INVESTIGATION OF SORTING TECHNOLOGY TO REMOVE HARD PEBBLES FROM AN AUTOGENOUS MILLING CIRCUIT

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ABSTRACT

Palabora Mining Copper has a unique ore body composition which unlike other copper ore bodies has three main components in significant proportions; these are copper bearing ore, magnetite and dolerite. The high content of dolerite, a hard barren material, creates a high proportion of pebbles which normally are recycled back to the mill. This action increases the mill bearing pressure and power progressively until corrective actions are taken.

A logical action to solve the pebbles generation would be to incorporate a pebble crusher. This in fact was done however two fundamental issues were encountered; the high content of magnetite and existence of a cyclone classification section. Due to the high content of magnetite, metal detectors have not been able to work efficiently to separate tramp metal which causes damage to the pebble crushers. The existence of cyclones in the circuit had a detrimental effect on the final product when the pebbles crusher was online producing coarse sandy material.

Due to the difficulties in treating pebbles via conventional procedures and the unique Palabora ore composition and characteristics, sorting technology was investigated at laboratory and pilot scale. It was found that a combination of optical and electromagnetic sorting could efficiently separate dolerite from the copper bearing and magnetite ores.

This paper reports the findings of the laboratory and pilot scale work performed and discusses the additional benefits to the circuit.

KEYWORDS

Autogenous mill, pebbles, ore sorting

INTRODUCTION

A well known natural phenomenon in autogenous (AG) mills is the build-up of pebbles. These pebbles are typically called “critical size material” and occupy a large volume of the mill and thus reduce the capacity for new material to be processed. In addition to the mill volume reduction, the critical size material is harder than the normal material and this contributes to additional power draw.

In order to overcome the effects of pebbles in the circuit, it is common to install pebble crushers in an AG/SAG circuit. This has increased the AG/SAG mills capacity in some cases by up to 25% for an iron ore operation (McIvor & Greenwood, 1996). However, the beneficial gain from crushing critical size material is relatively proportional to the amount of critical size material in the circuit. For example, O’Bryan (1996) reported a negligible gain in throughput for a critical size material less than 5% of the feed of an autogenous mill. Similarly, Mosher, Banini, Supomo and Mular (2006) suggests that pebble crushers, in general, should be designed to accommodate 25-35% of the new SAG feed tonnage.

HPGR (High pressure grinding rolls) have also been considered to treat pebbles as part of an AG/SAG circuit. Their application, however is only justified if the pebbles generated are a relatively large proportion of AG/SAG mill new feed (Morley, 2006).
Pebble crushers and HPGRs are generally the options considered for the treatment of critical size material. However, these two options are not suitable for Palabora, and so alternative technologies such as ore sorting were investigated.

**Pebbles at Palabora AG Mills Circuit**

Palabora Mining Company operates two 32 ft autogenous (AG) mills running in parallel with 2x3.5 MW motors each. These modular units are each fed by a dedicated run of mine (RoM) stockpile supplied by the underground mine. Historically the AG milling circuit has achieved the required production levels for the open pit mine. However, selective mining and segregation of dolerite (a hard and barren material), as was the case of the open pit mine, is no longer possible in underground block cave operations and an average of 12% of dolerite is now being delivered to the autogenous circuit. In addition, the feed to the AG mills has changed from the traditional foskorite ore to transgressive/banded carbonatite ore which constitutes the major ore type underground.

The processing of unwanted dolerite has restricted the AG mills throughput and increased the pebbles recirculating load. This material is normally recycled back to the mills without further treatment and, as expected, a build-up of pebbles in the mill is observed via increasing mill bearing pressure and power. The immediate action by the operator is to divert a fraction of the pebbles to the floor (“tap-off”) and/or stopping the feed. These actions ultimately reduce the plant throughput and introduce plant instabilities. To date, up to 700 Kt of pebbles have been accumulated and stored in a dedicated stockpile.

**Ore Sorters**

Sorting material by hand to remove a desired product from waste material has been practiced throughout history. The principle has not changed but the sensing techniques, mechanical handling and separation systems have rapidly advanced over the last 10 years.

Modern sensor based ore sorters work on a rock by rock basis. They rely on the sensing system being able to distinguish each rock that passes through the sorter, and provide information on that rock that can be used by the electronics processing system to establish if it is wanted product or waste, after which the ejection system is used to divert that rock into a different ore stream as required.

As seen in Figure 1, ore is fed into the sorter using a feeder or belt system to ensure a monolayer of stable particles are presented to the sensing system which sends data characterising each rock to the electronics. The electronics process this data and discriminates the ore from the waste. This information is then passed onto the ejectors that separate the feed into an accept and reject stream using blasts of compressed air to change the flight trajectory of selected rocks to fall below a dividing plate. These rocks form a different output stream to those not ejected.
Figure 1 - Schematic representation of ore sorter for material below 75 mm

An ore sorter can be broken down into four effective parts: the mechanical handling, sensing, processing electronics and the ejection systems. If any one of these parts is not optimised the efficiency of the sorter will be affected.

**Mechanical Handling**

The pressure on modern sorting installations is for higher throughputs in an effort to simplify the plant and maintenance and reduce the capital investment and running costs. Higher throughputs can be achieved by turning up the feed rate, using wider machines and faster moving conveyor belts and by sorting larger rocks.

**Sensing System**

Sensing systems span the entire electromagnetic spectrum to ensure that any measurable difference between an ore and its waste can be determined and exploited as a separation criterion. The sensing system generally scans across the sorting belt width and is placed as close to the ejection system as possible to maximise the accuracy of the sort.

**Electronics**

Historically most sorters used custom built dedicated parallel processors to ensure that the data was processed within the very short time that the particle takes to travel between the sensor and ejectors (Rech, Allen & Gordon, 2008). The exponential increase in the power of modern computing systems has brought these up to the point where they can be used in some sorting applications. The very highest speed systems and those that require intense data processing are still mostly done by the custom parallel processors but the flexibility and ease of programming computer based sorters has seen an increase in their use. It is a common misconception that the processing system is the limiting factor in the amount of ore that can be sorted per second. This is not usually the case as the speed of the sensor, physical stability of individual ore particles and physical separation systems usually form the limiting factors.

**Ejection**

With rocks moving through the sorter at up to 6 m/s, the speed and resolution of the ejectors has a dramatic effect on the efficiency of the sort. Commercially available ejections systems, including off-the-shelf air ejectors and flapper paddle systems have response times in the tens of milliseconds at best. A 20
ms ejector with a particle travelling at 6 m/s will result in a 120 mm ejection. To ensure that there are no neighbouring particles within this spacing, a reduced throughput is required. High pressure custom designed ejection systems with high flow characteristics and a response time of 2 ms have resulted in a step change in the accuracy of the ejection system increasing the throughput of the sorter. These systems are designed for the mining industry with significantly lower air filtering requirements and reduced maintenance.

EFFECTS OF HARD PEBBLES ON AG MILLS THROUGHPUT

Current Plant Practice

Figure 2 shows the current circuit configuration which include a double deck screen (18 mm and 5 mm aperture), and a cyclone cluster of 4 off 685 mm diameter cyclones. A pebble cone crusher is available but does not operate. The AG mills are operated in closed circuit at a nominal rate of 600 t/h varying according to the dolerite content in the feed (6 to 13%). The recirculation of pebbles is approximately 18% of the feed. When the mill conditions become unstable (particularly the mill power and bearing pressure) such as when the throughput is adversely affected by high dolerite level in the feed, the circulating load will be tapped off as a strategy to increase milling rates. The problem with the tap off strategy is that 4% of recoverable copper metal in the feed is lost. To recover this copper would require an additional reprocessing stage which will incur extra haulage and processing costs.

The AG mill circuits have not been able to sustainably achieve the design capacity of 30,000 t/d of underground ore. Thus, a fraction of the underground ore is diverted to the conventional circuit. The conventional circuit consists of crushers, rod and ball mills and traditionally has achieved lower copper recoveries than the AG circuit.

Critical Size Material (Pebbles)

Critical size material usually occurs in the 25-50 mm size fraction (Nappier-Munn, Morrell, Morrison & Kojovic, 1996) and can occupy a large volume in the mill increasing power draw and reducing mill throughput. The AG mills at Palabora have a pebble port size of 70 mm and the pebbles recycled back to the mills are in the range of 5-70 mm. The pebbles generated are formed primarily of dolerite, carbonatite and magnetite. Among these, dolerite (feldspar, pyroxine) is the major and hardest component.
Comparative rock strengths are: carbonatite 113-159 MPa, foskorite 65-99 MPa and dolerite, 360 MPa. Dolerite has a work index of 24 Kwh/t compared to 13 Kwh/t for the overall ore.

As discussed above, dolerite is the most abundant material in the critical size particles and it has a direct influence on the amount of material being tapped-off. For example, Figure 3 shows that as the percentage of dolerite in the feed increases, the fraction of mill tap-off also increases. The fraction of copper loss is also directly related to the contents of dolerite in feed.

Pebble Crushing

Pebble crushers are commonly used in autogenous and semiautogenous (AG/SAG) mills, as they are a much more efficient user of power on this material thereby reducing the specific energy and increasing the throughput.

As the recirculating pebbles are approximately 18% of the feed, the installation of a pebble crusher in the AG circuit seemed a prudent decision. Subsequently, a cone crusher was installed in each module. The installation of pebble crushers created new challenges to the circuit operation, among them was the removal of metal tramps (discussed below) and the generation of coarse; sandy material.

These issues were to be expected, as small and round pebbles were eliminated from the mill reducing the generation of fine particles. In addition, the existence of cyclones in the circuit aggravated the recirculation of coarse material to the mill, increasing the inventory of coarse material in the circuit affecting pipes and sumps. In order to use the existing pebble crusher, the removal of the cyclones and with the production of a considerably coarser product was considered. These options however, were discarded because of the costs associated with the replacement of the piping and pumping system. The autogenous milling circuit is located about 1.5 km away from the ball mills.

![Figure 3 - Effect of dolerite on tap-off (Rio Tinto T&I internal report)](image)

Tramp Metal

Efficient metal removal systems are important to protect pebble crushers and most circuits include belt magnets and metal detectors for that purpose. The Palabora pebble crushing circuit has a significant proportion of magnetite which represents 10-22% of the pebbles stream. It also includes high angle conveyors running at high speeds. Tramp metal detectors have evolved considerably and can be used for materials with high contents of magnetite. For example Iron Ore Company of Canada (IOC) uses highly sensitive tramp metal detectors in streams containing up to 30% of magnetite. However, metal detectors
can only detect objects greater than 25 mm at high speeds while the minimum size required for Palabora is 15 mm.

The inability to use tramp metal detectors effectively, the existing cyclone classification in the circuit and the considerable distance of the ball mills from the AG circuit, all result in a limited ability to utilise the existing pebble crusher in the circuit. Therefore alternative options such as ore sorting were evaluated.

SORTING TECHNOLOGY AS AN ALTERNATIVE TO REMOVE HARD PEBBLES FROM THE AUTOGENOUS CIRCUIT

As discussed above, most of the options to deal with the critical size material were unsuccessful or result in high copper losses so unconventional alternatives were investigated. One of the options was the use of sorting technology. Fortunately, Palabora has a unique ore composition which is amenable for ore sorting. The pebbles have three distinctive components; dolerite (black or grey colour), magnetite (black colour) and carbonatite (white or pink colour).

Pebbles Characteristics and Composition

Table 1 shows a typical composition of pebbles larger than 12 mm. It can be observed that a large proportion of the mass is constituted by dolerite which contains approximately 24% of copper. Most of the copper is contained in the carbonatite material.

Table 1 – Cu grades of pebbles 12 mm

<table>
<thead>
<tr>
<th>Rock types</th>
<th>Mass (%)</th>
<th>Cu (%)</th>
<th>Cu in each material (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbonatite</td>
<td>24.0</td>
<td>0.44</td>
<td>62.2</td>
</tr>
<tr>
<td>Magnetite</td>
<td>7.3</td>
<td>0.30</td>
<td>13.0</td>
</tr>
<tr>
<td>Dolerite</td>
<td>68.7</td>
<td>0.06</td>
<td>24.4</td>
</tr>
<tr>
<td>Total</td>
<td>100.0</td>
<td>0.17</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Figure 4 outlines the optical difference between the types of material; the copper bearing carbonatite (light coloured), the magnetite (dark coloured), and the hard unwanted dolerite (dark coloured). Both the carbonatite and the magnetite are wanted ores. This meant that a combination of optical sensing used to differentiate the colours as well as electromagnetic sensing, to differentiate between the magnetite and the dolerite, were used in the investigation.
Preliminary Sorting Testwork

Preliminary optical sorting test work was conducted at Mintek in South Africa in 2005. The testwork consisted of a batch scale and small bulk scale using optical sorting. A pebble sample of –50 mm was screened at 12 mm and the +12 mm fraction was tested for optical sorting. The sorter was setup in a combination mode to separate both according to colour as well as magnetic content since both the dolerite and magnetite have similar colour clouds and brightness.

Table 2 show the results obtained from the optical sorting testwork. 76% of the copper and 36.1% of the mass was recovered in the accepted stream. The losses of copper were almost entirely attributed to dolerite in the rejected stream. As observed, a mass of 64% material consisting primarily of dolerite was rejected. It is important to note that the primary objective of the project was to remove critical size material from the circuit, however additional benefits of recovering copper and magnetite are also observed.

<table>
<thead>
<tr>
<th>Stream</th>
<th>Mass (%)</th>
<th>Cu (%)</th>
<th>Recovery (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+12mm Feed</td>
<td>100.0</td>
<td>0.16</td>
<td>100.0</td>
</tr>
<tr>
<td>+12mm Rejected</td>
<td>63.9</td>
<td>0.06</td>
<td>23.8</td>
</tr>
<tr>
<td>+12mm Accepted</td>
<td>36.1</td>
<td>0.34</td>
<td>76.2</td>
</tr>
</tbody>
</table>

Bulk Sorting Testwork

The above preliminary results encouraged the investigation of sorting for the removal of unwanted pebbles from the circuit and a new campaign was initiated to collect representative samples for testing at Comodas Ultrasort facilities in Sydney, Australia. A bulk pebble sample was prepared at different particle size ranges and tested in an industrial sorter according to the procedure described below.

Using Multiple Sensors

Using the logic shown in Table 3, the sorter was setup to process the material according to Figure 5. With this system the sample was chosen to create a carbonatite stream (accepted) and then rerun the magnetite/dolerite (rejected) through the same sorter again to recover magnetite and reject dolerite stream. The two accepted streams i.e. carbonatite and magnetite were combined to give an overall recovery of copper and magnetite.
Table 3 – Material vs sensor response

<table>
<thead>
<tr>
<th>Material</th>
<th>Optical (light/white)</th>
<th>Electromagnetic response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbonatite</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Magnetite</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Dolerite</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

The sorter houses both the EM and optical sensor simultaneously and can process the data for both sensors, but the ejections system is designed to produce only two output streams. Ejection systems have been developed to produce three streams in one pass but these systems are very inaccurate especially with fast moving particles. However, the sample from Palabora does not require more than two streams and only the dolerite needs to be rejected.

The capacity of the sorters depends on the feed particle size, note that higher throughput is achieved at larger particle sizes and at the recommended maximum to minimum particle size ratio of 3:1 (see Table 4).

Table 4 – Size fractions for bulk testing and sorter capacities

<table>
<thead>
<tr>
<th>Size fraction</th>
<th>Throughput (t/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+16 – 25 mm</td>
<td>27</td>
</tr>
<tr>
<td>+19 – 40 mm</td>
<td>37</td>
</tr>
<tr>
<td>+40 – 75 mm</td>
<td>70</td>
</tr>
<tr>
<td>+19 – 75 mm</td>
<td>45</td>
</tr>
</tbody>
</table>

Figure 5 - Testwork Flowsheet

Metallurgical Results

Figure 6 summarises the results of the bulk sorting testwork, including optical sorting and electromagnetic (EM) sorting. The mass recovery in most of the cases is between 28 to 32%. It indicates that approximately 70% of unwanted material, consisting mostly of dolerite is rejected. Recoveries of copper are around 70% for pebbles with a wide range of size distribution (19-75 mm) and above 70% for pebbles of narrow size distribution. Figure 6 also show the recovery of iron (Fe) in the accepted stream. It is important to highlight that the values are for total Fe and no assay for magnetite was available at the time of publishing this paper. It is expected that the magnetite recoveries will be higher than that shown in the graph.
Figure 7 shows the grade of copper at different size fractions, the head grade in all cases is around 0.15%. It is upgraded to above 0.35% of copper in the accepted stream while the rejected stream has a copper grade below 0.06%. The wide size distribution sample (+19-75 mm) does not show much difference to the other samples. This is encouraging due to the interest of Palabora of processing the full AG mill top screen deck stream.

As seen in Figure 8, the optical sorting testwork showed distinctive products of accepted (carbonetite) and rejected (dolerite + carbonetite) streams. The electromagnetic sorting testwork also showed clear separation of magnetite from dolerite, although less mass recovery to the accepted stream was obtained.

Rejecting more than 70% the of critical size material of mostly dolerite material supported the continuation of the sorting project at Palabora. In order to test the effects of removal of critical size pebbles on the AG mill throughput, a plant trial was conducted. The plant trial consisted of simulating the effect of pebble removal continuously from the circuit, replicating a sorter on line. +19 mm pebbles were continuously removed from the circuit and stored in a pebble bin. The effects on the throughput were immediate and an incremental increase in throughput from 550 to 750 t/h was observed (see Figure 9). The trial continued for several weeks and the throughput increment was consistently above 10%.

The reduction of specific energy in the AG mill was significant from 11.5 kWh/t to 8.4 kWh/t during the trial period, stabilising to 9.6 kWh/t during the following weeks of the trial.

![Figure 6 – Optical/EM sorting results at different size fraction](image-url)
Figure 7 – Distribution of copper at different size fractions

Figure 8 – Sorting testwork products, (a) optical, (b) magnetic

Figure 9 – Effect of pebbles (+19 mm) removal from the circuit on throughput
DISCUSSION

With the removal of dolerite from the AG mills using sorting technology, the capacity of the AG circuit at Palabora will be able to achieve and exceed the original mill design capacity of 30,000 t/d. Other benefits are the reduced costs of power in the AG mills and in ball mills due to a fraction of dolerite being removed from the circuit. Copper and magnetite recovered from the pebbles stream add also value to the operation.

The bulk testwork has been performed in a single machine performing an optical sorting first followed by electromagnetic sorting. Ideally, Palabora would like to use a single machine to perform these two sorting methods i.e. recovering copper (in carbonatite) and magnetite at the same time and rejecting dolerite in one pass. This option exists and can be implemented.

Over the past eleven years Palabora has stockpiled about 700 kt of tap off pebbles from the AG mills with an average grade of 0.25% copper (pebbles +19 mm used for the testwork assayed at 0.16%). The sorter technology will be tested on this historic pile and a full plant scale implementation will be considered once the success criteria have been fulfilled. Figure 10 shows the new AG circuit for Palabora, with the ore sorter replacing the existing pebble crusher.

As per the tramp metal, they will be placed in the accepted streams in conjunction with the magnetite; however, a fine tuning of the sorter is possible in order to differentiate tramp metal from magnetite, so metal tramp can be disposed together with the dolerite stream.

CONCLUSIONS

Due to the Palabora special pebble characteristics and AG milling circuit configuration, pebble crushers and HPGR were not found to be suitable for treating critical size material.

It is also concluded that sorting technology is suitable for removing hard pebbles from the Palabora AG milling circuit and a combination Optical/EM sorting achieved the rejection of ~70% of dolerite in the pebble stream.

The rejection of dolerite from the circuit, as tested on site (top deck tap-off testwork), can increase the mill capacity by more than 10%.

The recovery of Cu in pebbles was above 70% (in the +16 mm fraction)
The specific energy of the AG mills has dropped significantly from 11.5 to 9.6 kWh/t.

ACKNOWLEDGEMENTS

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REFERENCES


