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Evolution of AG mill shell liner design at Gol-E-Gohar concentration plant

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Abstract

Liner design is becoming an increasingly more important tool for the AG/SAG mill performance optimization. The Gol-E-Gohar iron ore concentration plant uses three 9 m × 2.05 m autogenous mills (AG) in parallel in a dry operation. Due to large variations in feed characteristics and inadequate blending, the performance of AG mills has been lower than the target value. In order to increase the circuit throughput while maintaining the desired product size, based upon physical and numerical simulations, it was proposed to convert the AG mills to SAG mills. Simulation of the charge trajectory indicated that increasing the liner lifter face angle from 7 to 30° could provide an appropriate charge trajectory in the SAG mode. Installation of the new liners and conversion of AG mill No. 2 to SAG mill, by adding 5% (v/v) balls, resulted in an overall increase of 31% in throughput (from 419 to 548 t/h). Measurement of the wear profiles of shell liners indicated that the wear along the liner length was not uniform. In order to arrive at a uniform wear profile, a new liner design was proposed. Installing the second liner design in AG mill No. 1 and converting it to SAG mill increased the mill throughput by 18% (from 413 to 489 t/h), while the liner life showed a 7% increase. Measurement of the wear profiles of the second liner set indicate that the maximum wear occurs in the centre of the mill. A new liner design was then designed by increasing the width of the lifter top from 12.5 to 15 cm and increasing the lifter height from 16 to 26 cm to enhance the liner life.

Keywords: *AG/SAG Mill, Shell Liner, Gol-E-Gohar Iron Ore, Wear Profile, Non-Uniform Design.*

1. Introduction

Mill liner design influences the grinding performance by affecting the charge trajectory. 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. Hence, in designing liners, not only the life but also the favorable charge trajectory for a given duty should be considered. The liner profile will change over its life due to aggressive environment inside the mill, which, in turn, affects the charge trajectory resulting in the mill throughput and grinding performance variation. Although many research works have been carried out to model the liner wear and predict the liner profile over the liner life, due to the complexity of the mechanisms involved, a comprehensive model is yet to be proposed, which could provide reliable results over a wide range of operating conditions. This has made the design of liners an evolving activity in practice. Usually by monitoring the wear profile over few liner life times and identifying the areas of high and low wear, design of liner is accordingly adjusted to provide a uniform profile at the end of liner life, while maintaining the charge trajectory within the desirable regime [1, 2].

There are different criteria that could be used to evaluate the performance of liners. Liner life time (working hours or tonnes milled) and liner consumption (liners mass loss per ton milled) are the two criteria that are commonly utilized. However, the liner performance not only should include the liner life and cost of liners but also should incorporate the mill throughput and grind size [1-3]. It has been well-established that a change in the face angle on SAG (semiautogenous) mill shell lifters results in a change in the trajectory of charge. With the development of trajectory-generating computer programs, the effects of face angle, packing, and lifter height have been incorporated in the shell lifter design. Increasing the shell lifter face angles (for the same mill speed) does reduce the impact point of thrown balls, and can reduce shell liner damage [4-7]. The availability of large-scale cost-effective computing power in recent years has allowed the development of Discrete Element Modelling (DEM) computer programs, which model charge trajectory in mills. DEM helps to understand charge motion in SAG mills for given liner designs and lifters, ball and rock properties, and mill operating conditions. Based on the success of the 2D model of the SAG mill, the 3D model in DEM was developed. These types of models could help to study charge motion and energy draft more accurately [8-11]. Banisi and Hadizadeh (2007) have proposed and tested a method to determine the wear rate through building the 3D model of liners after any given operating time, and designed a liner wear profile measuring device [12]. The mill trajectory is the main concern in liner designing issues because the direct impact of balls to the liner shell could result in liner damage and breakage. The charge trajectory can be optimized by the modification of the liner design. Yahyaei and Banisi (2010) have designed a spreadsheet-based software (GMT; Grinding Media Trajectory) to model charge trajectory in tumbling mills [6]. Charge shape and impact points predicted by the GMT program was based only on a single ball trajectory. Maleki, Yahyaei, and Banisi (2013) have 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 impact points, the GMT software outputs became more realistic [13].

1.1. Gol-E-Gohar iron ore concentration plant

This study was carried out at the Gol-E-Gohar mining and industrial company located in the SE of Iran. Three 9 m × 2.05 m autogenous (AG) mills are used in parallel in a dry operation to grind a magnetite ore from a F_{100} (100% passing screen size) of 32 cm, which is the product of a gyratory crusher, to a P_{80} (80% passing screen size) of 120 mm. Each mill power is 3000 kW and works with a constant 12 rpm speed (i.e. 85% of critical speed) in one direction. Due to the different ore types, the operation of mill No. 1 is usually different from mills No. 2 and No. 3, both of which are fed from the same stockpile. The AG mill shells are lined with three 57-cm liners in length in 36 rows. According to the liner manufacturer recommendation, the liners should be changed when the lifter height reaches 100 mm, which is one third of its initial height. Due to large variations in feed characteristics (i.e. mineralogy, hardness, and size distribution) and inadequate blending, the performance of AG mills has been lower than the target value. The main objective of the operation was to increase the plant throughput, while maintaining the grind size. Therefore, it was proposed to convert the AG mills to SAG mill along with modification of the shell liners design to be favourable for the SAG mode. This conversion was thought to stabilize the operation of mills despite fluctuation in ore hardness.

In this project, three different liner designs were proposed and installed with the objective of providing an appropriate charge trajectory and arriving at a uniform wear profile at the end of liner life. In order 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 regarding the throughput and P_{80} were monitored to evaluate the effect of the new liner design on the grinding performance.

2. Methodology

The process of designing a new liner starts with simulation of the charge trajectory and modification of the liner geometry to arrive at the desired trajectory. A scale downed version of liners are then manufactured to be installed in a laboratory mill to investigate whether the charge motion matches that of the simulation. When the final refinements of the design are performed, engineering drawings are prepared to be provided to the liner manufacturer. This section provides details of each step as well as method of collecting the industrial data during the performance monitoring phase.

2.1. Charge trajectory predication software

In order to simulate the charge trajectory, a new version of GMT [13] was used. In the new GMT, Maleki, Yahyaei, and Banisi (2013) corrected the charge shape and the outer charge trajectory to take into account the effect of charge on trajectory. This was accomplished by applying the empirical relationships to modify the impact point angle at the end of its trajectory. The main feature of GMT is the ability to show the crescent-like shape of the charge along with the trajectory, which has not been incorporated in similar software packages. This provides an accurate estimation of the charge that can then be used to adjust the impact point of charge close to where toe will retain.

2.2. Model mill

In this research work, a model mill with a diameter of 100 cm and adjustable mill length from 3.6 cm up to 21.6 cm, with the increments of 3.6 cm, was used to investigate the accuracy of simulations for the selected liner design (Figure 1a). The transparent end of the mill makes possible to measure the charge trajectory accurately by recording videos and still images of charge while mill is running. A 2.5 kW motor with a variable speed drive was used, which provided a sufficient flexibility to test various mill speeds. The laboratory mill was a scaled down version of the industry AG mills with the ratio of 9 to 1. In order to duplicate the plant liners arrangement in the mill, a polyurethane ring was accurately machined to create 36 lifters in a row (Figure 1b) with the same design as industrial liners but with the scale of 9 to 1. This approach allowed to construct any liner design in small scale, and to study the charge trajectory at different mill fillings and speeds.

(a) (b)

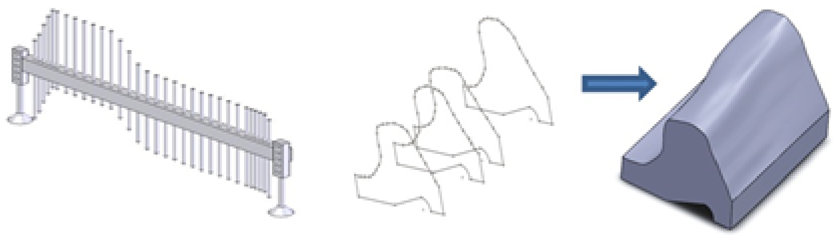
Figure 1. a) Model mill along with control and data acquisition system, b) polyurethane ring machined to scale down liners arrangement of an industrial mill.

2.3. 3D linear wear profile measurement device

Two techniques were used to measure the liner wear profile and build a 3D model of liners at any given operating time. A pin gage similar to the one introduced first by Powell (1991) [14] was used to measure the liner height at different sections (normally at 4 cross sections). To ease the use of the device, it was made of aluminium with the dimensions of 30 × 50 × 500 mm, which contained equally spaced holes (Figure 2a). In order to determine the wear rate, measurements were made at four equally distanced cross sections. To convert the measured cross sections into a 3D model, Solidsworks© was used (Figure 2b).

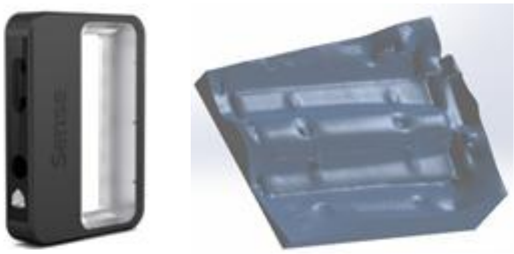
The 3D scanning technique was also implemented to measure the 3D profile of liners at each stage of their life. This method allows building of a 3D model of liners at any measurement time. This technique allows a faster and more accurate scanning of the liners compared to the pin gauge (Figure 3a). A typical snapshot of a scanned liner is shown in Figure 3b.

After developing the 3D model of the liners, it is possible to calculate the mass and the volume of the liner. Scheduled shut-down of the SAG mill at the plant made regular measurements and monitoring of the liners possible.



(a) (b)

Figure 2. a) Pin gauge, b) typical 3D model of a worn liner after 3000 h of operation at Gol-E-Gohar concentration plant.



(a) (b)

Figure 3. a) 3D scanner (Sense©) used in this research work, b) a typical snapshot of a scanned liner.

3. Results and discussion

3.1. Charge trajectory prediction

The charge trajectory, when using 125 mm balls and assuming 18% total filling (normal filling of the mill at the Gol-E-Gohar before changing the liners), was predicted by the GMT software (Figure 4). The ball impact points clearly indicated that with the original liner design, ball addition could result in direct impact of balls on the liners, causing a 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 impact from the falling load. The effect of different fillings on the position of the impact of ball was also studied. Impact points were measured in degrees, starting from the horizontal line passing the mill centre (i.e. 3 o'clock position) and moving counter-clockwise. The simulations indicated that even for a filling of 24%, which was considered high for the operation, there was a 32º difference between the ball impact points and the position of the toe.

3.2. New liner design

It was decided to keep the design of the new liner as close as possible to the original liner design in the first set of liners, while trying to provide an appropriate charge trajectory for the SAG mode. This relatively conservative decision was made due to the lack of information about the wear pattern of the original liners. Due to significant effect of the lifter face angle on the trajectory, the face angle was increased from 7 to 30°, and the ball trajectories were obtained by the GMT software (Figure 5). The results obtained indicated that when the face angle increased from 7 to 30°, the distance between the impact point and the toe decreased from 32 to 8° for 24% filling and decreased from 38 to 12° when the filling was 18% filling.

Since the ball impact points were within the safe operating windows (i.e. -6.4 to 12˚ [13]), a lifter face angle of 30° was selected for the new design. In order to ensure the appropriate load trajectory, the laboratory-scaled models of the original and new liners were constructed and tested in the laboratory mill. The steel balls within the size range of 4-12 mm were used to provide the desired fillings. For both the original and new liners, the tests were performed at 14, 16, 18, 20, and 24% fillings. Since the rotation speed of Gol-E-Gohar mills was fixed at 85% of the critical speed, this rotation speed was selected for all tests. Figure 6 illustrates the charge shape and trajectory for the original and new liners at 20% filling in the laboratory mill.

Given the promising results obtained in the laboratory mill, the new liners (design No. 1) with 30° lifter face angle and unchanged lifter height (i.e. 22.5 cm) were constructed and installed in the AG mill No. 2. Installing the new liners and converting AG mill No. 2 to SAG mill, by adding 5% (v/v) balls, resulted in an overall increase of 31% in throughput (from 419 to 548 t/h), while P_{80} of product decreased from 516 to 496 µm. Figure 7 shows the original and new liners. The mass of the liner was kept equal to the original design to avoid an increase in the total weight of the mill.

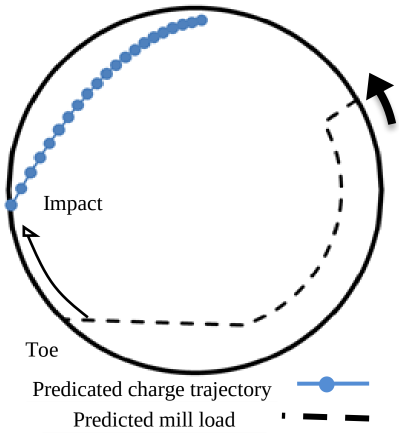


Figure 4. Simulation of 125 mm ball trajectory at 18% filling for old liner using GMT software.

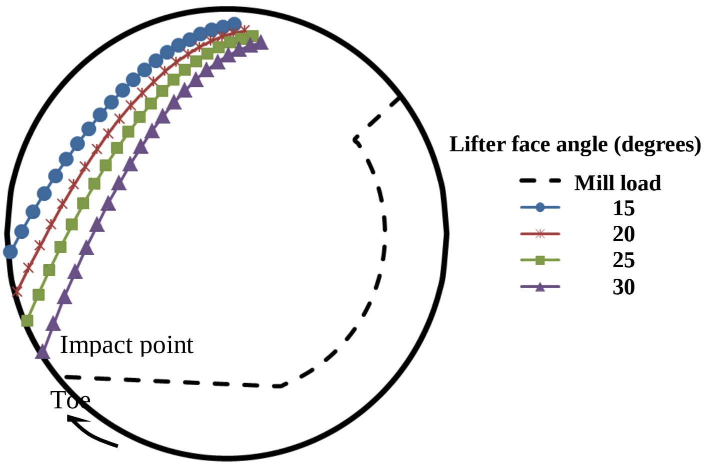


Figure 5. Simulation of 125 mm ball trajectories with different lifter face angles (24% filling).

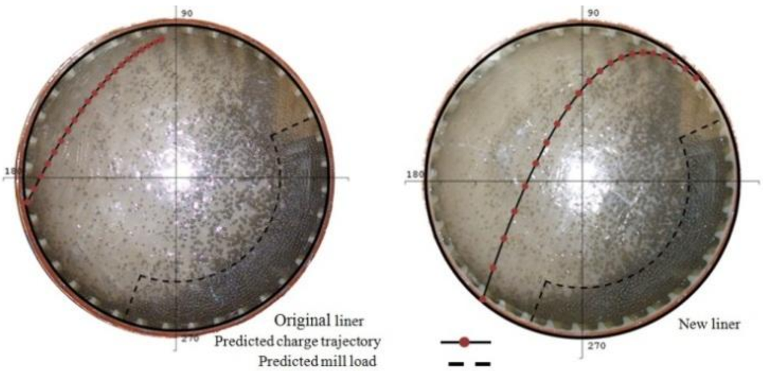


Figure 6. Charge shape and trajectory of original and new liners in laboratory mill (20% filling).

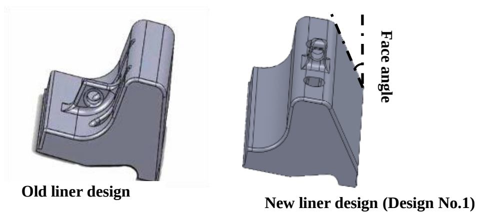


Figure 7. 3D model of original and new liners used at Gol-E-Gohar concentration plant mills.

3.3. Measuring liner wear profile

During the liner life time (6200 h), five series of measurements were performed at 2300, 3815, 4350, 5150, and 6200 h of operation, respectively. As a result, the height of lifters at specific locations (i.e. profiles 1–4) and the corresponding operation time were determined.

The profile of a liner after 6200 h of operation at four equal distances along the liner length was measured (Figure 8). Unlike the first profile that did not experience much wear profile 4, which is very close to the mill centre, showed the highest wear. The relative height difference between the second profile and the fourth one is 44%, which indicates a non-uniform wear profile along the mill length.

3.4. Non-uniform liner designs

Measurement of the wear profile indicated that the highest wear rate was found to be between 0.5 m and 1.2 m along the mill length (Figure 9). Therefore, to arrive at a uniform wear profile at the end of liners life, a modified liner was proposed with non-uniform lifter height. The main objective was to redistribute the metal from the low wear rate sections to those with a high wear rate. In the new liner design, the lifter height varies along the length of the liner that provides a curved shape. The lifter height in the new design was changed from the original height of 22.5 cm by -72, -48, -15, 21, 45, and 63 mm from the feed end toward the center of the mill. This meant 72 mm reduction of lifter height in profile 1 (i.e. the first profile from the feed end) and 63 mm increase in the lifter height in profile 6 (i.e. 0.8 m from the feed end). In Figure 9, the profile of the lifter height for the new liner design (the solid curved line) is compared with the uniform liner design (the solid horizontal line) and measured profile of the fully worn liners with the uniform design (the line with square markers). In the liner design No. 2, the lifter face angle was kept at 30^{o} similar to the design No. 1 to be favorable for the SAG mode.

Due to some concerns with regards to casting liners with curved lifters on top, it was decided to design the sloped surface for the feed end and discharge end sections, while the middle section was kept flat (Figure 10). It is worth noting that the weight of the proposed designs was retained equal to the original design. This ensured that the replacement of new liners would not face any difficulties due to additional mass.

It has been observed that the charge trajectory alteration due to the lifter height change is less than that of the face angle change. To gain a further insight, the effect of change in the lifter height on charge trajectory was investigated to check whether the design change could result in direct impact of ball on the shell. The study showed that, in the range of lifter height change (150–260 mm), the impact angle of the charge did not change significantly (i.e. in the order of 1–3° from the average impact angle). This provided enough assurance that the new liner design would not have any adverse effect on the mill as a result of direct impact of ball on the mill shell. The first non-uniform shell liners were constructed and installed in the AG mill No.1. The liner profiles were measured over the liner life, while measuring the mill performance parameters (i.e. mill throughput and the product size).

As shown in Figures 11 and 12, the worn liner of non-uniform design provides smoother worn profile than uniform liners (i.e. design No. 1). However, the measurement of the wear profiles of the first non-uniform shell liners indicated that the maximum wear was observed in the centre. The highest wear occurred between 0.8 m and 1.2 m from the feed end. To address this issue, the second design with non-uniform profile was proposed.

Due to some concerns raised with regards to material segregation inside the mill when using sloped lifter top in design No. 2, the second non-uniform design (design No. 3) was proposed, where the lifter height was changed in steps. In the new liner design, while the lifter face angle and height were kept similar to design No. 1, the width of the lifter top was increased from 12.5 to 15 cm at the middle section. The width of the lifter top for feed and discharge ends was kept as 12.5 cm (Figure 13). Changes in the mill throughputs before and after changes are summarized in Table 1.

The first and second liner designs increased the mill throughput by 2.6 and 7.5%, respectively. After conversion to SAG milling on the account of liner change, 18% (from 413 to 489 t/h) increase in throughput was obtained. It was predicted that the liner design No. 3 would increase the liner life time by 10% and would reduce the scrap metal from the current value of 59% to 50%. The measurement of profiles of non-uniform liners during 6220 h of operation indicated that the objective could be achieved. It is important to note that during the liner design change period, the hardness of feed increased, which was observed and verified in the other parallel dry mills. In other words, the reported increase in throughput is conservative and the actual increase is higher.

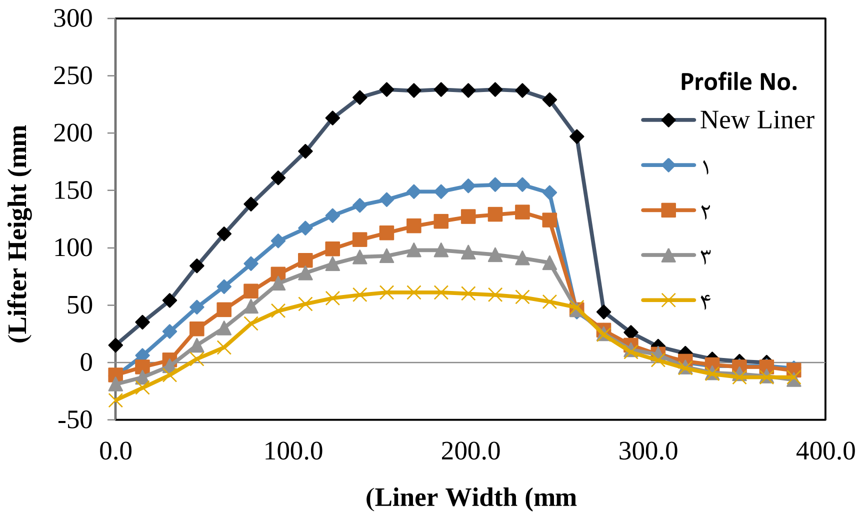


Figure 8. Wear profiles of a liner after 6200 h of operation at four points along length of liner.

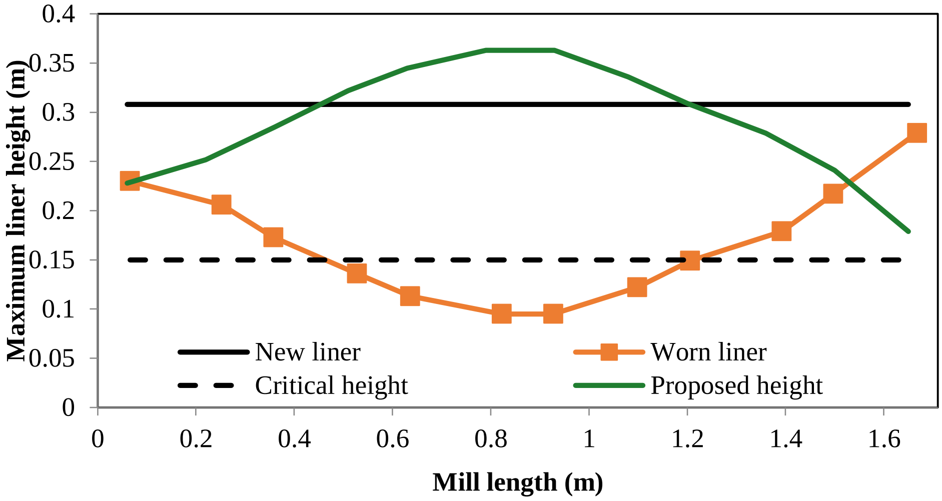


Figure 9. Variations in maximum lifter heights along liner after 6200 h of operation.

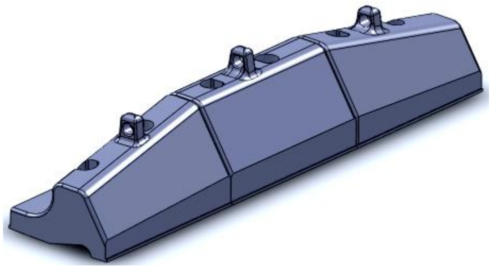


Figure 10. 3D model of non-uniform liner (design No. 2).

(a) **(b)**

Figure 11. Snapshot of shell liners at end of life time; a) uniform liners (design No. 1), b) non-uniform liners (design No. 2).

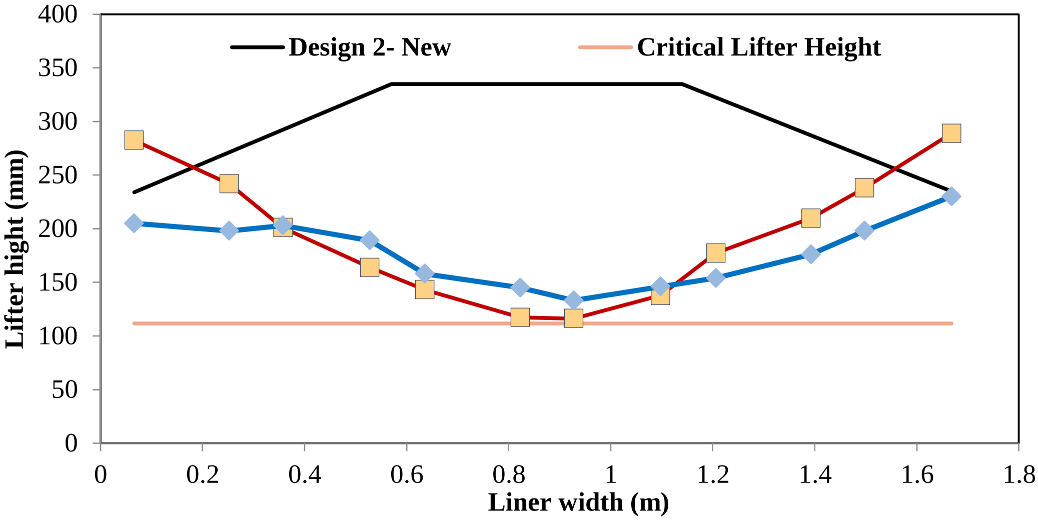


Figure 12. Variations in maximum lifter heights along mill length for uniform and non-uniform liners after 6200 h of operation.

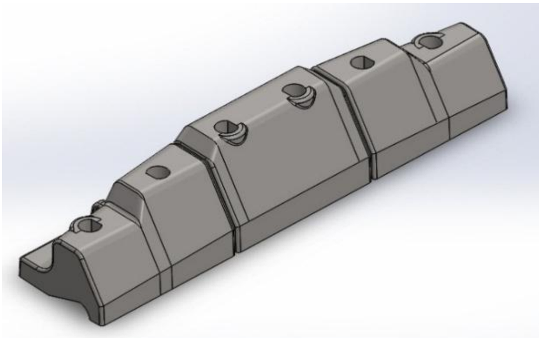


Figure 13. 3D model of second non-uniform liner (design No. 3).

Table 1. Throughputs and product sizes of mill before and after liner change and after balls addition.

Liner type	Observation period (months)	Throughput (t/h)	P_{80} (µm)
Original liners	18	413±56	502±25
Liner design No. 1	13	424±47	501±28
Liner design No. 2	6	489±25	529±26

4. Conclusions

- Shell liners of the AG mills of the Gol-E-Gohar iron ore concentration plant were modified to increase the plant throughput, while maintaining the grind size.
- It was found by simulation that increasing the liner lifter face angle from 7 to 30°, while maintaining the original lifter height (i.e. 22.5 cm), can reduce the distance between the impact point and the toe from 32 to 8° for 24% filling and from 38 to 12° for 18% filling.
- The liner life was increased by 7%; more uniform wear profile was achieved through installing non-uniform liners by re-distributing metal from areas with low wear rate (i.e. feed and discharge ends) toward high wear rate (i.e. middle of mill length).
- Improvement in the shell liner design was obtained by monitoring and measuring the liner wear profile. Modification of the design to keep the uniform wear profile and increase the liner life resulted in more than 15% improvement in mill throughput.

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چکیده:

طراحی آستر روشی برای افزایش کارایی آسیاهای خودشکن و نیمه خودشکن است. در مدار آسیاکنی شرکت سنگ آهن گل‌گهر، از سه آسیای خودشکن خشک با قطر ۹ متر و طول ۲/۰۵ متر استفاده می‌شود که به طور موازی کار می‌کنند. کارایی خردایش در این آسیاها با توجه به تغییر در خصوصیات مواد ورودی، کمتر از مقدار در نظر گرفته شده در طرح اولیه است. لذا در این پژوهش، تبدیل آسیای خودشکن به نیمه خودشکن با انجام شبیه‌سازی‌های فیزیکی و عددی پیشنهاد شد تا با خردایش بهتر سنگ معدن دانه بندی محصول ریزتر بیشتر شده و ظرفیت بار ورودی به آسیا افزایش یابد. شبیه‌سازی مسیر حرکت بار نشان داد با افزایش زاویه صفحه بالابر آستر از ۷ به ۳۰ درجه و بدون تغییر ارتفاع بالابر، مسیر مناسب حرکت بار فراهم می‌شود. پس از نصب آستر جدید در آسیای خودشکن شماره ۲ و تبدیل آن به نیمه خودشکن با اضافه کردن ۵٪ گلوله به آسیا، ظرفیت آن ۳۱٪ (از ۴۱۹ به ۵۴۸ تن بر ساعت) افزایش یافت. بررسی آسترهای سائیده شده نشان داد که الگوی سایش در آسترهای جداره آسیاهای خودشکن غیریکنواخت است. لذا طرح غیریکنواخت آستر جهت رسیدن به روند سایش یکنواخت در انتهای عمر آستر پیشنهاد شد. با نصب طرح دوم آستر در آسیای خودشکن شماره ۱ و تبدیل آن به نیمه خودشکن، ظرفیت آسیا ۱۸٪ (از ۴۱۳ به ۴۸۹ تن بر ساعت) و عمر آستر ۷٪ افزایش یافت. بررسی سایش آسترهای طرح دوم نشان داد حداکثر سایش در وسط آسیا اتفاق می‌افتد؛ بنابراین طرح سوم آستر با افزایش عرض بالابر از ۱۲/۵ به ۱۵ سانتی‌متر و افزایش پله‌ای ارتفاع بالابر از ۱۶ تا ۲۶ سانتی‌متر ارائه شد.

کلمات کلیدی: آسیاهای خودشکن و نیمه خودشکن، آستر جداره، معدن سنگ آهن گل گهر، مقطع سایش، طرح غیریکنواخت.