OPTIMIZATION OF THE DAMANG MINE

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ABSTRACT

Abosso Goldfields Limited has been optimizing the comminution circuit at the Damang Mine Operation for the treatment of 100% primary ore. The optimization process started at a base rate of 343 tph when treating primary crushed primary ore, and was increased to above 600 tph with partially crushed primary ore. Abosso Goldfields engaged Orway Mineral Consultants (OMC) to assist with the optimization process in 2009 and the two companies have been working together since, to further refine the process. Continuous improvement was achieved through crushing circuit modifications, changes in operating processes and grinding control system utilization. This paper discusses the improvements developed for the increase in milling capacity and improvements in final product size.

KEYWORDS

Optimization, Damang Mine, Coarse Tertiary Crushing, comminution, modelling

INTRODUCTION

Abosso Goldfields Limited approached OMC in 2009 to assist in the optimization of their comminution circuit, and to propose plausible circuit modifications to allow processing in excess of 600 tph of primary ore, achieving a product size (P_{80}) of 125 - 150 µm. A partial coarse tertiary crushing circuit was implemented to achieve the throughput and the grind size. This option was selected following comminution circuit modelling utilizing real survey data. In 2010, after commissioning the partial coarse tertiary crushing circuit, Abosso Goldfields Limited in conjunction with OMC, continued with post commissioning optimization. The changes to the Damang Mine, as developed by Abosso Goldfields Limited and OMC, are discussed in this paper.

Background

The DAMANG MINE Mineral Resource Management Team (2010) reported that the Abosso GoldFields Limited – Damang Mine is situated in South Western Ghana, approximately 300 km by road west of the capital Accra, at a latitude 5º11'N and longitude 1º57'W. The closest town of Tarkwa is some 30 km to the south with reasonable access roads and a main road connecting the town to the port of Takoradi a further 90 km south.

The Damang Mine exploits oxide and fresh hydrothermal mineralization in addition to Witwatersrand style, palaeoplacer mineralization.

CIRCUIT DESCRIPTION

In 2009, prior to the optimisation, the comminution circuit was configured as follows:

Crushing Circuit

The primary crusher, a 54/75 gyratory with open size setting (OSS) of 140 - 160 mm, was designed to receive feed from either front end loaders (FEL) or direct tip dump trucks. Ore was crushed and drawn from the crusher vault by an apron feeder at a regulated rate onto conveyor 1 (CV01). CV01 discharged onto conveyor 2 (CV02), via a right angle transfer station, and discharged onto the coarse ore stockpile.

Stockpile and Milling Circuit

Primary crushed ore was reclaimed from the stockpile via two apron feeders with a third emergency apron feeder provided. The feeders discharged onto conveyor 3 (CV03), the Semi Autogenous (SAG) mill feed belt. The SAG mill feed, together with recycled crushed pebbles, were fed into the SAG mill.

The SAG mill, Ø8.0 m x 5.46 m effective grinding length (EGL), was installed with a 5.8 Megawatt (MW) motor. The mill motor is equipped with a slip energy recovery (SER) variable speed drive however this could not be utilized due to power stability issues and therefore the mill was operated at fixed speed, 79.2% critical speed (Nc) or 12 revolutions per minute (rpm).

The SAG mill discharged over a trommel with 15 mm slotted apertures. Trommel oversize was then washed on a dewatering screen with a 5 mm aperture prior to crushing by a cone crusher, Metso HP500 with a closed side setting (CSS) of 12 mm. The crushed pebbles recycled back to the SAG mill feed conveyor. The trommel and dewatering screen undersize gravitated into the SAG mill discharge hopper and this mixture was pumped to the ball mill feed.

The overflow ball mill, Ø6.1 m x 9.0 m EGL fitted with a 5.8 MW drive, received feed from both SAG transfer and cyclone underflow. The ball mill discharge passed through a trommel and into the cyclone feed hopper.

The ball mill product was combined with the gravity tail in the cyclone feed hopper and pumped to the cyclone cluster for classification. The cyclone cluster consisted of 16 x 400 Cavex (CVX) cyclones. Typically 7 - 8 were operated at any time. The cyclone overflow reported to the carbon in leach (CIL) trash screen and the cyclone underflow gravitated to the ball mill feed for further size reduction. A portion of cyclone underflow was bled to the gravity circuit to scalp free gold. The gravity circuit was split into two trains; each consisting of a scalping screen and a 48 inch Knelson concentrator. The scalping screen oversize and Knelson tails recombined and flowed via gravity into the cyclone feed hopper.

The circuit is graphically presented in Figure 1.

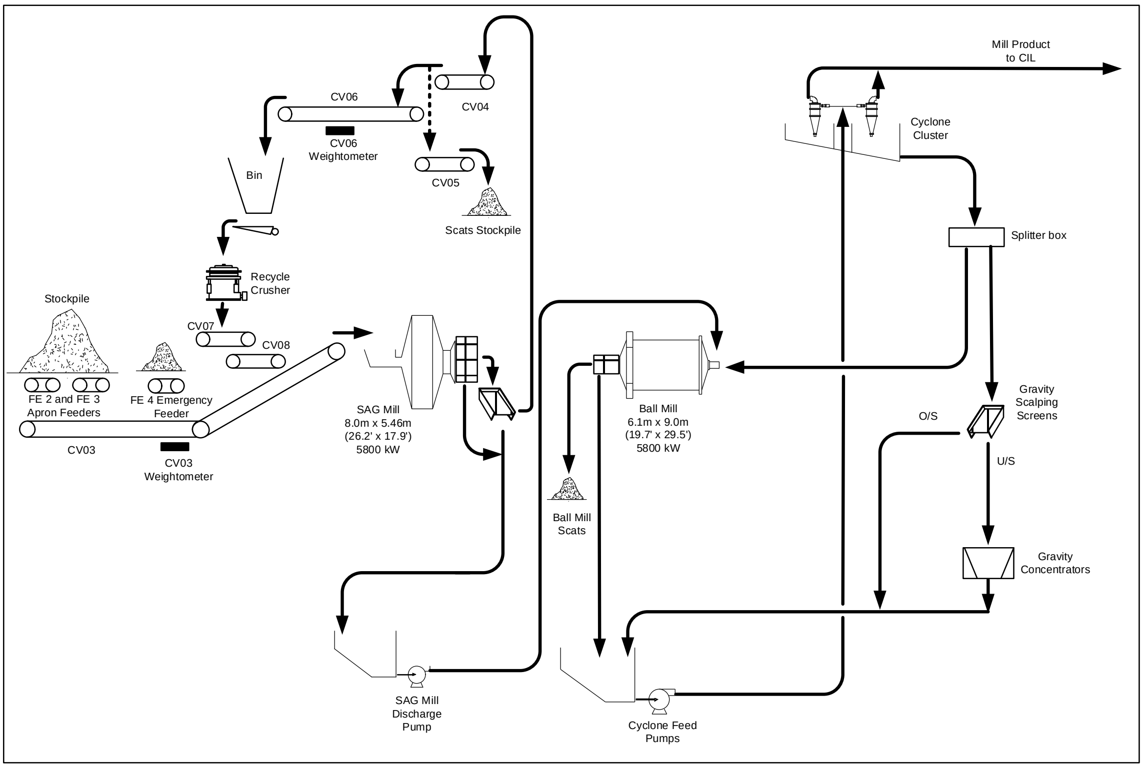

Figure 1 - Grinding circuit process flow diagram

PRODUCTION DATA (Q1 2009)

Production data from the first quarter of 2009 (January 1 – March 31) was analyzed and showed that the Damang plant averaged 659 tph while treating approximately 50% primary ore and achieved a P_{80} of 149 µm. When 100% primary ore was treated, throughput between 300 and 400 tph was achieved. Production data also indicated that the SAG mill was operated at 92% of installed power while only 62% of ball mill installed power was utilised. This indicated that the circuit was constrained by the SAG mill (SAG mill limited), even while treating oxide blends.

Figure 2 and 3 showed that the throughput rate was decreasing despite the percentage of primary ore trending downwards. The SAG power draw on the other hand was trending upwards, which was a sign that the ore was getting more competent or the feed was getting coarser. This confirmed that the grinding circuit was soon to be limited by the SAG mill at lower than budgeted capacities.

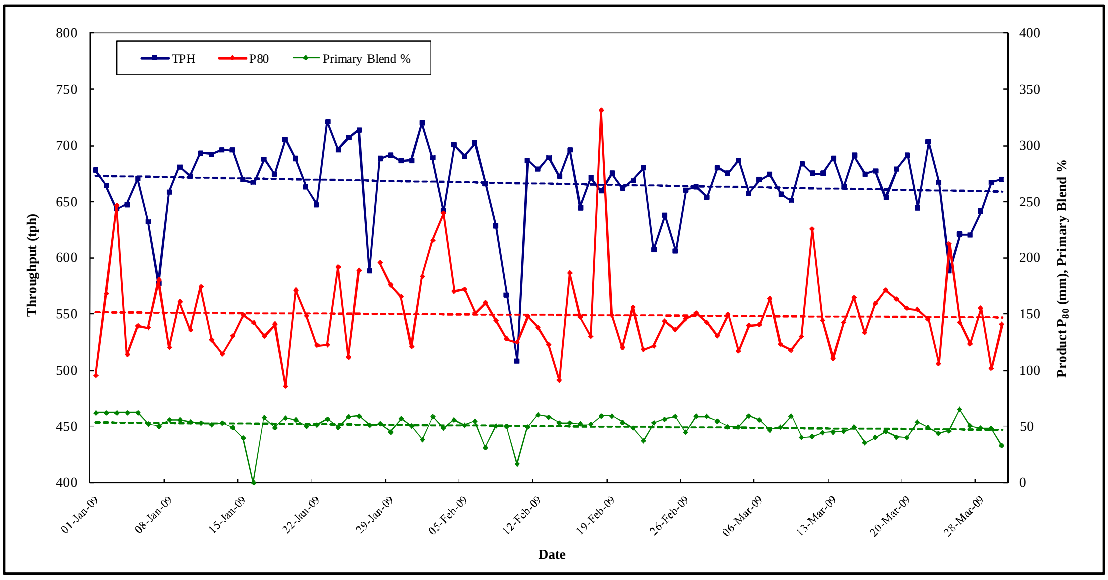

Figure 2 - Throughput, product size (P_{80}) and percentage of primary blend

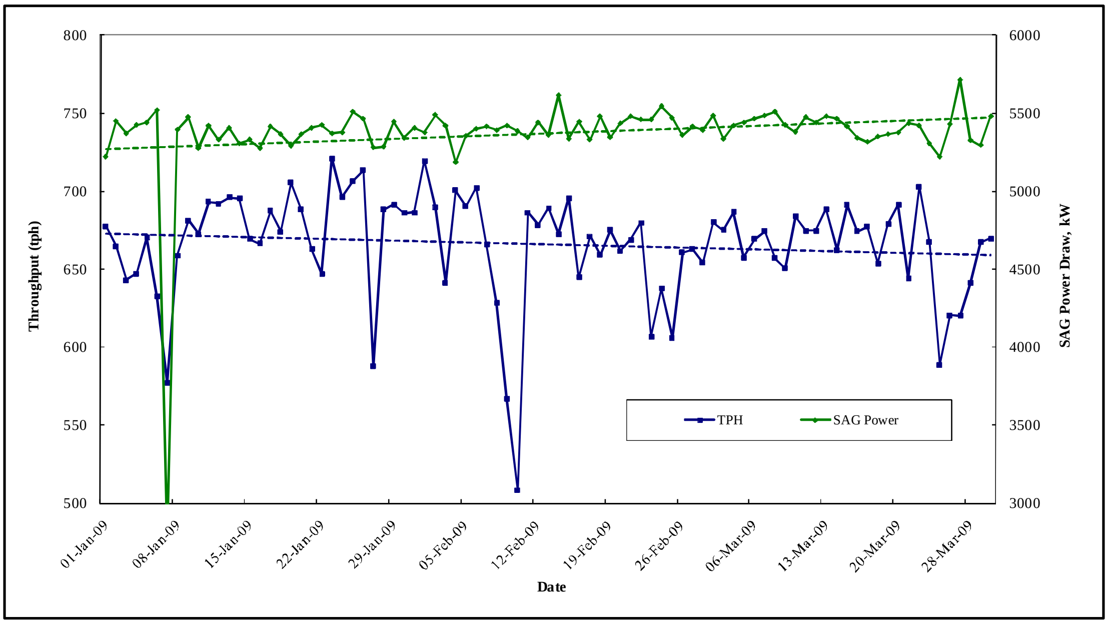

Figure 3 - SAG power draw in kilowatts (kW) vs. throughput (tph)

ORE CHARACTERISTICS

Two grinding circuit surveys were conducted, one on a blend of primary and oxide ore, while the other, was solely on primary ore. A sample of the SAG mill feed from each survey was submitted for SAG mill comminution (SMC) testing and Bond work index (BWi) determinations. The testwork results showed that the primary ore was extremely competent with an Axb of 29.6 and a crushing work index (CWi) of 22.9kWh/t. This is in agreement with the high SAG mill specific energy requirement. When examined, the testwork results indicated an imbalanced power requirement when treating primary ore at a coarse product size. This was demonstrated in the plant with the SAG mill drawing close to maximum power and the ball mill being underutilized.

Table 1 presents the survey testwork parameters.

Table 1 – Primary ore and oxide ore characteristics

Parameter	Units	Survey 1	Survey 2	Oxide
Feed Blend (Primary : Oxide)		100 : 0	57.1 : 42.9	0 : 100
BWi	kWh/t	15.7	15.9	14.6
Mill Feed CWi	kWh/t	22.9	-	-
Recycle Crusher Prod. CWi	kWh/t	39.7	-	-
SG		2.8	2.8	-
SMC Testwork				
DWi		9.1	7.5	-
Mi_a		23.7	20.3	-
Mi_h		18.6	15.4	-
Mi_c		9.6	8.0	-
A		73.9	64.5	-
b		0.4	0.6	-
A x b		29.6	38.7	-
ta		0.3	0.4	-

OBSERVATIONS

In addition to the plant data analysis, OMC also observed the following during the audit and circuit survey:

- Large variation in calculated milling efficiencies
- Packing between SAG mill lifters
- Large surges in the SAG mill feed rate
- SAG mill discharge fed directly to the ball mill
- Product grind size was coarser than target, although sufficient power was available in the ball mill

OPTIMIZATION STRATEGIES

Recommended optimisation strategies can be sub-categorised as options that could be immediately implemented, and future short term implementations that would require engineering and structural modifications to the circuit.

Based on the observations during the audit and the surveys of the comminution circuit, the following conclusions were drawn, and the corresponding optimisation strategies were recommended for immediate implementation:

- The large variation in the circuit efficiency and the product size suggested that improving the control philosophy was necessary It was recommended that increasing the ball milling density would improve the grind size reduction and reducing the cyclone feed density would improve the cyclone cut size and product P_{80}

- The SAG mill lifter face angle and spacing was reviewed to determine the effects of packing and subsequent impact damage on the liners from the grinding balls. Due to the fixed high speed of the SAG mill (79.2% Nc), the packing that occurs between the lifters when new is necessary to protect against direct ball impact on the liners. As the lifters wear, the face angle of the liners increases and the ball trajectory is reduced, minimising direct strikes to the liners. Packing between the lifters is also reduced. No action was required to the liner angles as the current configuration was not deemed detrimental
- The rate of pebble production was 100tph; however the batch recycle crushing rate was 250 tph which introduced surges of crushed pebbles to the SAG feed as the crusher cycled. These surges from the pebble crushing circuit contributed to large surges in the SAG mill feed rate. To stabilise the SAG mill feed rate, it was recommended that the pebble crusher be utilized continuously (trickle feed) instead of on-off operation or at least increase the on-off frequencies. It was noted that this may cause higher wear and maintenance costs for the crusher, and should be monitored

Future Short Term Implementations

The following implementation strategies required engineering and structural modification to the circuit. As such, they were recommended as future short term implementations.

- Direct the SAG mill discharge to the cyclone feed hopper to undergo classification and remove product size material from the ball mill feed, prior to being fed to the ball mill. This will minimize the energy loss for over grinding and reduce volumetric flow through the ball mill
- Install larger cyclone spigots to increase circulating loads to flush the fines from the mill, as well as increase the ball mill discharge density to improve grinding efficiency
- Install a leach feed thickener to enable the cyclones to operate at a more dilute feed density. High feed densities typically cause short circuiting in the cyclones, whereby product size material miss reports to underflow. A leach feed thickener, in conjunction with efficient cyclone operation, would reduce this occurrence

ACHIEVING ABOVE 600 TPH ON 100% PRIMARY ORE

The Damang plant processed primary ore, which was generally hard and was blended with oxide/lateritic ores at various percentages to achieve optimum throughput. The feed blend ratio ranged between 60% - 63% primary and 37% - 40% oxide ore. This blend ensured a mill throughput of 5.2 Mt per annum.

The grades of the primary ore were higher than that of the oxide ore. It was anticipated that maximum gold production would be achieved with a high proportion of the primary component in the mill feed. It was identified however, that the previous arrangement of the crushing system would have a detrimental impact on the throughput, which in turn would decrease gold production if only hard ore was to be treated. Additionally the current life of mine (LOM) plan estimated that the weathered ore would be exhausted by 2012.

Given this, the only option available was to process 100% primary ore, resulting in a considerable reduction in gold production. In order to achieve gold production targets, it is necessary to modify the comminution circuit to increase primary ore throughput.

OMC recommended a partial coarse tertiary crushing circuit (open or closed circuit) for the treatment of above 600tph of 100% primary ore. Partial coarse tertiary crushing was selected for two reasons:

- To retain some presence of coarse rock in the feed to provide media and load in the SAG mill. The maximum ball charge allowed in this mill is 15% and media/load is required to protect the liners from ball impact damage as there is no speed control available to control ball trajectory.

- To balance the grinding power requirements between the two stages, allowing throughput and grind size to be optimized

Two crushing circuit configurations were considered; open circuit and closed circuit. The configurations are presented in Figure 4 and Figure 5. In order to maintain throughput in excess of 600 tph, a large portion of the feed is required to be crushed to less than 30 mm. Scalping the mid size fraction of the primary crushed product was not a viable solution. To achieve 85 - 90% crushing, the open circuit would have had to be configured as shown in Figure 4.

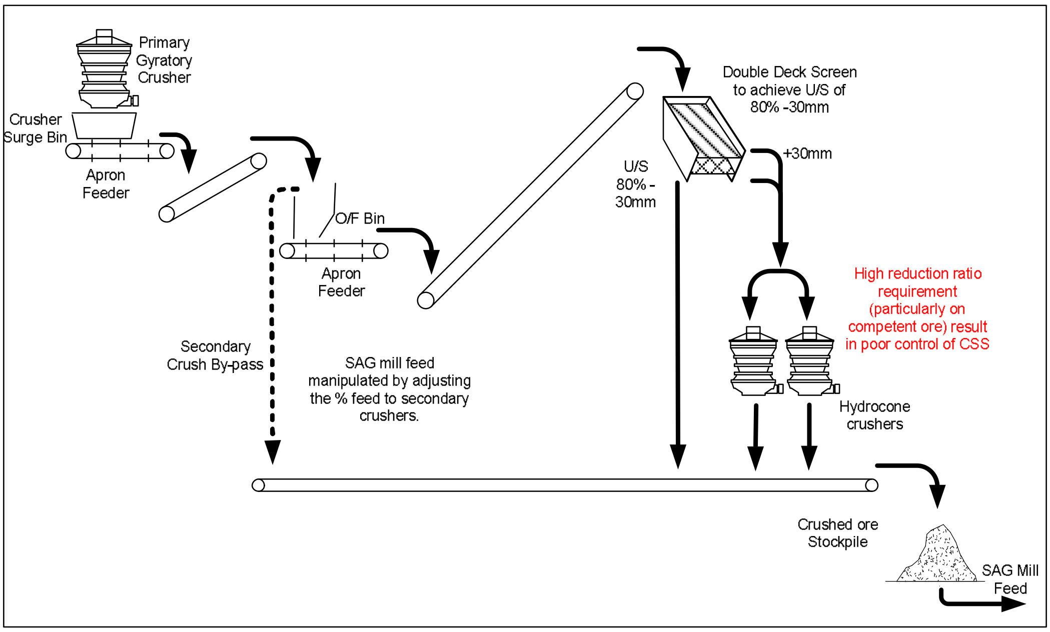

Figure 4 - Open circuit secondary crushing block flow diagram

The cone crushers operating in open circuit configuration are likely to be power limited and therefore it would be difficult to maintain the gap closed side setting on the crushers. This problem becomes more pronounced with very competent ores. The effect is an inconsistent product size. If the closed circuit configuration runs into a power limited scenario, it would restrict throughput, however product size would be more consistent. Consistent crusher product is crucial for maintaining load in the SAG mill. The circuit would be much more stable and easier to control in closed circuit configuration and for this reason, this circuit was favoured.

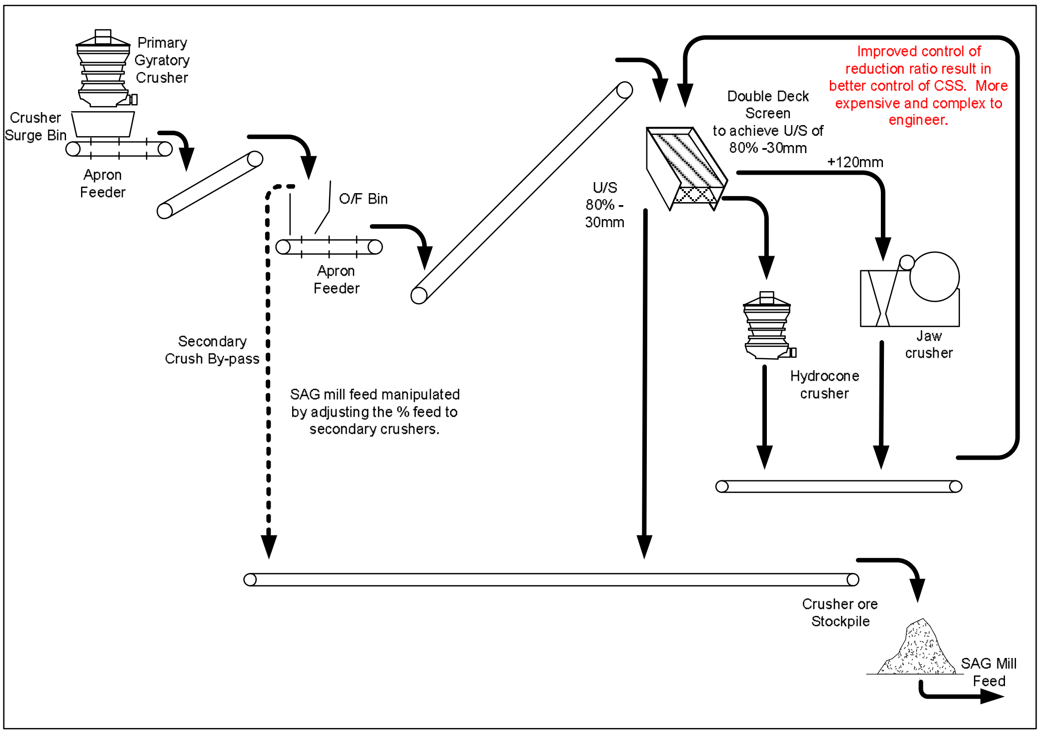

Figure 5 - Closed circuit partial coarse tertiary crushed

Excess coarse rock would be difficult to crush given rock competency and the required reduction ratio. Preliminary modeling indicated that the available H4800 crushers could not undertake the duty in a single stage. For this reason, a secondary crusher was incorporated into the design, essentially making the design partial coarse tertiary crushing. The top size from the primary crusher will be scalped off and fed to the secondary jaw crusher to allow a more controlled top feed size to the tertiary cone crushers. Figure 5 shows the secondary jaw crusher incorporated into the flowsheet.

The recommended coarse rock by pass for the competent ore was 10 - 15% in order to achieve above 600 tph. Modelling indicates this will achieve utilisation of up to 5.5 MW in the SAG mill and ball mill, grinding to a product size P_{80} of 106 µm.

IMPLEMENTATION OF PARTIAL COARSE TERTIARY CRUSHING CIRCUIT

In November 2010, Abosso Goldfields requested OMC to conduct a comminution circuit survey and audit. The aim of this work was to accelerate ramp up of the circuit following commissioning of the tertiary crushing circuit. The comminution circuit was configured as follows:

Crushing Circuit

Figure 6 presents the flowsheet of the modified partial closed tertiary crushing circuit.

The primary gyratory crusher operated as per previous with no changes. The discharge conveyor 1 (CV01) was modified to divert to a new conveyor 10 (CV10) which feeds the new double deck screen.

The double deck screen, was fitted with a 100 mm x 100 mm top deck and a 30 mm x 40 mm bottom deck, and it produced three product streams.

The double deck screen top deck oversize reported to the secondary crusher, crusher 3 (CR3) via conveyor 11 (CV11) or was diverted to conveyor 15 (CV15) and to the SAG stockpile. The secondary crusher was operated in open circuit. A hydroset type cone crusher was selected instead of a jaw crusher proposed as it enabled a more efficient size reduction (allowed tigher closed side settings).

The double deck screen bottom deck oversize reported to the tertiary crushers, crusher 4 (CR4) and crusher 5 (CR5) via conveyor 12 (CV12).

The double deck screen bottom deck undersize reported to the SAG mill feed stockpile via CV15, which tied in to CV02. The tertiary crushers operated in closed circuit with a separate single deck product screen.

The CR3, CR4 and CR5 products were combined via conveyor 14 (CV14) and conveyed to the single deck screen. The single deck oversize stream reported back as the tertiary crusher feed via CV12 (combined with the double deck middlings), while the single deck screen undersize combined with the double deck screen undersize. Both products reported to the SAG mill feed stockpile via CV02.

The crusher by-pass feeder 09 (FE09) was available to divert coarse lump rock directly to the stockpile as required to achieve the desired SAG feed particle distribution, nominally 10 – 15% of the total circuit throughput.

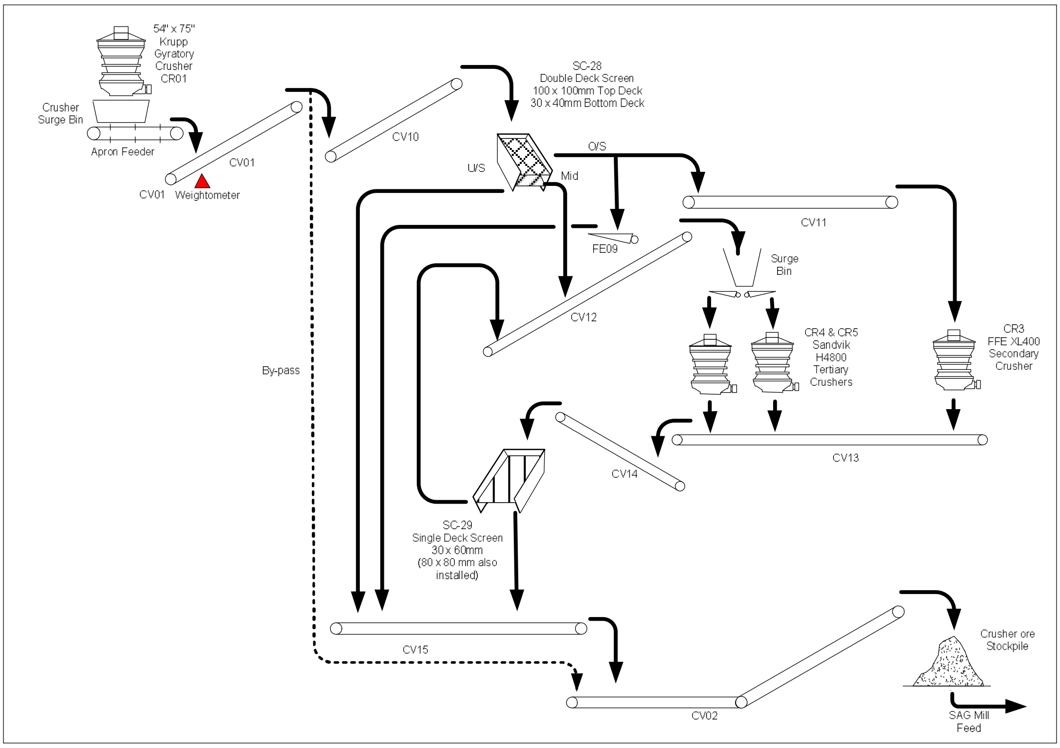

Figure 6 - Damang mine tertiary crushing circuit process flow diagram

Stockpile and Milling Circuit

The stockpile and milling circuit had not undergone any major changes, except for the provision to direct the SAG mill discharge to the cyclone feed hopper. The option to pump SAG discharge to the ball mill feed still exists.

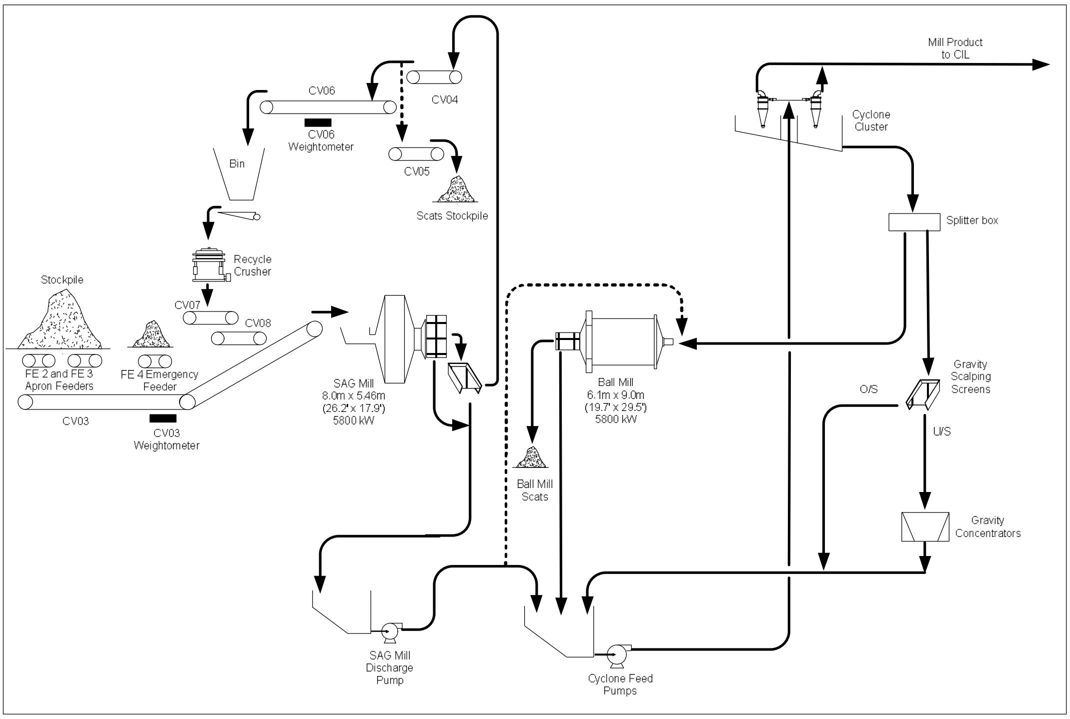

Figure 7 – Damang mine grinding circuit process flow diagram

PRODUCTION DATA ANALYSIS (3Q2010)

Production data from a period of the third quarter of 2010 (August – October) was analyzed and it showed that the Damang plant averaged 613 tph while treating 100% primary ore. This was marginally short of the Abosso Goldfields business plan target throughput of 628 tph. The daily sizing of the grinding circuit product composite was consistently above the target grind size of P_{80} 106 µm. The feed rate to the SAG mill was erratic, resulting in an inconsistent SAG mill power draw. This erratic feed rate was attributed to the difficulty in maintaining consistent rock content to the mill from lack of control over the coarse lump rock bypass feeder, FE09.

In addition to control issues, the mill feed ore characteristics had changed from design samples tested, with a higher CWi and BWi's coupled with a lower competency, A x b. The following table details the change in ore characteristics.

Table 2 – Ore characteristics comparison

Parameters	**Units**	**Survey Blend 3^{rd} April 2009**	**Survey Blend 6^{th} November 2010**
Feed Blend (Primary : Oxide)		100 : 0	-
CWI	kWh/t	22.9	27.9 (increased)
Mill Feed BWI	kWh/t	15.7	16.6 (increased)
Closing screen	µm	-	106
Ore SG		2.8	2.7 (lower)
SMC Testwork			
DWI	kWh/m^3	9.1	5.91
A		73.9	62.0
b		0.4	0.72
A x b		29.6	44.6 (less competent)
ta		0.3	0.44

OBSERVATIONS

A post commissioning analysis identified a number of operational issues that needed to be addressed in order to optimise the comminution circuit performance. These issues are:

- The slow feeder FE09 rate was causing blockage of trouser leg chute, resulting in inconsistent retention of coarse grinding media
- High screen deck loads on single deck screen
- Low volume of ore on stockpile
- Segregation of coarse and fines on tertiary crushed stockpile
- Manual discharge hopper water addition at the ball mill which resulted in variable densities to the cyclone
- Manual control for cyclone on-line/offline which resulted in variable cyclone operating pressure

CIRCUIT ANALYSIS

The role of the crusher by-pass function is to direct coarse lump rock directly to the stockpile, as required, to achieve the design SAG feed particle size distribution. The design of the coarse rock by-pass is not achieving the goal of providing a controlled amount of coarse lump grinding media due to the selection of a vibrating feeder, which made control of the by-pass proportion difficult.

The feeder was originally running very slow in an attempt to get a continuous feed of +100 mm material to by-pass the secondary / tertiary crushers. This however caused the material to frequently block the trouser leg chute.

The speed of the feeder was then increased to overcome the blockage problem, however this caused the feed rate to become excessive.

In addition, the coarse material continued to flow for a period after the feeder has stopped. Essentially there was no control over the amount being by-passed. Measures were taken to improve the desired percentage by-pass control.

Based on screen modeling, the single deck screen load was calculated at 122% load, with 84% screening efficiency. This indicated that the screen was over loaded during the survey. Screen efficiencies of 84% indicated that approximately 16% of screen undersize material would misreport to screen oversize.

CAUSE AND EFFECT

Control of the coarse lump by-pass proportion to the SAG feed is critical for the operation of the circuit as it enables control of the power balance between the SAG mill and ball mill.

Without sufficient coarse material in the SAG mill, a sufficient load could not be maintained. This resulted in low power draw, due to the reduced weight of the charge, and in turn a reduction in grinding media which exposed the mill liners to direct impact damage.

With the absence of the required power and media in the SAG mill, the finely crushed feed passed through the mill at high throughput rates and resulted in a much coarser feed size to the ball mill. The ball mill in turn did not have sufficient power to process the ore at such extreme conditions, causing the ball mill to become the circuit bottleneck.

The cyclones were operated at extremely high densities resulting in an increase in product size. As a consequence of this, downstream problems, mainly recovery, sanding up of the circuit and grit in the carbon were observed.

On the other hand, when too much coarse material was fed to the SAG mill, the mill load and power increased and restricted throughput.

The lower throughput translated to a finer product size due to the power available in the ball mill. These extremes demonstrated the importance of balancing the mix of coarse and fines in the feed. The middling fraction (-100 +30 mm) was to be minimized.

AUDIT RECOMMENDATIONS

Based on the issues experienced in the crushing and grinding circuit, the following recommendations were made to stabilize the comminution circuit performance:

- Installation of chains to stop the flow of material from feeder FE09 once stopped and to help regulate the feed rate with changes in feeder speed
- Operate the feeder on a timed on-off basis if difficulties in operation persisted
- Operate the stockpile at higher live capacity to reduce the segregation of coarse rock from fines, and to provide some surge between the crusher and the milling circuit
- Remove the 80 mm x 80 mm panels on the single deck screen and replace with a 48 mm x 48 mm to reduce the screen load and therefore improving screening efficiency. A 94% screen efficiency and 86% load was calculated for the change in aperture
- Control the cyclone feed pump speed to maintain a constant cyclone pressure. The water addition to the hopper would be varied to maintain a constant hopper level which results in variation in the density of the cyclone feed but consistent pressure for better product size and circulating load control

With the constant pressure strategy, the cyclone feed density changes with the circulating load, thereby changing the cut point of the cyclone. If the circulating load increases (due to insufficient grinding power for the cyclone P_{80}), the cyclone feed density increases and thus the product size increases to match the available power.

If the circulating load decreases, the cyclone feed density decreases thus lowering the product size. In this way the product is self compensating, matching the available power and prevents rapid changes in circulating load.

Site personnel reported that the first four recommendations have been implemented which has led to consistencies in the mill feed and improvements in the milling circuit. The coarse lump by-pass feeder is now operated on a 10 minute on / 30 minute off basis while the single deck screen was replaced with a 40 mm x 55 mm aperture deck to control critical feed size to the SAG mill.

ACHIEVING TARGET THROUGHPUT

Historical modelling indicated that the SAG mill feed should contain no more than 15% coarse material if the required grind was to be achieved at 600 – 650 tph. A new model of the circuit was constructed from the most recent survey results. The modelling indicated that a maximum throughput of 539 tph was predicted for a P_{80} of 106 µm. 641 tph was predicted for a coarse P_{80} of 160 µm. These predictions assumed a 10% lump feed.

With 15% lump feed to the SAG mill, a maximum throughput of 536 tph could be obtained for P_{80} 106 µm. A throughput of 639 tph was predicted with coarse P_{80} 160 µm. These predictions were based on the utilization of 5.1 MW in the SAG mill and 5.0 MW in the ball mill. The power draws were down-rated from previous predictions due to volumetric constraints in the ball mill which impacted on the power draw.

As for the SAG mill, it was decided to utilize a sustainable power draw point of 5.1 MW, which has been achieved during operation.

Table 3 - Partial coarse tertiary crush power utilisation

Parameters	Units	Base Case Survey	Sim 1	Sim 2	Sim 3	Sim 4
			Target P_{80}	**Coarse P_{80}**	**Target P_{80}**	**Coarse P_{80}**
			10% rock		**15 % rock**	
Net Milling Rate	tph	639	539	641	536	639
Feed F_{80}	mm	113	32	32	36.5	36.5
Product P_{80}	µm	**231**	**106**	**160**	**106**	**160**
SAG Mill Pinion Power	kW	4,579	5,100	5,100	5,100	5,100
Recycle Crushing (% of new feed)	%	17.8	21.2	17.7	21.3	17.8
Ball Mill Pinion Power	kW	4,320	5,000	5,000	50,00	5,000
Energy Utilization						
Spec Crush Energy from 150mm to F_{80}		0.1	0.8	0.8	0.7	0.7
SAG Mill Specific Energy	kWh/t	7.2	9.5	8.0	9.5	8.0
Recycle Crusher Specific Energy	kWh/t	0.3	0.3	0.3	0.3	0.3
Ball Mill Specific Energy	kWh/t	7.0	9.3	7.7	9.3	7.8
Total Specific Energy	kWh/t	14.5	19.9	16.9	19.9	16.8

Another option proposed to achieve the budgeted throughput of 629 tph for a product size of P_{80} 106 µm was the installation of an additional 2.6 MW ball mill.

It can be seen that with a combination of proper control of the feed size, utilization of available power and changes in the operating control philosophy, the Damang mine would be able to achieve the target throughput at the coarser product size.

As opposed to previous predictions, the additional power required in the milling circuit was due to the finer product size targeted (106 µm compared to 125 µm) and the change in Bond ball mill work index.

CONCLUSIONS

The process to improve the Damang comminution circuit involved several surveys, audits, desktop modeling, crushing circuit installation, and regular communication between site personnel and OMC staff. It was also crucial to understand the behaviour/characteristics of the ore, the limitations of the existing circuit and place importance on the selection of suitable equipment to meet the processing of 100% primary ore at target throughput rates.

Following circuit modelling by Orway Mineral Consultants, the Damang mine adopted a partial coarse tertiary crush feed to the SAG mill to enable the treatment of 100% competent primary ore through their existing circuit and thus achieve increased primary ore throughput. Modifications were undertaken through the addition of a tertiary crushing circuit to scalp out coarse lump and crush the remaining SAG feed. The manipulation of the primary feed size distribution through partial crushing allowed the available power in the existing SAG and ball mill to be optimised and controlled to achieve the target throughput at desired grind sizes.

It was crucial to the operation to maintain the balance of lump and fines to ensure the right feed size distribution to the SAG mill. Change to the control philosophy on the operation of the classification circuit was also crucial to ensure that the grinding circuit throughput was maximized at all times.

ACKNOWLEDGEMENTS

OMC would like to thank the personnel of the Damang Mine for their constant efforts in working alongside and engaging OMC for this project and their aim in continual improvements.

NOMENCLATURE

A	=	Ore impact breakage parameter
b	=	Ore impact breakage parameter
BWi	=	Bond Ball Mill work index (kWh/t)
CWi	=	Crushability work index (kWh/t)
DWi	=	Drop weight index (kWh/m^3)
Mi_a	=	Work index related to the breakage property of an ore for grinding from the product of the final stage of crushing to P_{80} of 750 µm (coarse particles) (kWh/t)
Mi_b	=	Work index related to the breakage property of an ore for grinding from 750 µm to the final product P_{80} normally reached by conventional ball mills (fine particles) (kWh/t)
Mi_c	=	Crushing ore work index provided directly by the SMC® Test (kWh/t)
ta	=	Abrasion ore parameter, $^1/_{10}{}^{th}$ of the rate of t_{10}
t_{10}	=	Percent passing $^1/_{10}{}^{th}$ of the initial mean particle size

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