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Shifting the Comminution Workload from Secondary to Regrind Stage: An Energy Efficient Approach

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ABSTRACT

A novel approach to the circuit design through smart application of conventional processing units is the most viable solution to overcome the challenges in the mining industry when dealing with low-grade, competent, and finely disseminated ores. Construction of large-scale concentrators with large grinding mills such as SAG and ball mills does not solve the intrinsic limitations of that equipment in treating the challenging ores. Conversely, additional grinding power in the secondary stage or introduction of the tertiary stage grinding are the typical options for the brownfield expansion. This paper is proposing an alternative approach to process low-grade, competent and finely disseminated ore bodies. The idea is to shift the grinding workload from secondary grind stage to regrinding stage by coarsening the SAG-Ball mill-crusher (SABC) circuit product to 300 μm and introducing the coarse flotation in between the secondary and regrind stages plus introducing the energy efficient grinding technology such as the TowerMill to prepare the feed for rougher flotation with particle size of 95 μm. A simulation study was done using the SABC and TowerMill circuit model from industrial survey data. The comparison study had shown that the proposed circuit consumed 42 % less energy and 23 % lower operating cost (OPEX) compared to the conventional SABC with a tertiary grinding ball mill to prepare 95 μm rougher flotation feed. Furthermore, the recovery in the rougher flotation was 2 % higher due to narrow particle size distribution. Based on these outcomes, there are opportunities to improve the comminution circuit energy efficiencies and reduction in comminution OPEX by shifting the workload from secondary to regrind stage.

INTRODUCTION

Low-grade ore bodies, increased in rock competency, finely disseminated valuable minerals in the ore bodies, ore variabilities and water scarcity are among the technical challenges faced by the mining industry. These challenges have increased the risk of the mining projects, size and complexity of the concentrator plus the overall concentrate production cost. In future, the level of these challenges will be augmented. In this case, what will be the direction of the industry? Are there going to be super capacity concentrator with double or triple the current equipment size or multiple lines of large equipment in parallel? Either way, the energy consumption in the comminution circuit will increase. The question is if this approach is sustainable for our industry?

The high throughput concentrators were built to cope with some of the challenges mentioned above. Large grinding mills, pumps and hydrocyclones were installed in these concentrators that led to energy intensive operations. For example, the grinding mills in Australia had increased from 4.5 MW in the late 60’s to 28 MW autogenous mill in an iron ore concentrator recently (Meka and Lane, 2010). Existing plants are undergoing brownfield expansion by installing additional crushing and grinding power to increase throughput or to achieve finer grind size (Meka and Lane, 2010). Moreover, new energy efficient technologies such as HPGR and stirred mills has been introduced in the comminution circuit to cope with some of these challenges. Besides that, the interest in gangue rejection or pre-concentration had increased recently. The magnetite and platinum concentrators had pioneered the gangue rejection concept by introducing the separation unit processes in between the comminution stages (Palaniandy et. al., 2017). Conversely, Huang (2015) and Pokrajcic (2010) have mentioned that there is potential to float partially liberated (15 %) valuable minerals. Combinations of these opportunities may enable coarse grinding and flotation to be as part of the concentrator to remove the bulk of gangue minerals before the subsequent fine grinding and rougher flotation.

This paper will be discussing on shifting the comminution workload from the secondary to regrind stage by introducing the coarse flotation in between these two grinding stages, to prepare the feed for rougher flotation. The main idea in this work was to coarsen the secondary grind circuit product, remove the gangue minerals and followed by a regrind stage to prepare the feed for rougher flotation. This approach will reduce the overall comminution OPEX in the concentrator.

Current practices and opportunities

Most of the copper and gold concentrators have adopted the SABC circuit for comminution to prepare the feed for the rougher flotation – see Figure 1. The typical SABC circuit product particle size was ranged between 150 – 180 µm (80 % passing). In this circuit, the whole SAG mill feed will be ground down to the targeted grind size to liberate the valuable minerals. As the ore characteristics have changed and the volatility in the commodity prices, the SABC circuit has undergone several types of modifications to cope with the increase in plant throughput, ore hardness or to achieve finer grind size. Among the circuit layout modifications were;

- Installation of the secondary stage crushing and tertiary stage HPGR crushing

- Additional grinding power in the secondary ball mill circuit
- Installation of tertiary grinding circuit – either ball mill or vertical stirred mill circuit (Meka and Lane, 2010)

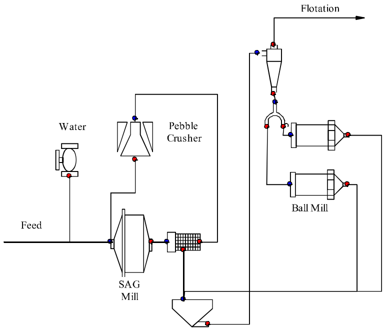

Figure 1 SABC circuit layout

The expansion mentioned above routes will address some of the challenges but at the same time, will increase the OPEX. Contrarily, there are other opportunities to reduce the comminution OPEX but achieving the targeted product size in the concentrator. For example, incorporation of energy efficient comminution equipment and couple it with gangue rejection may reduce the overall comminution circuit specific energy consumption. Pokrajcic (2010) had mentioned that there are an opportunities to reduce the comminution energy by 66 % in the Pb-Zn concentrator by engaging coarse gangue rejection and stirred milling with good understanding and interpretation of mineral liberation data.

SHIFTING THE COMMINUTION WORKLOAD

Based on the opportunities mentioned in the previous section, a modified circuit layout was proposed to reduce the overall OPEX in the Cu-Au concentrator. The proposed circuit has the following criteria;

- Coarsen the SABC circuit product size to 300 µm.
- Introduce of coarse flotation for bulk removal of the gangue minerals in between SABC and regrind circuits.
- Regrind the coarse flotation concentrate in the TowerMill.

This approach is conservative as the choice of the targeted grind size for the SABC circuit is within the range that the conventional flotation cell is capable of operating. Figure 2 shows the simplified flow diagram of the proposed circuit. The product from the SABC circuit undergoes separation process in the coarse flotation cell to remove the bulk of the liberated gangue minerals. The coarse flotation concentrate will be ground in the TowerMill circuit to produce the circuit product of 95 µm (P80). The regrind mill circuit product will be fed to the rougher flotation circuit to improve the concentrate recovery.

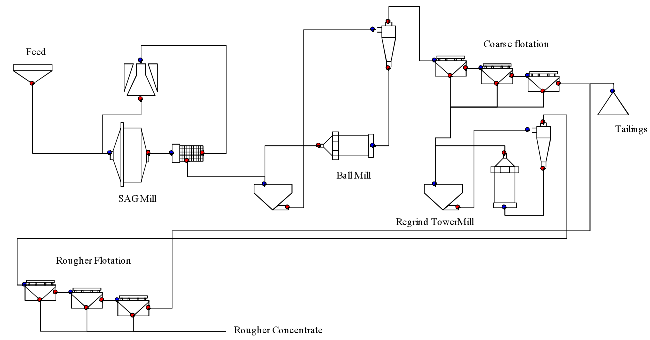

Figure 2 Modified energy efficient circuit layout

Advantages of the proposed modified circuit

The proposed circuit has several advantages such as

- Improved technology utilization i.e. SABC circuit for coarse grinding and the TowerMill circuit for fine grinding below 100 µm.
- Bulk removal of liberated gangue reduces the subsequent grinding power requirement to prepare the rougher feed.
- Adaptation of the TowerMill technology has several advantages such as 30 – 45 % more energy efficient than the ball mill circuit (especially to produce circuit product below 100 µm), narrow product size distribution, minimal wear parts, excellent wear life of the screw liner, easy maintenance, quick installation, low grinding media consumption, require less floor space (essential when the mills are installed in between the flotation circuits), greater operational safety due to fully enclosed mill body, simple foundation requirement, excellent turn-down capability and quiet operation (Palaniandy et. al, 2017, Palaniandy et. al., 2017).
- The sump in the TowerMill circuits can absorb the fluctuation from the SABC circuit and regulate the feed to rougher flotation.

Circuit energy consumption comparison

Based on the industry practice and new circuit proposal, four circuits were chosen for the comparison simulation study to evaluate their performances. The chosen circuits were;

Circuit 1	SABC – Figure 1
Circuit 2	SABC plus tertiary grind ball mill - Figure 3
Circuit 3	SABC plus tertiary grind TowerMill - Figure 4
Circuit 4	SABC plus gangue rejection plus regrind TowerMill - Figure 2

Circuit 1 is the base case in this comparison study. Circuit 2 and 3 were chosen based on the typical expansion exercise to produce finer circuit product of 95 μm. Circuit 4 is the proposed new circuit concept to produce the targeted circuit product 95 μm.

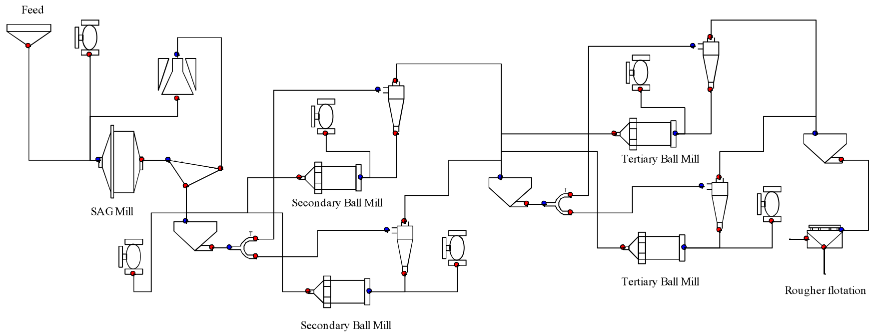

Figure 3 SABC plus tertiary ball mill circuit

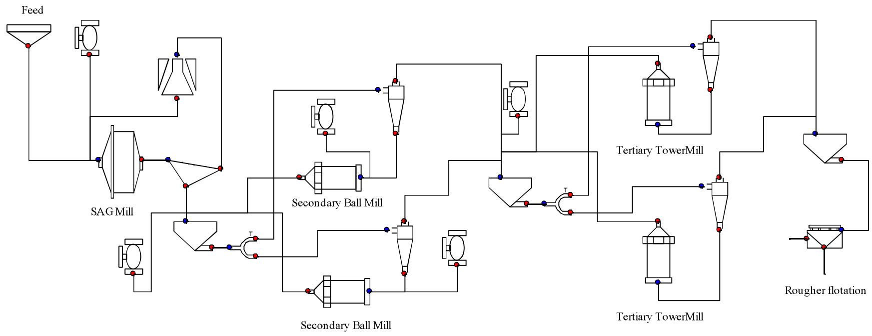

Figure 4 SABC plus tertiary TowerMill

The base case SABC circuit data, rougher flotation size-recovery curve and TowerMill circuit data were obtained from two surveys that were conducted at the Cu-Au concentrators. The ore properties are shown in Table 1. The SABC and TowerMill circuits' data were model fitted in the JKSimMet software and in-house TowerMill circuit simulator respectively. The single component efficient curve in the JKSimMet was used to represent the flotation for simplification purpose. It is understood that the flotation design and operational variables have a significant impact on the recovery but that aspects are beyond the scope of this paper. The feed, concentrate and tail particle size, % solids and throughput data from the Cu-Au rougher flotation cell was used to model fit the flotation with an efficiency curve. This section will focus on the impact of circuit-specific energy, particle size and the metal recovery in the rougher flotation circuit.

Table 2 shows the feed rate and the power draw of the mills in the circuits. The power draw of the SAG mill and ball mill was obtained from the Morrell power model while the TowerMill power was determined using the Nippon Eirich's '*in-house*' power model. The power estimation in each unit process is essential to achieve the targeted product size. The Morrell power draw calculation is well accepted in the industry for tumbling mills. Nippon Eirich's *'in-house'* power model is developed based on a large number of TowerMill application data base in various grinding duty. The TowerMill power model is based on the circuit operating condition and design data. Circuit 1 had the coarser product size as this was the base case circuit while the other circuits' product sizes are close to 95 µm. The total installed power in the Circuit 2, 3 and 4 were compared. Circuit 2 shows the highest installed power. Circuit 3 shows 15 % lower installed power compared to the Circuit 2, due to the energy efficiency of the TowerMill in the fine grinding regime. Circuit 4 has the lowest installed power and specific energy consumption (see Figure 5) by adopting the following strategies;

- Coarsened the SABC circuit product size (approximately 300 µm) reduce the power requirement in the ball mill circuit.
- The coarse flotation rejects 46 % of the liberated gangue mineral from the stream that reduces the subsequent grinding power.
- Application of energy efficient grinding technology in the regrind circuit to prepare the feed to rougher flotation.

Table 1 Ore Properties

Ore Properties	Value
A*b	36
Specific gravity	2.7
Bond ball mill work index (kWh/t)	18

Table 2: Feed rate and power draw of the mills in the circuits

Circuit	1	2	3	4
SABC feed rate (t/h)	2500	2500	2500	2500
Regrind 1 feed rate (t/h)				1347
SAG Mill Power (kW)	19600	19600	19600	19600
Secondary Ball Mill Power (kW)	19356	19356	19356	9754
Tertiary Ball Mill Power (kW)	0	21640	0	0
Tertiary TowerMill Power (kW)	0	0	12553	0
Regrind TowerMill Power (kW)	0	0	0	3174
TOTAL INSTALLED POWER (kW)	**38956**	**60596**	**51509**	**32528**
SABC circuit feed F80 (mm)	92.1	92.1	92.1	92.1
SABC circuit product P80 (mm)	0.220	0.220	0.220	0.310
Tertiary ball mill product P80 (µm)	-	96	-	-
Tertiary TowerMill product P80 (µm)	-	-	95	-
Regrind TowerMill product P80 (µm)	-	-	-	93

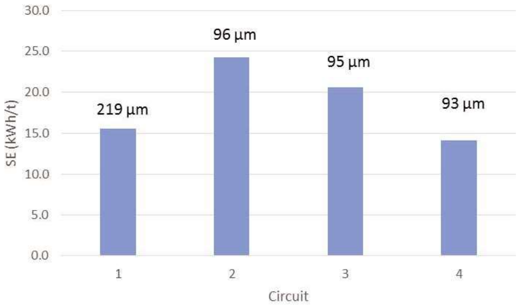

Figure 5 Specific energy consumption of various circuits and its circuit product size

Also, Figure 6 shows that Circuit 4 has the highest recovery although it has similar P80 to the Circuit 2 and 3. Figure 7 shows the particle size distribution of the rougher flotation feed and the size-recovery curve. Circuit 4 has exhibited sharper particle size distribution within the floatable regime (within the envelope of the size-recovery curve).This characteristic had enhanced the Cu recovery in the rougher flotation circuit. Conversely, Circuit 2 that had a wider particle size distribution with a high amount of fine particles exhibited slightly lower recovery compared to Circuit 4. Furthermore, the poor reduction ratio at the coarse end i.e. F98/P80 had decreased recovery as well. These results indicate that narrow particle size distribution is essential for higher metal recovery.

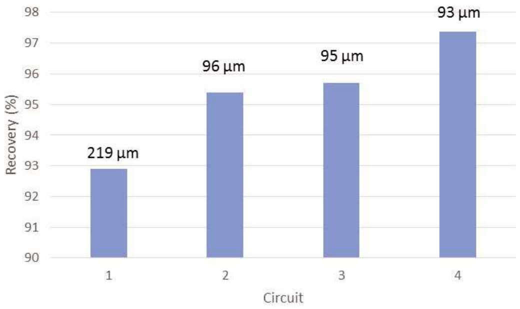

Figure 6 Cu recovery in various circuit

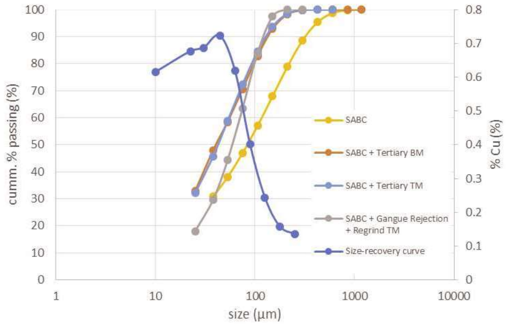

Figure 7 Particle size distribution of rougher flotation feed

OPERATING COST COMPARISON

The operating cost is one of the key measures in circuit layout and technology selection. Circuit design with high OPEX may not be favourable although it might exhibit higher energy efficiency. The operating cost comparison of the four circuits was made based on three essential cost in the grinding circuit i.e. energy, grinding media and liner cost. The key values used in the OPEX calculations are;

- Power is from grind supply, and the cost is $ 0.09/kWh (Anon, 2015)
- Grinding media consumption for SAG mill is 400 g/tonne ore ground (Daniel et. al., 2010)
- Grinding media consumption for ball mill is 500 g/tonne ore ground (Daniel et. al., 2010)
- Grinding media consumption for TowerMill is 250 g/tonne ore ground (data obtained from a Cu-Au and magnetite operation)
- Grinding media cost is $ 1200 for SAG/ball mill and $ 1400 for TowerMill, delivered to site (current data from operating sites)
- Tumbling mills liner consumption is 0.3 kg/ tonne of ore ground, and the cost is $ 250/tonne
- TowerMill liner consumption is 56 g/ tonne of ground ore (data obtained from a Cu-Au operation)

Figure 8 shows the calculated comminution OPEX. Circuit 4 shows lower OPEX compared to Circuit 2 and 3 due to

- Specific energy consumption reduction in the ball mill circuit.
- Decrease regrind throughput after the coarse flotation reduces the grinding power requirement, grinding media and liner consumption.
- Utilisation of energy efficient technology further reduced the energy consumption.
- The particle size of coarse flotation concentrate is finer compared to the coarse flotation feed that further reduces the grinding power requirement.

Note: The OPEX for Circuit 4 is compared to Circuit 2 and 3 only as Circuit 2, 3 and 4 has the similar circuit product size – 95 µm. The circuit product size for Circuit 1 is coarse i.e. 220 µm. The OPEX to produce coarser circuit product is lower as the energy requirement is lower compared to the finer circuit product at 95 µm.

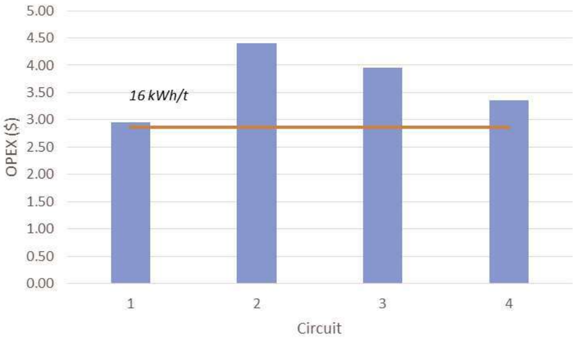

Figure 8 Comminution operating cost/ tonne of processed ore

The line graph in Figure 8 shows the reference operating cost for the SABC in Cu-Au operation with Bond Work Index value of 16 kWh/t and the circuit product of 210 µm (Grigg and Delemontex, 2010). The calculated OPEX is in close agreement with the Circuit 1 that indicates that the assumption made in the calculation is reasonable for evaluation. Site-specific OPEX variation will occur where the energy cost, grinding media and liner consumption are significantly different. Nevertheless, this exercise shows that Circuit 4 shows 23 % reduction in OPEX compared to the Circuit 2 to produce rougher flotation feed of 95 µm. Table 3 shows the sensitivity analysis for OPEX (OPEX/tonne of ground ore). The analysis shows that OPEX/ tonne of ground ore reduces as the circuit feed rate increases and the Circuit 4 shows the lowest OPEX.

Table 3 OPEX sensitivity analysis

	Circuit feed rate (t/h)				
	2000	2250	2500	2750	3000
Circuit 1	3.3	2.9	2.6	2.4	2.2
Circuit 2	4.9	4.4	3.9	3.6	3.3
Circuit 3	4.4	3.9	3.5	3.2	3.0
Circuit 4	3.8	3.4	3.0	2.8	2.5

FUTURE VALIDATION

The best validation is when a full-scale plant is built based on the proposed circuit i.e. Circuit 4. In the meantime, there are several roots that can be used to validate the proposed idea which includes laboratory and pilot scale test work plus industrial survey. The proposed root are as follows;

- Conduct a survey in an existing SABC circuit with coarser circuit product i.e. 300 µm.
- Conduct liberation analysis on the SABC circuit product to determine the valuable minerals surface exposure for separation process i.e. mineral liberation analysis
- Laboratory coarse flotation test
- Regrind in the KM-5 TowerMill
- Moreover, followed by the laboratory scale rougher flotation

The above-mentioned activities can be adopted to validate the current idea before the build of a full-scale plant.

CONCLUSION

This study had shown that coupling the liberated gangue mineral rejection concept and energy efficient stirred mill technology such as the TowerMill had demonstrated a more energy efficient circuit plus reduces the overall Cu-Au concentrator OPEX. The key criteria in the proposed circuit were coarsened the SABC circuit product, removal of liberated gangue particles in coarse flotation and application of energy efficient grinding solution. The comparison study had shown that the proposed circuit consumes 42 % less energy and 23 % less OPEX compared to the conventional SABC with a tertiary grinding ball mill. Furthermore, the recovery in the rougher flotation was 2 % higher. It is understood that more detail studies (comminution, flotation and mineral liberation) are required to forward this concept into practical application in the concentrator.

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