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The development of regrind-flotation pre-treatment of the CIL feed in copper-gold plants

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Abstract

This study focused on the development of a new method, regrind-flotation pre-treatment, to improve the performance of the CIL (Carbon-in-Leach) circuit at copper-gold concentrators. Occlusion of gold by iron sulphide gangue minerals and the fine grain size of gold associated with them contribute to the low gold recovery in the CIL circuit. Fine grinding of the CIL feed increased gold recovery significantly from the leaching process. However, fine grinding increased the amount of liberated copper which is cyanide soluble resulting in significantly higher cyanide consumption. A proposed method of regrinding of the CIL feed followed by copper flotation was developed as an appropriate pre-treatment method for the CIL circuit that increased gold recovery while reducing cyanide consumption related to the presence of copper.

Keywords: regrinding; refractory gold; cyanide soluble copper; cyanide consumption

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1. Introduction

In porphyry/skarn copper-gold flotation plants gold recovery is often well below copper recovery [1]. With liberated and copper-associated gold readily recovered in the flotation stage, this recovery difference is often due in part to operating strategies that require rejection of gold-bearing iron sulphide gangue minerals in order to maintain a saleable copper concentrate grade. To minimise gold losses, it is a common practice for gold un floated in tailings to be leached with cyanide [2]. However, a number of studies and industry practices show that the Carbon-in-Leach (CIL) circuit of copper flotation tailings where gold is dissolved in the slurry through a chemical process incorporating agitation, oxygen and cyanide, is often economically unviable due to the high cost to recover the relatively low amount of gold [2, 3].

The association of gold with iron sulphide gangue in flotation tailings is often in the form of total or partial encapsulation of fine gold grains as identified in the previous study [4]. The encapsulation impedes access of cyanide to gold for dissolution, reducing the effectiveness of subsequent CIL circuits in copper-gold plants. A common pre-treatment method to overcome this type of refractory ores is to increase gold liberation by ultra-fine grinding of iron sulphide minerals [5-7].

However, copper minerals unrecovered by the flotation process are also present in the CIL feed and, similar to gold, these copper minerals are also encapsulated by the rejected iron sulphide minerals. In the case study previously reported by Burns et al. (2014) on Telfer gold mine’s CIL circuit, the use of an ultra-fine grinding pre-treatment process to liberate gold was found to increase CIL gold recovery [4]. However, pyrite-encapsulated copper minerals were also liberated during the regrinding process, consuming a significant amount of cyanide [4]. Muir et al. (1989) demonstrated that copper ions derived from the oxidation and dissolution of copper
minerals form a variety of Cu$^+$ complexes with cyanide [8]. During copper sulphide mineral dissolution, free cyanide is oxidised to cyanate if the reduction of Cu$^{2+}$ to Cu$^+$ is required, and is also converted to thiocyanate in the presence of released sulphide ions [9, 10]. These mechanisms would increase cyanide costs and, in the Telfer case study, would render the CIL process economically unviable. Therefore, the previous study recommended an ultra-fine regrinding process, but followed by flotation to recover newly-liberated copper minerals, prior to the CIL circuit [4]. This flotation stage may produce an acceptable copper concentrate grade that would allow it to be combined with some part of the preceding copper flotation circuit. Gold not recovered to the concentrate by this flotation stage could be then recovered by CIL treatment of copper-depleted flotation tailings. The development of this regrind-flotation pre-treatment method using laboratory and pilot-scale test procedures is the focus of this study, and Telfer CIL circuit is also chosen as the case study following the previous work [4].

At Telfer, the copper flotation tailings are pre-concentrated prior to CIL treatment via bulk flotation of a gold-bearing, pyrite concentrate. Thus, to implement the regrinding-flotation process prior to the CIL circuit, the prerequisite is to float sufficient copper minerals while rejecting the majority of pyrite in the flotation stage after ultra-fine grinding to ensure an acceptable concentrate copper grade. The effect of grinding environments on mineral flotation and separation has been well studied and reviewed. Grano (2009) summarised five chemical mechanisms that can operate during grinding: (1) galvanic coupling, (2) iron hydroxide surface coatings, (3) oxygen reduction, (4) Eh reduction and (5) precipitation. These mechanisms affect mineral flotation through the alteration of surface wettability [10]. In general, electrochemically active grinding media (e.g., mild steel) produces lower mineral
flotation than electrochemically inert grinding media (e.g., stainless steel, high chromium steel and ceramic media) due to the formation of hydrophilic iron hydroxides preventing collector adsorption on mineral surfaces [10, 11]. Meanwhile, electrochemically inert grinding media produces more reducing conditions with lower Eh and dissolved oxygen which may prevent the adsorption of thiol collectors requiring an oxidising condition [10, 12].

Besides grinding environments, breakage mechanisms can also affect mineral flotation. Typically, plant-scale ultra-fine grinding is carried out by a stirred mill, such as an IsaMill, operating primarily with the attrition breakage mechanism, while in the laboratory, tumbling mills (e.g., rod mills) are normally used with impact being the predominate breakage mechanism [13]. Based on regrinding and flotation tests on pyrrhotite in the presence of the activator, copper sulphate and collector, potassium amyl xanthate (PAX), Ye et al. (2010) found that the impact breakage of tumbling mill produced particles which had a remnant collector coating, whereas the attrition grinding of the IsaMill produced particles that were denuded, or stripped, of collector and consequently depressed [14]. They also found that the addition of collector and activator after regrind allowed the IsaMill product to return to full unground floatability. However, this floatability was only partially restored for the rod mill case due to iron hydroxide surface contamination rather than particle breakage effects [14]. Stirred mills are more energy efficient with the attrition breakage mechanism in fine grinding than tumbling mills and have seen increasing application in the industry [13, 15]. In this study, both stirred and tumbling mills were tested.

Pyrite displays low floatability in alkaline solutions due to the formation of iron hydroxide coatings on the surface. This is the reason why the separation of other base metal sulphide minerals from pyrite by flotation is often conducted in alkaline
solutions. However, in practice, cyanide is also added in flotation to depress pyrite flotation. Prestidge et al. (1993) demonstrated that the depression action of cyanide on pyrite flotation was through the depletion of xanthate adsorption on the pyrite surface because cyanide had stronger affinity for pyrite than xanthate [16]. Miller et al. (2006) proposed that the addition of cyanide reduced the pulp potential to a point at which xanthate could not be oxidised and then adsorbed on the pyrite surface resulting in the depressed pyrite flotation [17].

2. Experimental

In this study, samples were taken directly from Telfer processing plant CIL feed stream. Time-varying conditions were experienced in the plant and therefore the feed grades of laboratory tests varied. However, for the same series of tests, one sample was taken from the same plant location and representatively split. Therefore the feed quality of laboratory tests in that series was the same. The average grades, listed with standard deviation, of the CIL feed samples were 4.61 ± 1.66 ppm Au, 0.20 ± 0.07 % Cu and 47.2 ± 5.2 % S.

2.1. Regrinding and flotation

CIL feed samples were collected from the Telfer processing plant at an average P80 of 75 µm. Either a laboratory rod mill or a pilot scale IsaMill was used in this study to regrind the CIL feed to the desired product size before laboratory flotation. When the rod mill was used, 1 kg of slurry was collected from the processing plant and filtered to remove excess water. The filter cake was immediately repulped with process water to 67 wt.% solids for grinding in a 300 mm diameter stainless steel laboratory batch rod mill with inert grinding media, stainless steel rods. Grinding time was selected from calibration data to achieve the desired product size for each flotation test. When the IsaMill was tested, a 40 dm³ sample of fresh CIL feed was
collected from the processing plant and placed into the agitated feed tank of the pilot M4 IsaMill with inert grinding media, ceramic beads. The entire sample was processed by the IsaMill in consecutive passes until a desired product size for each flotation test was achieved. A sample for each flotation test was drawn from the agitated slurry holding tank in between the consecutive passes. At each consecutive pass, the cumulative power input in to the IsaMill was recorded to enable calculation of the net grinding energy requirement using the method detailed by Larson et al. (2011) [18].

After grinding, by either the rod mill or IsaMill, a slurry sample containing 1 kg solids was transferred to a 5 dm³ laboratory flotation cell. Telfer raw water was added to dilute the slurry to a volume of 5 dm³, corresponding to 17 wt.% solids. Slurry pH was adjusted to 11.0 with lime and conditioned for 1 min. Cyanide was added as solid sodium cyanide and conditioned for 1 min. 10 g/t collector RTD11A (isopropyl ethyl thionocarbamate) supplied by Tall Bennet was added and conditioned for 1 min. These initial pH and collector conditions were developed from plant practice at Telfer. Before flotation, the slurry was aerated at 5 dm³/min for 3 min to increase slurry Eh for effective collector adsorption.

A 15 min kinetic flotation test was performed with compressed air. Five separate concentrates were collected after 1, 3, 6, 10 and 15 min flotation. The Orica supplied frother, DSF004A, was dosed as required and water added throughout the test to maintain a constant pulp level within the flotation cell. Concentrate solids were oven-dried at 65 °C, weighed with a Mettler-Toledo analytical balance and assayed for Au, S and Cu using standard analytical techniques of fire assay (Au), Leco analysis (S) and atomic adsorption spectroscopy (Cu).

2.2. Cyanide leaching of flotation tailings
The flotation tailings were further treated in laboratory cyanide leaches to identify total gold and copper extraction achievable from the CIL feed and the required cyanide consumption. The flotation tailings were filtered and sub-sampled for assaying of Au, S and Cu. The remaining sample was transferred to a 5 dm$^3$ leach bottle and sufficient Telfer raw water was added to dilute the slurry to 50 wt.% solids. Slurry pH was adjusted to 10.0 with lime, for reason of safety, and initial free CN concentration set to 10,000 ppm. This concentration was selected to create an intensive leach condition and ensure leaching proceeded without cyanide limiting the extent. Leaching then commenced for 24 hours with bottle rolling to agitate and aerate the slurry. At completion, the sample was filtered and the pregnant solution assayed for Au, Cu and residual free CN. Residue solids were sized and assayed for Au, S and Cu.

3. Results and discussion

3.1. Experimental reproducibility

To investigate the reproducibility of the combined regrind, flotation and leach experimental procedure, a common sample of plant CIL feed was representatively split in to four samples. The experimental procedure was conducted in replicate on each sample after regrinding in a rod mill to a P80 of 36 µm. Average flotation recovery, listed with standard deviation, was 3.9 ± 0.3% mass, 60.6 ± 3.9% gold and was 75.1 ± 2.2% copper. Average combined flotation and leach recovery, listed with standard deviation, was 81.8 ± 1.0% gold and 91.5 ± 1.8% copper. Average cyanide consumption during leaching, listed with standard deviation, was 2.3 ± 0.4 kg/t.

3.2. Selective flotation
At Telfer, copper flotation is conducted to produce a gold-bearing copper sulphide concentrate, and the copper flotation tailings are floated sequentially to produce a gold-bearing pyrite concentrate treated by a CIL process for the recovery of contained gold. Copper is simultaneously leached in the CIL circuit. As the Telfer CIL feed was composed on average of 83% pyrite and a relatively low average copper content (0.18% Cu) during the period when the current study was conducted, the effective iron sulphide depression was required for a selective flotation stage that could achieve a sufficiently high copper concentrate grade. Zheng et al. (2010) reported the results of initial laboratory flotation tests on CIL feed samples reground in a stainless steel laboratory rod mill to a P80 of 36 µm without adding a collector. These tests highlighted that regrinding fully depressed pyrite flotation with 0.5% recovery [1]. This is in line with Ye et al. (2010) proposing that regrinding generated new surface area having no or little adsorbed collector resulting in reduced mineral flotation [19].

Following the initial work of Zheng et al. (2010) [1], regrind-flotation tests on fresh CIL feed samples identified that the floatability of pyrite was not sufficiently depressed despite being reground during times of high collector PAX (potassium amyl xanthate) addition rates to the pyrite rougher flotation circuit preceding the CIL circuit. The relationship that existed between plant PAX addition rate at the time of sample collection and pyrite recovery obtained from laboratory regrinding-flotation pre-treatment stage is shown in Fig. 1. Obviously, when a large amount of collector is carried from rougher flotation concentrate, the newly created fresh surfaces after regrinding may adsorb residual collector in solution resulting in effective pyrite flotation. For example, when 85 g/t PAX was added in the pyrite rougher flotation in the plant, about 90% pyrite recovery was achieved in the cleaner flotation after grinding in the laboratory. In the plant, the addition of PAX in pyrite rougher flotation
depends on feed grade and operation in upstream processes and there is no guarantee
of a low PAX addition rate. As a result, cyanide has to be added to ensure the
depression of pyrite in the flotation after regrinding.

Fig. 2 shows the effect of cyanide additions on pyrite flotation after regrinding
with the laboratory rod mill and pilot IsaMill on the same CIL feed. A variety of
cyanide addition ratios were tested to identify the minimum addition required for
economic and selective flotation. For both mills, pyrite flotation was depressed with
cyanide addition. An addition ratio of 100 g/t cyanide was required to effectively
depress pyrite flotation. Fig. 2 also shows that more pyrite was depressed with IsaMill
compared to the rod mill in the absence or presence of cyanide, which is consistent
with Ye et al. (2010), who demonstrated that more pyrrhotite recovery was depressed
after regrinding with the IsaMill than with the Magotteaux Mill® (a tumbling mill) at
the same product size [14]. They hypothesized that this phenomenon was probably
due to the removal of hydrophobic species on particle surfaces by stirred mill
regrinding which had a greater contribution from the abrasion mechanism than in the
tumbling mill [14]. However, at 200 g/t cyanide, pyrite was completely depressed
regardless of the mill type. Apparently, 200 g/t cyanide decomposed or displaced all
residual PAX on pyrite surfaces.

While pyrite flotation is depressed, flotation of copper and gold minerals is
desired. Fig. 3 shows gold and copper recovery and selectivity against pyrite in
ongoing regrind-flotation tests on fresh CIL feeds. An average P80 of 36 µm was
selected for these tests, in line with the previous study by Zheng et al. (2010) [1].
IsaMill was used and 100 g/t cyanide was added in flotation. These tests confirmed
that an addition ratio of 100 g/t cyanide effectively depressed pyrite flotation across
the range of time-varying conditions experienced in the CIL feed. Gold and copper
minerals display much better floatability than pyrite. In a number of tests, more than 80% gold and 70% copper were floated despite cyanide addition in flotation to depress pyrite recovery. However, Fig. 3 also shows that gold recovery and copper recovery were less than 50% in the majority of tests, indicating that the regrinding and flotation conditions may not be optimised for gold and copper flotation although pyrite flotation was successfully retarded.

To further increase copper and gold recovery, flotation was conducted with the addition of collector RTD11A which is more specific for copper and gold minerals. RTD11A was selected as it was the incumbent copper collector in use at Telfer processing plant and showed good copper and gold flotation.

A fresh CIL feed sample was reground to a P80 of 36 μm. The first four concentrates of the kinetic flotation test described above were recovered without the addition of collector. Then 10 g/t of RTD11A, in line with plant practice at Telfer, was added prior to the final 5 min concentrate. Results are shown in Fig. 4.

The addition of RTD11A significantly improved the recovery of both gold and copper without affecting the depression of pyrite. The observed increase in copper recovery was likely due to the recovery of secondary copper minerals such as chalcocite and bornite which do not readily show collectorless flotation behaviour [20, 21] but are higher in copper content than chalcopyrite which can float readily without collector [14, 22]. Collector addition was included in further flotation tests as part of regrind-flotation pre-treatment stage due to the observed increase in gold and copper recoveries and continued pyrite depression.

3.3. Grind size dependence of flotation recovery
Initial testwork by Zheng et al. (2010), identified a possible relationship between grind size and collectorless flotation recovery [1]. During the current study, after regrind in the IsaMill, flotation performance in the presence of collector and cyanide also showed dependence on regrind product size as shown in Fig. 5. Similar to results observed by Zheng et al. (2010) [1], both copper and gold recoveries increased with a decrease in grind size as the liberation of both from pyrite increased. Gold recovery reached a maximum in the $P_{80}$ range of 20-25 µm at 71% and copper recovery reached a maximum in $P_{80}$ range of 30-40 µm at 66%, respectively. Below a $P_{80}$ of 20 µm, gold and copper recoveries both reduced dramatically.

It is known that fine particles exhibit low flotation rate and recovery due to the low bubble-particle collision efficiency [23]. Fine particles follow the streamlines around the bubbles due to their small inertial force and do not collide with the bubbles using conventional flotation machines. Fig. 5 suggests that while the liberation of copper and gold from pyrite is essential to improve copper and gold recovery, over-grinding has a detrimental effect on copper and gold flotation.

### 3.4. CIL performance after the regrind with and without flotation

An initial direct comparison of the conventional regrind pre-treatment and leach process with the developed regrind-flotation pre-treatment and leach process was conducted on a common sample of CIL feed. Regrind size $P_{80}$ was 36 µm. The tests for each processing path were conducted twice. The average results are presented in Fig. 6. The use of regrind-flotation pre-treatment reduced the amount of gold, and both total copper and cyanide soluble copper reporting to the leaching stage. As a result of the removal of cyanide soluble copper species from the leach feed, cyanide consumption during the leach stage after regrind-flotation pre-treatment was 66% less than during the regrind pre-treatment. Total gold recovery was the same for both
methods, whereas the combined copper recovery increased when flotation preceded the leaching stage.

Ongoing regrind-flotation-leach and regrind-leach tests on fresh CIL feed were performed to compare the two processing paths across the range of time-varying conditions experienced in the CIL feed. Regrind product size was extended beyond 36 μm to develop a comparison across a range of product sizes since a close control of the regrind size in future plant implementation is unlikely. Results are presented in Fig. 7. Trends identified with the direct comparison were confirmed by the ongoing test programme.

As can be seen from Fig. 7, the choice of pre-treatment method had no impact on the total gold recovery, with the leach stage acting as a scavenger on the flotation stage, to maintain a similar overall gold recovery as the regrind-leach processing path. However, the use of the regrind-flotation pre-treatment method greatly increased total copper recovery. Flotation recovered copper minerals (e.g., chalcopyrite) that were not readily recoverable by leaching alone. Cyanide consumption by the leach stage was reduced due to the prior flotation recovery of cyanide soluble copper minerals (e.g., chalcocite).

3.5. Grind size dependence of combined flotation-leaching performance

Combined flotation-leaching recovery results, presented in Fig. 7, demonstrated that grinding finer than P\textsubscript{80} of 36 μm further increased the combined gold and copper recovery. The previous study showed that liberation of the fine-grained gold and copper minerals continues to increase past this grind size [4]. With flotation recovery decreased at finer grind sizes, highlighted in Fig. 5, the combined recovery increase was driven by improved cyanide access for leaching.
Inclusion of flotation as a pre-treatment stage aimed to reduce cyanide consumption in the subsequent CIL circuit, by the prior recovery of copper from the pre-treated CIL feed. When copper flotation recovery reduced at finer grind sizes, the pre-treated CIL feed copper grade increased due to poor flotation recovery and the proportion of copper that is readily leachable increased due to greater liberation. With the cyanide consumption of the subsequent CIL circuit linked to the amount of readily leachable copper in the CIL feed [4], the cyanide consumption of the CIL stage would be dependent on the grind size of the pre-treatment. Cyanide consumption would reduce to a minimum and then tend to increase.

Fig. 8 presents the observed relationship between grind size and cyanide consumption during leaching, a comparison with Fig. 5. It highlights that the minimum cyanide consumption coincided with maximum copper flotation recovery in the range of 30-40 µm. Cyanide consumption increased at finer P80. Fig. 8 also presents the measured net regrinding energy requirements to achieve a desired P80 with the Isamill. The net grinding energy requirement significantly increases as the P80 reduces below 30 µm, as is typical for fine and very fine grinding environments [13, 22]. When regrinding to the finest size possible to achieve maximum gold recovery, both these factors likely have a deleterious impact on process economics. Consequently, an important process economics consideration is the expected existence of a limiting grind size, finer than which the combined incremental cost of increased regrinding energy requirement and CIL cyanide consumption would offset the incremental benefit of increased gold recovery. Factors that would coarsen this limiting grind size include increased cost of power, cost of cyanide, pre-treatment feed copper grade. Factors that would act to reduce this limiting grind size include increased price of gold, price of copper and pre-treatment feed gold grade.
4. Conclusions

The presence of a low amount of copper in the feed of a CIL circuit after copper flotation is detrimental to process performance. Fine grinding of the CIL feed to liberate gold from iron sulphide gangue minerals increased gold recovery from the leaching process, but simultaneously increased the amount of liberated copper which is cyanide soluble and resulted in significantly higher cyanide consumption. In the case of the CIL circuit of the studied copper-gold plant, CIL pre-treatment by fine grinding alone would be uneconomical due to this increase in cyanide consumption.

A regrind-flotation pre-treatment method for CIL has been developed and is an appropriate pre-treatment method for the CIL circuit in copper-gold plants. Compared to regrind alone, it does not increase total gold recovery but does increase total copper recovery and reduce cyanide consumption from the CIL circuit. In the case of the CIL circuit of the studied copper-gold plant, this CIL pre-treatment method enables an increase in gold and copper recovery that would not have been economically achievable by pre-treatment with fine grinding alone. Implementation of the new CIL pre-treatment method in a copper-gold plant will be reported separately.

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References


Fig. 1. Pyrite recovery in the flotation after regrinding the CIL feed with a laboratory rod mill as a function of PAX addition in plant pyrite rougher flotation circuit: regrind P80=36 µm; no collector addition in laboratory flotation.

Fig. 2. The effect of cyanide additions at various ratios on pyrite flotation after regrinding with the laboratory rod mill and IsaMill on a same CIL feed: regrind P80=36 µm; no collector addition in laboratory flotation.
Fig. 3. Gold recovery (a) and copper (b) recovery as a function of pyrite recovery from flotation in the presence of 100 g/t cyanide after regrinding CIL feeds with IsaMill: regrind P80=36 μm; no collector addition in laboratory flotation.

Fig. 4. Copper and gold grade as a function of recovery from the flotation of the CIL feed after regrind with collector RTD11A addition prior to final concentrate.
Fig. 5. Copper and gold recoveries from the flotation of CIL feed as a function of regrind size.
Fig. 6. Comparison of the regrind pre-treatment and leach process with the developed regrind-flotation pre-treatment and leach process at regrind size of P80 36 μm: total gold recovery (a); total copper recovery (b); NaCN consumption in leaching (c); cyanide soluble copper recovery after regrind (d).
Fig. 7. Comparison of the regrind pre-treatment and leach process with the developed regrind-flotation pre-treatment and leach process at regrind size at various regrind sizes: copper recovery (a); gold recovery (b); cyanide consumption (c).

Fig. 8. Consumption of NaCN in leaching and net energy required during regrinding at various regrind sizes.
Graphical abstract
Highlights
- Regrind-flotation is effective prior to the CIL circuit in copper-gold plants.
- This new method recovers copper minerals that are not readily leachable.
- It also recovers cyanide consumable copper minerals.
- Compared to regrind alone, this method increases total copper recovery.
- It also reduces cyanide consumption from the CIL circuit.