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Low-Cost Approaches to Promote Performance of Comminution Circuit at Steel-Sirjan Iron Ore Complex

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Abstract

The energy consumed by the comminution equipment accounts for the main part of the operating cost of the mineral processing plants. In order to conserve energy, attempts were made to increase the efficiency of the conventional comminution equipment. As a case study, in this research work, a process audit was carried out in the comminution plant of the Steel-Sirjan Iron Ore Complex in order to find the low-cost solutions to improve the product quality and decrease the maintenance and operating costs. Three main steps of the audit were (1) studying the operating manuals and checking the standard process procedures, (2) process data analyzing, and (3) proposing and implementing the proper solutions. Plant audit revealed a low equipment efficiency. The main defects were the crusher operation in the half-full condition, high pressure grinding roll (HPGR) operation in a non-standard condition, high amounts of rejected materials in the HPGR circuit, and low efficiency of the screen. Following this, a series of modifications were made in the crushing and grinding circuit. This consequently caused an increase of 9.3% in the crushing plant throughput in the choked condition of the crushers as opposed to the half-full condition. By increasing the HPGR operational pressure and the hopper level, BBWI of the HPGR product in the super-choked condition was decreased from 16± 0.20 kWh/t to 14.9± 0.25 kWh/t. By modifying the screen process, the circulating load decreased from 79% to 59%, and the screen efficiency increased from 63.5% to 89.5%.

1- Introduction

Comminution is usually carried out in order to liberate valuable minerals from the gangue, make the freshly mined material easier to handle, and in the case of the quarry products, to produce a material of controlled particle size [1]. The crushers reduce the run-of-mine (ROM) particle size in order to prepare an appropriate feed for the grinding circuit until the valuable minerals and gangue are produced as the separate particles. Conventional grinding is carried out in tumbling mills such as rod, ball, and SAG mills. In the recent years, a new comminution device that is somewhat intermediate between fine crushing and coarse grinding is the high pressure grinding rolls (HPGRs) [1]. The role of classification at each stage is to pass the material finer than the desired top size to the next stage and return the material coarser than the top size to the previous size reduction step for further size reduction [1, 2].

The energy consumed by the comminution equipment accounts for the main part of the operating cost of the mineral processing plants. In order to conserve energy, attempts have been made to increase the efficiency of the conventional comminution equipment [3-6].

Performance of the cone crushers has a direct effect on the performance of the downstream processes, and optimization of the cone crushers has received a considerable attention [6, 7-11]. The main method used for increasing the circuit

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throughput is to maintain the power utilization of the crushers at the highest possible value [1]. Achieving the maximum efficiency of a cone crusher directly depends on the type of feeding arrangement (i.e. choke fed or trickle fed) [8, 11]. As a result of operating the crusher in the choke fed condition, not only a more uniform product is produced but also the life of the crusher parts increases that is due to an even distribution of pressure and promotion of the inter-particle interactions [12-14].

The evolution of comminution from the conventional three-stage crushing and screening to hybrid comminution circuits or HPGR-based operations caused to increase the complexity of the comminution circuits [15, 16]. Among all the comminution devices, HPGR is increasingly used as a final crushing or primary grinding stage due to the low operating costs, low energy consumption, and high energy efficiency [17-20].

The operating parameters in HPGR are also different in comparison to the other tumbling mills. Its main parameters are hydraulic pressure, roller speed, and level of the material inside the hopper (hopper level) [21, 22].

An appropriate condition of the HPGR product is a compacted cake that requires to use the de-agglomeration equipment before or during screening in order to separate the product particles. Different screening devices are usually applied to classify the HPGR product [23-25].

The circulating load and classification efficiency have a main impact on the closed HPGR circuits performance [26, 27]. Pamparana and Klein (2021) have developed a novel gap-calibrated methodology and modelling method in order to predict the energy consumption and the size reduction capabilities for an HPGR [28]. In the recent years, the discrete element method (DEM) has been increasingly used for the HPGR simulation [29-31]. Barrios and Tavares (2016), have displayed an appropriate agreement between the DEM modeling and the power model results [32]. The effect of the roll stud condition on the HPGR throughput was investigated by the DEM simulation [33]. Cleary and Sinnott through the DEM method have demonstrated that only small changes in the confining cheek plate locations are required to allow a significant axial bypass, a strong axial variation of discharge mass flow rate, and a coarser product [34].

In addition, conscious laboratory (CL) has been recently developed as a new concept. Well-structured CL investigations and models of the HPGR operational parameters and their products using the explainable artificial intelligence (EAI) systems and based on the datasets have been recorded in the industrial scale [35]. However, extensive investigations are still required in order to increase the HPGR efficiency and overall performance, and no specific study has dealt with the effect of the classification efficiency on the industrial HPGR circuit.

This research work investigates various faults and challenges in the design and operating conditions that have a major impact on the process performance. The process audit in the case study plant used to find the design and operating faults and propose the appropriate solutions in order to increase the comminution circuit performance. All the required modifications that had a major effect on the process were done with minimum capital costs.

2. Iron ore crushing and pre-grinding plant of Steel-Sirjan Iron Ore Complex

The Steel-Sirjan Iron Ore Complex is located in the southeast Iran. Figure 1 shows a process flowsheet of its crushing plant. Three stages of crushing were considered to provide the proper feed for the concentration plant. Jaw crusher, standard head cone crushers, and short head cone crushers were used as the primary, secondary, and tertiary crusher units, respectively. In the concentration plant, a HPGR in closed circuit with a wet vibrating screen was used as the pre-grinding circuit. The final product of the HPGR circuit (screen underflow) was fed to a ball mill-hydrocyclones circuit.

As shown in Figure 1, a grizzly screen was used to remove (fed to next section) the material under 150 mm before feeding to the primary crusher. A standard cone crusher as the secondary crusher was used after the primary dry double screen to crush the material coarser than 30 mm. Then a short head cone crusher as the tertiary crusher was operated in a close circuit with the secondary dry double screen to crush the material larger than 30 mm. The final product of the crushing circuit is the materials finer than 30 mm in size. The technical specifications of the crushers are presented in **Error! Reference source not found.**.

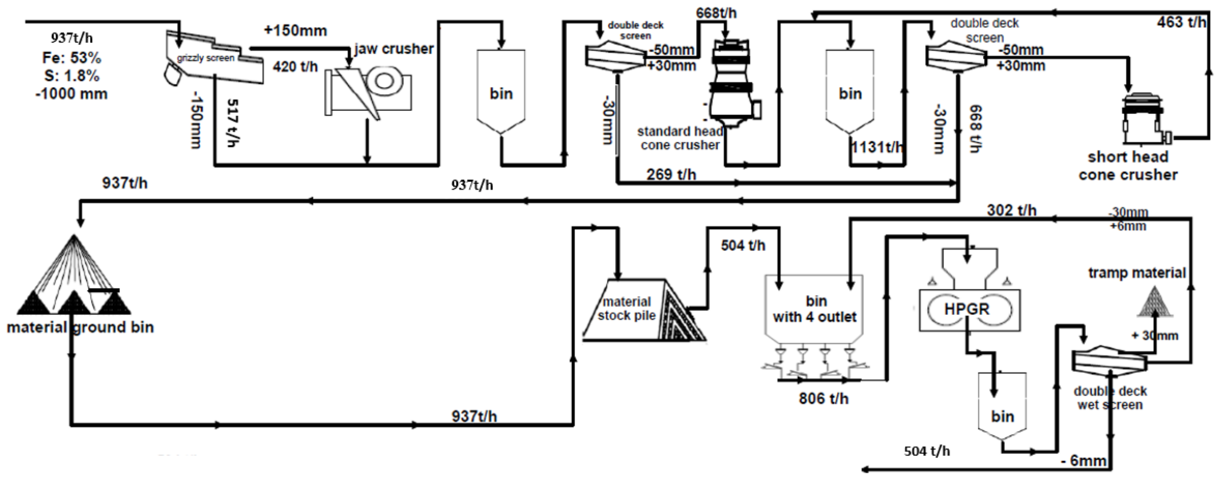


Figure 1. Iron ore crushing plant of Steel-Sirjan Iron Ore Complex.

Table 1. Crusher technical specifications of comminution circuit.

	Primary crusher	Secondary crusher	Tertiary crusher
Crusher type	Jaw crusher	Standard cone crusher	Short head cone crusher
Throughput (t/h)	433	689	477
Feed size (mm)	< 1000	< 250	32-63
Product size (mm)	< 250	< 63	< 32
Product P_{80} (mm)	Approx. 175	48	20
Closed side setting; CSS setting (mm)	150	45	18
Maximum power darw (kW)	160	315	315

The HPGR mill operates in the concentration plants as a pre-grinding stage in order to provide the desired feed for the downstream circuit. The technical data of HPGR is presented in **Error! Reference source not found.**. This HPGR is used in the closed circuit with a wet double-deck vibrating screen.

The double deck vibrating screen is used in the HPGR circuit. The technical data of this screen is shown in Table 1. Three products of this screen are (1) particles finer than the second deck's aperture size that are transferred into the classification circuit, (2) middle size particles (finer than the first deck's aperture size and coarser than the second deck' aperture size) that are returned to HPGR for re-grinding, (3) particles coarser than the first deck's aperture size that aggregated and then eliminated from the process.

Table 2. Technical data of installed HPGR.

Throughput capacity	900 t/h
Maximum operating pressure	230 bars
Roll speed	9–23 rpm
Feed moisture	≤ 5%
Drive rating	2 × 1000 kW
Max feed size: F100	30 mm
Specific pressing force	4 N/mm^2
Roll diameter	1.5 m
Roll width	1.1 m

Table 1. Technical data of wet double-deck vibrating screen.

Throughput capacity (t/h)	900 t/h
Aperture size: upper deck	14 mm- 7 rows 30 mm -1row
Aperture size: down deck	6 mm
Screen length	9 m
Screen width	2.5 m
Inclination	Dual Slop, 25/15 deg.

3. Materials and Methods

Plant audit was selected as a monitoring method in order to standardize the whole crushing and pre-grinding process plant. First, the operating manuals was studied. Then the standard process procedures were checked. In the process the data was analyzed. Finally, the proper solutions were proposed and implemented. The plant troubleshooting revealed the low efficiency of the comminution equipment. The main troubles were as follow: all the crushers operated in a half-full condition, HPGR operated in a non-standard condition that resulted in a high amount of reject materials in the HPGR circuit, and the screen operated in a low efficiency mode.

Trials with the half-full and super-choked conditions of the secondary and tertiary crushers were conducted. Both the bin level and the power draw were maintained stable during the trials. For the half-full and the super-choked conditions, the speed of the secondary crushers feeders was set at 50% and 95%, and for the tertiary crushers was set at 50% and 75% for the half-full and super-choked condition, respectively. The conveyor belt scales were calibrated before the trail in order to ensure the accuracy of the measurements as well. Sampling for each trial was conducted after 30 min of the operation in order to ensure the stability of the process. For each trial, the power draw and throughput were measured. During the trial, the material level was controlled by adjusting the feeder speed, and monitored directly using a level sensor. A view of the HPGR hopper level can be seen in Figure 2.

In order to increase the HPGR comminution efficiency, the operational pressure and the hopper level were modified, and the reduction ratio was compared before and after the modification. In order to investigate the hardness (grindability) comparison of the choked condition product and half-full (25% of hopper level) condition, the standard BBWI (Bond Ball mill Work Index) was conducted for the product of both operating modes.

Due to the importance of wet screening in the circulating load, the aperture sizes of the screen upper deck were changed in this stratification unit. The screening evaluation index was efficient. The screening efficiency was calculated using Equation 2-1.

$$E = \frac{(f-o)u(f-u)(1-o)}{(u-o)f(o-u)(1-f)} \quad (1)$$

f, o, and u are the mass fraction of the material finer than the aperture size in feed, coarse product, and fine product, respectively [1].

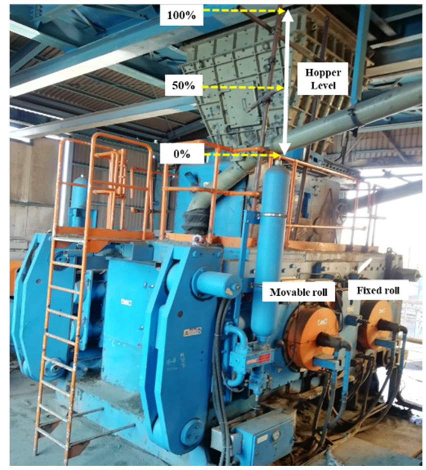


Figure 2. A view of HPGR and its hopper level.

4. Results and discussion
4.1. Crusher circuit

Three crushing stages were considered in the crushing circuit. Based on the design data, the feed rates of the primary, secondary and tertiary crushers were 433, 689, and 477 t/h, respectively, and the power draws of crushers were 160, 315 and 315 kW, respectively. Process audit of primary (Closed Side Setting; CCS = 185 mm), secondary (CSS = 58 mm), and tertiary (CSS = 28 mm) crushers in 4 months showed that the average feed rates were 368, 510, and 405 t/h, respectively, and their average power draw were 115, 102, and 127 kW, respectively. The investigation results revealed that the crushers operated in a half-full condition. The reasonable solutions were adjusting the crushers close side sitting (CSS) and increasing the feed rate to make the choke fed operating condition.

Two trails at the half-full and super-choked conditions were conducted. The effect of chamber filling on the size distribution of the crusher product are shown in Figures 3 and 4 and Table 4. The results obtained indicated that the operating crushers in the super-choked condition reduced P_{80} of the final (ground bin feed), secondary and tertiary product by 15.2%, 17.5%, and 16.5%, respectively, compared with that of the half-full mode.

(a) (b)

Figure 3. Product view of secondary crusher in half-full (a) and choke fed operating (b) conditions.

(a) (b)

Figure 4. Product view of tertiary crusher in half-full (a) and choke fed operating (b) conditions.

Table 4. Comparison of P_{80} (mm) of crusher product for half-full and super-choked conditions

Condition	Secondary crusher product	Tertiary crusher product	Final product
Half-full	77.30	35.37	32.17
Super choked	63.71	29.53	27.21

The key performance indicators including the throughput, power draw, specific energy (E_{cs}), amount of -32 mm product generated, and size specific energy at 32 mm are presented in Table 5. When operating the crushers in super-choked as opposed to half-full, 9.3% increase in the plant throughput, and the size specific energy at -32 mm decreased by 15.6%. Choked feeding of a cone crusher promotes inter-particle breakage, and consequently, lead to improved energy utilization and production of fines that consequently results in the crusher throughput increasing at a higher power draw. Analyzing the key performance indicators showed that the operating secondary and tertiary crushers in super-choked compared with the half-full condition enhanced the energy efficiency of the cone crushers. The improvement in energy efficiency could translate to a more capacity, a finer product, and a less production cost.

Table 5. Performance indicators for all crushers with half-full and super-choked conditions.

Condition	Throughput (t/h)	Power draw (kW)	Specific power, Ecs (kWh/t)	Amount of final product, -32 mm (t/h)	Size specific energy $SSE_{-32\ mm}$ (kW/t)
Half-full	846	344	0.41	678	0.51
Super-choked	897	379	0.42	872	0.43

4.2. HPGR circuit

Before the modifications, HPGR was operating in a non-standard operational condition. In order to increase the HPGR comminution efficiency, the operational pressure and the hopper level were modified. In the first step, the pressure and the hopper level were increased from 120 bar and 25% to 160 bar and 55%, respectively. Afterwards, the other operational parameter conditions were changed after the pressure and hopper level modifications (Table 6). Changing the operational pressure and hopper level caused increase in the reduction ratio from 1.8 to 2.4. The operation in the choked condition (more than 50% of hopper level) increased the inter-particle breakage, which promoted the propagation of cracks in the particles. Note that the hardness (grindability) of the product of the choked condition differed compared to that of the product of the half-full (25% of hopper level) condition. A snapshot view of the HPGR belt product in the operational pressures of 120 bar and 160 bar is shown in Figure 5.

Figure 5. HPGR belt product in the operational pressures of 120 bar and 160 bar.

The ideal mode of the HPGR product is a compacted cake or flake. As the figure shows changing the operational pressure causes the production of the proper product. In order to investigate this comparison, the standard BBWI (Bond Ball Mill Work Index) was conducted for the product of both operating modes. The product BBWI of the choked condition was obtained to be 14.9 ± 0.25 kWh/t as opposed to the BBWI of 16 ± 0.20 kWh/t for the half-full condition. This difference translates to a 7% reduction in the particle grindability. In addition, the bulk densities of flake relative to the real density in 120 bar and 160 bar are 72% and 84%, respectively. This highlights the efficiency improvement of the HPGR circuit. A summary of the modification results in the HPGR circuits is provided in Table 6.

Table 6. Average operational data of HPGR before and after operating modifications.

	Before modifications	After modifications
Fresh feed (t/h)	393	465
Throughput (t/h)	699	738
Operational pressure (bar)	120	160
Roll speed (RPM)	11.6	12.3
Hopper level (%)	25	55
Power draw (kW)	280	325
Reduction ratio RR80	1.8	2.4

5. Wet double screen unit

The wet screen audits showed that the aperture sizes of the first (7 rows) and second parts (1 row) of the upper deck were 14 mm and 30 mm, respectively. One of the most important factors involved in the screen performance is the open area that is the ratio of the net apertures area to the total area of the screening surface. With the fineness of the screen aperture, the open area generally decreases [1]. The screen upper deck works as a bumper or a scalper in order to prevent the scraps to HPGR. The use of panels with the 14 mm aperture size in the upper deck caused reduction of the screen open area. Consequently, the fine particles did not have enough time to pass through the upper deck, and thus caused that the whole screening area of the lower deck was not used for stratification, and some particles finer than the lower deck aperture size (6 mm) were recycled to HPGR. Due to this, the HPGR circulating load and the rejected materials increased and the screen product rate decreased. The aperture size of 2 rows of lower deck was increased from 6 mm to 8 mm. This change reduced the circulating load, while caused the transportation of coarse particles to the screen underflow, increased the wear rate of pipe lines and pump liners by 7%, and increased the particle size of hydrocyclones overflow. All of the mentioned issues reduced the screening efficiency. In order to improve the screen efficiency and decrease the rejected particles, it can be proposed to increase the aperture size of the upper deck from 14 mm to 30 mm (Figure 6). A comparison of the screening operation before and after the modifications is shown in Table 7.

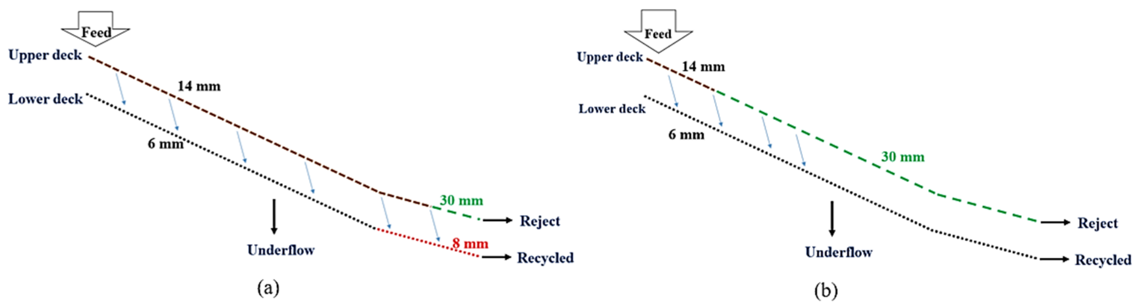


Figure 6. Wet double screen before (a) and after (b) modifications.

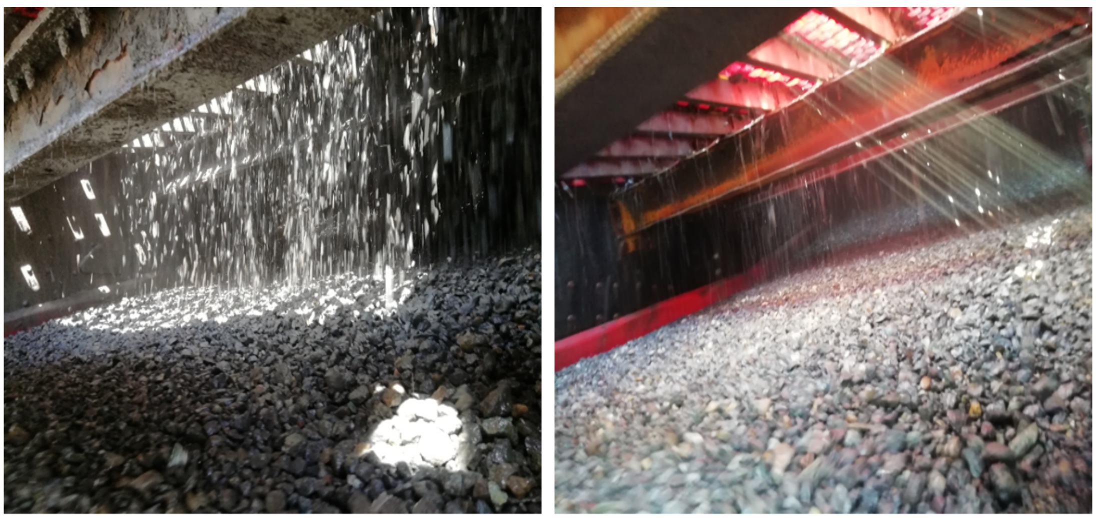
Table 7. Average operational data of screening before and after operating condition modifications.

Stream	Current operational data	
	Before modifications	After modifications
Aperture sizes of upper deck	14 mm (7 rows) 30 mm (1 row)	14 mm (2 rows) 30 mm (6 row)
Aperture sizes of down deck (mm)	8 mm (2 rows) 6 mm (6 rows)	6 mm (8 rows)
Feed (t/h)	699	738
Underflow (t/h)	387	463
Recycle (t/h)	306	273
-6 mm in recycle (%)	46	20
Material thickness on end of down deck (mm)	47	33
Reject to fresh feed (%)	~1.6	~0.5
Circulating load (%)	79	59
Screen efficiency (%)	63.5	89.5

As the results indicated, the feed and underflow rate increased from 699 and 387 t/h to 738 and 463 t/h, respectively. The amount of the desired product (-6 mm material) and the material thickness on the second deck decreased from 46% and 47 mm to 20% and 33 mm, respectively. Therefore, by modification, the circulating load decreased from 79% to 59% and the screen efficiency increased from 63.5% to 89.5%. In addition, the down-stream results indicated a reduction of the ball consumption from 565 g/ton to 535 g/ton. A snapshot of the recycled material before and after the modifications is shown in Figure 7. Figure 8 shows the spill situation from the upper deck and material flow on the second deck.

(a) (b)

Figure 7. Recycled material of screen before (a) and after (b) modifications.



(a) (b)

Figure 8. Material spill on second deck before (a) and after (b) modifications.

Note that these improvements did not incur additional costs, and could only be achieved by changing the process direction. Implementing the plant audit and process standardization not only reduced the operating costs (such as ball consumption) but also increased the revenue from the concentrate sales.

Since the throughput increase is also accompanied by a reduction in the operating cost, which means that the circuit production becomes closer to the desired value, the improvement in the efficiency of the process is more than what is estimated here. Implementing these simple modifications could increase the concentrate production at least 20 t/h and reduce the ball consumption by 30 g/t. In order to demonstrate the economic benefits of the project, only reduction in the ball consumption that saved $60,000 per year and cost of plant audit implementation were considered. The economic calculation for obtaining the project NPV is shown in Table 8.

Table 7. Economic calculation for obtaining project NPV.

		rd_{cost}	0.07	$rd_{benefit}$	0.12
	Year	0	1	2	3
Cost	Min possible	45000			
	Most expected	40000			
	Max possible	55000			
Saving	Min possible			55000	60500
	Most expected		60000	66000	72600
	Max possible		70000	77000	84700
PV cost	Min possible	45000			
	Most expected	40000			
	Max possible	55000			
PV saving	Min possible			43845.66	43062.70
	Most expected		53571.43	52614.80	51675.25
	Max possible		62500.00	61383.93	60287.79
PV project	Min possible	-45000.00	62500.00	61383.93	60287.79
	Most expected	-40000.00	53571.43	52614.80	51675.25
	Max possible	-55000.00	0.00	43845.66	43062.70
NPV project	Min possible	139171.72			
	Most expected	117861.47			
	Max possible	31908.37			

(NPV: Net Present Value, rd_{cost}: discount rate of cost, $rd_{benefit}$: discount rate of benefit)

As indicated in Table 8, the economic advantage of this project is significant, and by applying simple, low-cost and wise routes, a highly economic leverage is achievable. This is the method that can be used by the other plants.

6. Conclusions

In this research work, in order to increase the comminution circuit efficiency, the process audit and some low-cost modification routes were presented, and implemented at the iron ore crushing and pre-grinding plant of the Steel-Sirjan Iron Ore Complex. To do this, the plant operating manuals and standard process procedures were studied, the main process data was analyzed, and the proper solutions were proposed and implemented. The main defects observed were as follow: the crusher operation in the half-full condition, the HPGR operation in the non-standard condition, high amounts of the rejected materials in the HPGR circuit, and a low efficiency of the screen. Based on the data analyzed, a series of modifications were implemented in the crushing and grinding circuit.

- It was shown the super-choked condition of the crushers reduced P_{80} of the final product and the size specific energy at -32 mm by 15.2% and 15.6% compared to the half-full mode. Also the crushing plant throughput was increased by 9.3%.
- By increasing the HPGR operational pressure (120 bar to 160 bar) and the hopper level (25% to 55%), the particle grindability measured as BBWI was decreased by 7%. In addition, the reduction ratio increased from 1.8 to 2.4.
- By increasing the aperture size of the upper deck from 14 mm to 30 mm (useful area), the circulating load decreased from 79% to 59%, and the screen efficiency increased from 63.5% to 89.5%. Also the amount of the rejected materials decreased from 1.6% to 0.5%.
- An increase of at least 20 t/h in the concentrate production and a reduction of 30 g/t in the ball consumption were achieved by implementing the proper modification.

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بکارگیری روش‌های کم هزینه برای بهبود عملکرد مدار خردایش مجتمع سنگ آهن فولاد سیرجان

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چکیده:

انرژی مصرفی تجهیزات خردایش، بخش عمده‌ای از هزینه عملیاتی کارخانه‌های فرآوری مواد معدنی را تشکیل می‌دهد. به همین منظور، تلاش‌های زیادی برای افزایش کارایی این تجهیزات انجام شده است. در این تحقیق، بازرسی فرآیند در کارخانه فرآوری مجتمع سنگ آهن فولاد سیرجان به منظور یافتن راه حل‌های کم هزینه برای بهبود بهره وری و کیفیت محصول و کاهش هزینه‌های نگهداری انجام شد. سه مرحله اصلی بازرسی فرایند عبارت بودند از (۱) مطالعه دستورالعمل‌های عملیاتی و بررسی روش‌های راهبری فرایند، (۲) تجزیه و تحلیل داده‌های فرایند و (۳) پیشنهاد و اجرای راه حل‌های مناسب. بازرسی فرایند کارخانه، کارآیی پایین مدار و تجهیزات را نشان داد. نتایج بررسی‌ها نشان داد، مشکلات اصلی، کار سنگ شکن در حالت نیمه پر، شرایط غیر استاندارد آسیای غلتکی فشار بالا (HPGR)، میزان بار در گردش زیاد در مدار HPGR و بازدهی پایین سرند بود. جهت رفع این مشکلات، یک سری تغییرات در مدار سنگ شکنی و آسیاکنی انجام شد. این اقدامات باعث افزایش ۹/۳ درصدی در ظرفیت کارخانه سنگ شکن در شرایط پرکار کردن سنگ شکن در مقایسه با شرایط نیمه پر شد. با افزایش فشار عملیاتی HPGR و سطح قیف خوراک‌دهی، BBWI محصول HPGR در حالت خفه از ۱۶±۰/۲ کیلووات ساعت بر تن به ۱۴/۹±۰/۲۵ کیلووات ساعت بر تن کاهش یافت. با اصلاح فرایند سرندکنی، میزان بار گردش از ۷۹ به ۵۹ و کارایی سرند از ۶۳/۵ به ۸۹/۵ درصد افزایش یافت.

کلمات کلیدی: بازرسی فرآیند، سنگ شکن فکی، سنگ شکن مخروطی، آسیای غلتکی فشار بالا، سرند.