination of simulation and physical modelling provided a unique opportunity to acquire sufficient knowledge in the course of a new liner design. Upon final refinements of the liner design, engineering drawings are prepared and sent to the liner manufacturer.

3.1. GMT software

In order to simulate the charge shape and motion, a new version of GMT [16] was used. In the new version of GMT, Maleki-Moghaddam et al. (2013) corrected the charge shape and the outer charge trajectory to take into account the effect of charge on trajectory. The main feature of GMT is the ability to show the crescent-like shape of the charge along with the charge trajectory, which has not been incorporated in the previous version and similar software packages. A typical result page of the GMT software is shown in Figure 1.



	Liner 1	Liner 2	Liner 3	Liner 4	Liner 5
Face Angle (deg)	14.00	20.00	25.00	30.00	35.00
Lifter Height (mm)	152.00	152.00	152.00	152.00	152.00
Distance from Angle (mm)	0.00	0.00	0.00	0.00	0.00
Speed (% of C. S.)	76.00	76.00	76.00	76.00	0.76
Point of Equilibrium					
Xe (m)	4.03	4.29	4.48	4.63	4.74
Ye (m)	2.63	2.18	1.76	1.31	0.82
Angle (deg)	33.09	26.91	21.47	15.78	9.85
Point of Free Flight					
Media Speed (m/s)	4.96	4.87	4.79	4.70	4.60
Release Angle (deg)	54.60	48.63	43.37	37.89	32.23
Point of Impact (Single Ball)					
Xi (m)	-3.65	-3.08	-2.48	-1.77	-0.96
Yi (m)	-3.14	-3.70	-4.12	-4.47	-4.71
Angle (deg)	220.68	230.21	238.94	248.36	258.44
Vi (m/s)	12.71	12.87	12.93	12.90	12.76
Kinetic Energy (kj)	0.64	0.66	0.67	0.66	0.65
Point of Impact (Charge)					
Xi (m)	-3.81	-3.49	-3.15	-2.73	-2.23
Yi (m)	-3.04	-3.40	-3.72	-4.04	-4.34
Angle (deg)	218.60	224.26	229.76	235.96	242.82
Charge Shape					
Toe (deg)	216.05	216.05	216.05	216.05	216.05
Shoulder (deg)	31.01	28.89	27.13	25.36	23.60
Toe Departure (deg)	282.60	282.60	282.60	282.60	282.60
ri (m)	3.13	3.09	3.06	3.03	2.99

Figure 1. A typical result page of the GMT software.

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

DEM modelling is a powerful tool available to allow comparative analysis of various liner designs within the mill, and has been widely used for liner design in the recent years. In this research work, three-dimensional DEM simulations were performed using the KMPC_{DEM} software at the same operating conditions for the old and proposed liners in order to predict the charge shape and impact point. The development of the software started in 2013 at the Kashigar Mineral Processing Research Center (KMPC) [24]. Full access to the software source codes enabled us to add or modify the algorithms and the related relationships. Further details can be found elsewhere. The data entry part of the software includes three main sections. The first section includes importing the geometries that had been designed in the SolidWorks software. In the second section, the physical properties of the geometries and their speeds (if it was necessary) were defined. In this section, the users must specify the location of the entering and exiting particles. The particle properties such as the size distribution, physical properties (density, elasticity modulus, Poisson's ratio), and equipment throughput were entered in the third section [25]. The ball size distribution and the parameters used for the DEM simulations in this research work are presented 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 (%)	29.1	9.6	26.7	7.2	14.1	7.7	5.6

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	0.75
Contact force model	Liner spring-dashpot

3.3. The model mill

In this research work, a model mill with a diameter of 100 cm and an adjustable mill length (from 3.6 cm up to 21.6 cm) was used to determine the accuracy of simulations (Figure 2a). Based on a previous work, to prevent the end-wall effects, a mill length of 10.8 cm was used [26]. The transparent end of the mill makes it possible to measure the charge motion accurately by recording videos and taking photos of charge while mill is running. A 2.5 kW motor with a variable speed drive was used, which provided sufficient flexibility to test various operating conditions. The scale-down ratios of 10 to 1 were used to construct the model mill using the plant mill dimensions. In order to duplicate the plant liner arrangement in the mill, a polyurethane ring (Figure 2b) was accurately machined to create liners.

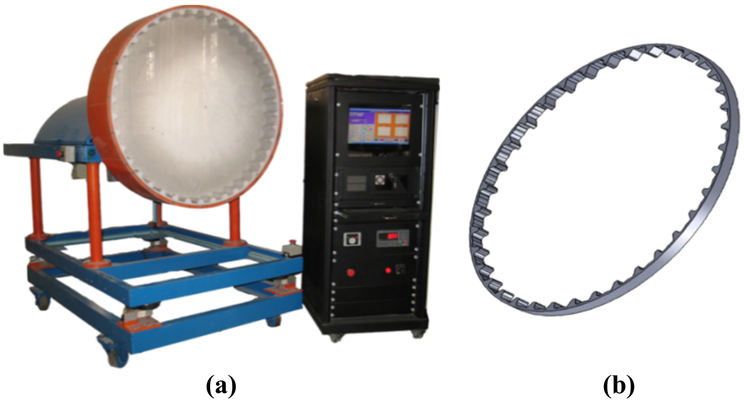

(a) (b)

Figure 2. (a) The model mill along with control and data acquisition system, (b) The polyurethane ring machined to scale down the liners arrangement of an industrial mill.

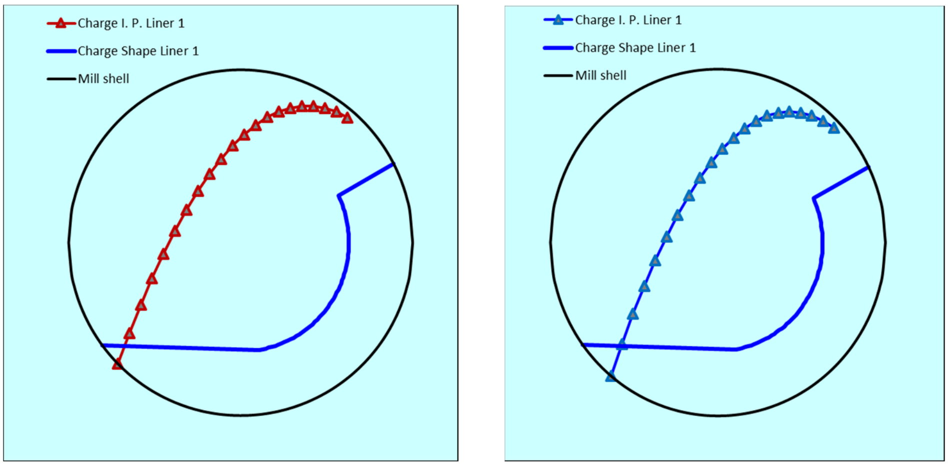
4. Results and discussion

4.1. Charge trajectory prediction

The original mill shell is lined with Hi-Low type liners with 10 and 20 cm height and a release angle of 22 degrees. Since the Hi liners play a major role in the load motion, the simulation results of these liners are studied in this section in detail. The charge trajectory of Hi original liner with the face angle of 22º and lifter height of 20 cm, when using 125 mm balls and assuming 25% total filling (normal filling of the mill at the Sarcheshmeh SAG mills) was predicted by the GMT software (Figure 3a). The small difference between the toe angle and ball impact points (7º) clearly indicated that with the original liner design, ball addition could result in a direct impact of balls on the liners at low mill filling resulting in and causing severe damage. The low throughput of the mill could also be attributed to the inappropriate trajectory, where the toe of the charge does not receive any appreciable direct impacts from the falling charge. All points were measured in degrees, starting from the horizontal line passing the mill center (i.e. 3 o'clock position) and moving counter-clockwise.

It was decided to keep the design of the proposed liner as close as possible to the original liner design in the first set of liners, while trying to provide an appropriate charge trajectory. Due to the significant effect of the lifter face angle on the trajectory, the face angle was increased from 22° to 26°, and the lifter height changed from 10 cm and 20 cm for Hi-Low design to 18 cm for Hi-Hi design. The charge trajectory obtained by the GMT software is shown in Figure 3b. The results obtained indicated that by these changes, the difference between the impact point and the toe increased from 7° to 20° for 25% filling. Increasing the shell lifter face angle (for the same mill speed) reduces the impact point of thrown balls but increases the distance between ball impact points and liners, which results in reduction of the shell liner damage.

Three-dimensional DEM simulations were performed at the same operating conditions in order to compare the charge shape and impact point of the original and the proposed liners using the $\mathrm{KMPC_{DEM}}$ software. The SAG mill along with the detailed features of liners was drawn in Solidworks© (2016 version), and the geometry was imported to the $\mathrm{KMPC_{DEM}}$© software. Figure 4 shows the typical DEM simulations at the same operating conditions (25% filling, 75% of critical speed). The charge dynamics of the original and the proposed liners profile are illustrated through using various colors for particle velocity (blue = slow to red = fast). As Figure 4a indicates, when the original liners are used, the difference between the location of the impact point and the toe is in the range of 10-15 degrees. This difference between the toe angle and the ball impact points indicated that with the original liner design, ball addition could result in the direct impact of balls on the liners at a low mill filling, resulting in a severe damage. This implies that for lower charge levels, a larger fraction of the charge is in the cataracting status, and the direct impacts on liners could occur. As Figure 4b shows, using Hi-Hi liners, the cataracting region of the charge becomes more compact, and the impacts are directed on the toe.



(a) (b)

Figure 3. Simulation of 125 mm ball trajectory at 25% filling using the GMT software for (a) the original liner, (b) the proposed liner.

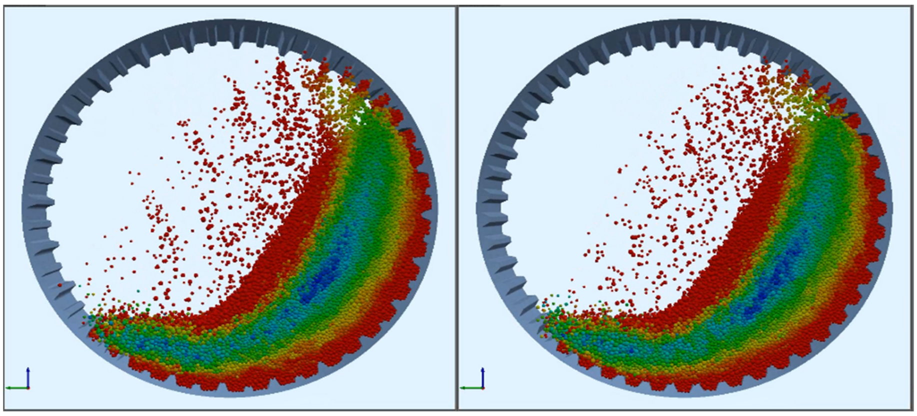
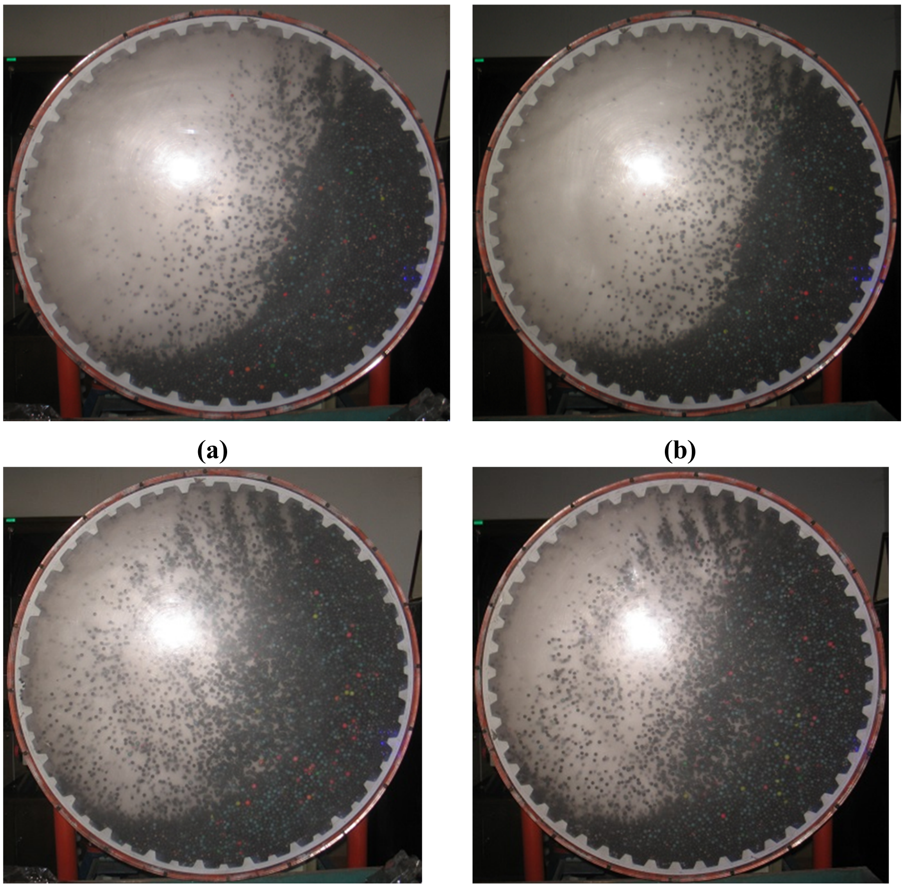

(a) (b)

Figure 4. The typical images taken from the DEM simulations of (a) the original and (b) the proposed liners in the model mill (25% filling, 75% of critical speed).

The DEM simulation results (Figures 4a and 4b) re-confirmed that changing the liner type from Hi-Low to Hi-Hi could provide an appropriate charge trajectory.

To validate the proposed liner design obtained by the simulation, the laboratory-scaled models of the original and the new liners were constructed and tested in the laboratory mill. Steel and plastic balls within the size range of 4-12 mm were used to provide the desired fillings. For both the original and the new liners, the tests were performed at 65, 70, 75, and 80% of the critical speed. Figure 5 illustrates the charge shape and trajectory for the original and the new liners at 25% filling and 75% and 80% of critical speed in the laboratory mill.


(a) (b)

(c) (d)

Figure 5. Charge shape and trajectory of (a) the original at 75% of critical speed, (b) the proposed at 75% of critical speed, (c) the original at 85% of critical speed, and (d) proposed liners in the laboratory mill (25% filling).

As Figure 5 shows, the change of liners from the Hi-Low to a Hi-Hi design on account of achieving more appropriate charge trajectory could reduce the number of direct ball impacts to liners. Also the results indicated that there was a good agreement between the simulated and measured positions of shoulder, toe, and impact points.

As the laboratory and simulation results indicated on account of an increase of 4 degrees in the lifter release angle with the new liner design, increasing the ball filling and addition of larger steel balls (125 mm) became safe and practicable.

Given the promising results, the new liners with 26° lifter face angle and 18 cm lifter height were constructed and installed in the SAG mill phase 2. Figure 6 shows the original and new liners installed in the mill.

To evaluate the effects of the new liner design, the number of broken shell liners and average throughput of the mill (SAG mill phase 2) for a period of liner life before and after liner change was compared. The throughput increased from 750 to 850 t/h after the new liners were installed. This significant increase of 13% in the throughput could be attributed to the change in the charge trajectory and to larger balls used, which led to an improved grinding efficiency. The use of larger balls increased the ability of the mill in encountering hard ore types and reduced performance variation. With the new liners, the number of broken liners over liner life (4300 h) reduced from 6 to 0 piece, the total changing time for one liner decreased from 21 to 16 min, and no cold welding of shell liners was observed.


(a) (b)

Figure 6. (a) The original and (b) new liners installed in the SAG mill of phase 2.

5. Conclusions

Because of breakage of Low type liners and cold welding of Hi-Low liners, the replacement of Low with new Hi type liners became very difficult and time-consuming in the SAG mill (phase 2) at the Sarcheshmeh copper complex. With the objective of finding a new design for liners, charge trajectory was determined at various conditions by DEM simulation and physical modelling in a laboratory mill.

It was found that changing the liner type from Hi-Low to Hi-Hi could provide an appropriate charge trajectory. Due to the significant effect of the lifter face angle on the trajectory, the face angle was increased from 22° to 26°, and the lifter height changed from 10 and 20 cm for Hi-Low design to 18 cm for Hi-Hi design.

The new Hi-Hi type shell liners were designed, manufactured, and installed. On account of an increase of 4 degrees in the lifter release angle in the new liner design, the addition of larger steel balls (125 mm) became safe and practicable.

With the new liners, the number of broken liners over liner life reduced from 6 to 0 piece, the total changing time for one liner decreased from 21 to 16 min, and no cold welding of shell liners was observed. The throughput increased from 750 to 850 t/h after the new liners were installed. This significant increase of 13% in the throughput could be attributed to the change in the charge trajectory and the larger balls used.

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تغییر آسترهای آسیای نیمه خودشکن مجتمع مس سرچشمه از طرح کوتاه- بلند به بلند- بلند با استفاده از مدل‌سازی عددی و فیزیکی

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چکیده:

طراحی آستر امروزه یکی از مهم‌ترین ابزارهای بهینه‌سازی عملکرد آسیاهای خودشکن و نیمه خودشکن است. در کارخانه پرعیارکنی مجتمع مس سرچشمه از یک آسیای نیمه خودشکن استفاده می‌شود که دارای ۴۸ ردیف آسترهای نوع کوتاه- بلند (Hi-Low) است. به دلیل شکست آسترهای نوع کوتاه در طول عملیات و جوش سرد آسترها، تعویض آستر، به فرایندی سخت و زمان‌بر تبدیل شده بود. برای بررسی عملکرد طرح‌های موجود و پیشنهادی آستر، شبیه‌سازی مسیر حرکت بار با استفاده از نرم‌افزار سه‌بعدی راگ (روش اجزای گسسته) و مدل‌سازی فیزیکی انجام شد. نتایج نشان داد با تغییر آسترها از طرح کوتاه- بلند به بلند- بلند، مسیر مناسب حرکت بار فراهم می‌شود؛ بنابراین آسترهای جدید، طراحی، ساخته و در آسیا نصب شدند. بررسی‌ها نشان داد با استفاده از طرح جدید آستر، تعداد شکست آسترها از ۶ قطعه به صفر رسید و به دلیل عدم جوش سرد آسترها زمان تعویض هر آستر از ۲۱ به ۱۶ دقیقه کاهش یافت. مقایسه تناژ ورودی به آسیا نشان داد، ظرفیت ورودی به آسیا بعد از نصب آسترهای جدید، از ۷۵۰ به ۸۵۰ تن بر ساعت افزایش یافت که نشان‌دهنده افزایش انعطاف‌پذیری آسیا در برابر نوسانات سختی بود.

کلمات کلیدی: آسیای نیمه خودشکن، پروفیل سایش، سرچشمه، عمر آستر.
