IMAGING TECHNOLOGIES TO UNDERSTAND GRINDING AT PARTICLE SCALE IN A UG-2 PLATINUM ORE PROCESSING PLANT

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ABSTRACT

Grinding is the most energy consuming step in mineral processing, however, it is still poorly understood and its efficiency is difficult to monitor. Mill performances are traditionally measured at the mill discharge, on the basis of a mass percentage passing a certain sieve. This approach does not reflect what happens to the fines through milling.

On another hand, if many macroscopic parameters, such as the percent solids of the pulp, its viscosity or its mean residence time in the mill are known to be related to grinding efficiency, the link between these parameters and particle size distribution (PSD) is still unclear. Here, a methodology is established to understand the effect of ball mill operating conditions on particle size and shape distribution in the grinding process.

The study focuses on the particular case of an Upper Group 2 (UG-2) platinum ore concentrator. Due to the very low grade of sulphide and PGM (Platinum group metals) in UG-2, grinding mechanisms are entirely control by gangue minerals. These two minerals have contrasted properties and PGM content and these properties immediately affect the entire recovery process. So, the grinding of both gangue minerals is studied on a size by size basis. At particle scale, three parameters are addressed: particle size, particle composition and particle shape. The specific behavior of chromite and silicate grains is demonstrated.

As a conclusion, this study gives some clues to operate ball mills in a more efficient manner regarding chromite issue in the processing of UG-2.

Keywords: ball milling control, UG-2, chromite, fine particle, particle shape, segregation

INTRODUCTION

This study is part of a larger research program for ball milling optimization undertaken by Magotteaux Belgium and the University of Liege. Many macroscopic parameters, such as the slurry density, slurry viscosity, or the mean residence time in the mill are known to be related to grinding efficiency, but, the link between these parameters and particle size distribution (PSD) is still unclear. However, since these parameters can be easily monitored than PSD, they are usually used for ball milling control.

For several years now, some parameters can even be monitored in real time owing to the Magotteaux Sensomag®. So the aim of this study was to reconcile the Sensomag data, first with macroscopic parameters and then with ore parameters and especially PSD (Clermont *et al*, 2008).

The Upper Group 2 (UG-2) reef is part of the Bushveld Intrusive Complex (BIC) in South Africa. It is approximately 4g/t rich, but accounts for around 54 percent of the global platinoids reserves (Cawthorn, 1999). UG-2 mineralization consist of little base metal sulphide (usually ~0.1 percent) that can be or not associated with platinum group metals (PGM). The main gangue minerals are chromite (up to 90 percent), orthopyroxenes and minor plagioclases. Chromite contains minor proportions of PGM, while silicates contain fine (<10 µm) grain disseminated platinoïds (McLaren and DeVillers, 1982). Thus, the trend is to very finely ground silicates to enhanced PGM recovery. However, chromite constrains the fine grinding because if it is too finely ground it is

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entrained in the concentrate and can cause trouble in the pyrometallugical process (Hay and Roy, 2009). So smelters usually charge with penalties the concentrate higher than chromite 2.5 percent in chromite. Indeed, chromite is penalizing for UG-2 pyrometallurgical process because it increases smelting temperature and disables proper mixing of the matte (Wesseldijk *et al*, 1999).

Here an attempt is made to understand the conditions that favour fine grinding of chromite. The grinding of both gangue minerals is studied size by size. At particle scale, three parameters are addressed such as particle size, particle composition, and particle shape. The specific behavior of chromite and silicate grains is demonstrated. The results are then related to measurable macroscopic pulp parameters.

MATERIAL AND METHODS

The main objective of this research is to bring together a large amount of data collected during several Sensomag® surveys around a chromite regrinding circuit of a UG-2 recovery plant on the Western Limb of the BIC. To acquire a deep understanding of particle behavior during mill operation, a methodology based on single particle analysis is established.

Sampling Campaign and Sensomag® Data

In 2009, Magotteaux conducted a series of surveys at a UG-2 plant equipped with a Sensomag®. Each survey lasts one hour during which densifier underflow (DU) and mill discharge (MD) are both continuously sampled to obtain one-hour composites. At the same time the output data of the Sensomag® is recorded. The assays were conducted at controlled and stable percent solids and ball filling degree (FD). To ensure the stability of the mill, the experimental ball filling degree and percent solids were set at least 2 hours before the beginning of the survey. Afterwards, all the samples underwent a four-class sieving procedure (sieving size: 106µm, 75µm and 38µm). Chrome and PGM content were assayed for each size fraction. As most of the UG-2 concentrator plant, the surveyed ball mill is an open circuit mill with an overflow configuration. It has the specificity to mainly treat chromite since a densifier is installed prior to mill and divert the overflow towards an IsaMill®.

On another hand, the chromite distribution in some low and high grade UG-2 concentrates (from a neighboring plant) was assessed to identify the size fraction that is most sensitive to chromite entrainment.

Size, Shape, and Nature of Particles

Image analysis has been used for particle size measurement for long (Medalia, 1970) and it is known to be very accurate for particle size down to 1µm. In this study, a pilot installation based on the standard version of the Occhio Instruments FC 200 is used to acquire images of diluted pulp samples from the surveys. The FC200 device is equipped with a high pressure peristaltic pump that flushes the samples of pulp in a thin glass chamber. The imaging operation consist in a brief back-lighting of the chamber at each pump stops. Hundreds of thousands of particles can be imaged this way in a few minutes.

The drawback of image based analysis is that for wide particle size distributions it become difficult to image the coarser and the finer particles at the same time since the captor size (either CCD or CMOS camera) are usually limited to a few millions pixels. Indeed the actual size of acquired image depends on the magnification, which itself has to comply with the size of the finer particle one wants to capture. To tackle this problem a methodology based on multi-scale image acquisition was developed. This methodology relies on the principle that each particle is imaged at its optimal magnification.

The particle size resolution results obtained at different magnification are then gradually recombined owing to the coherence that exists for two close size fractions that are imaged at two different magnifications (refer Figure 1). Hence, at each scale it is not the global proportion of one size fraction which is measured but the ratio between two adjacent size fractions.

At figure 2, it is shown that for the MD samples, three magnifying scales (0.38µm/pixel -1.19µm/pixel -2.38µm/pixel) are enough to fit the curve obtain with a six-class sieving procedure (sieve size: 11µm-20µm-38µm -75µm -106µm -150µm).

Grinding mechanisms in a ball mill are usually described as either associated to attrition forces or compression (impact) forces. The importance of these co-existing forces is strongly related to the percent solids and to the liners design, and thus should impact the PSD and the particle shapes. Here the intention is to use shape

measurement as an indicator of the different mode of breakage (attrition or impact) occurring in a ball mill and to link this observations with macroscopic operating parameters recorded by the Sensomag.

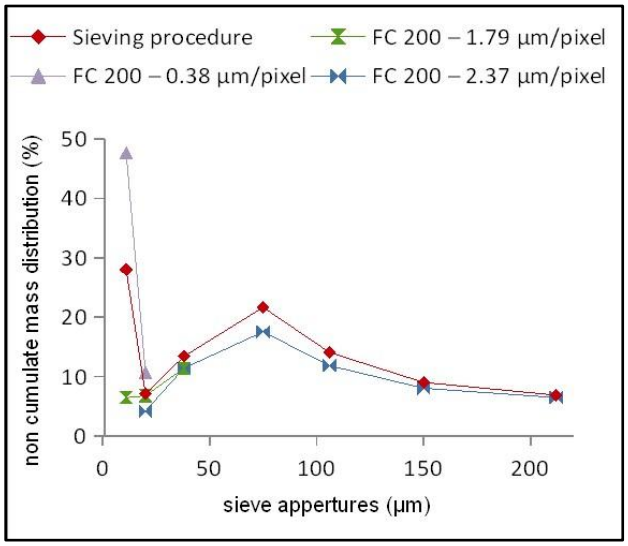

Figure 1. Particle size measurements of a mill discharge sample acquired at variable magnification

The feasibility to recognize chromite from silicates minerals in a UG-2 ore by means of an image segmentation (based on the measurement of single particle opacity) was demonstrating previously (Leroy *et al* 2011). Some modifications in lighting (use of a specular panel) allow to enhance silicates translucency and to achieve a high confidence level for chromite identification in the bulk pictures (refer Figure 2).

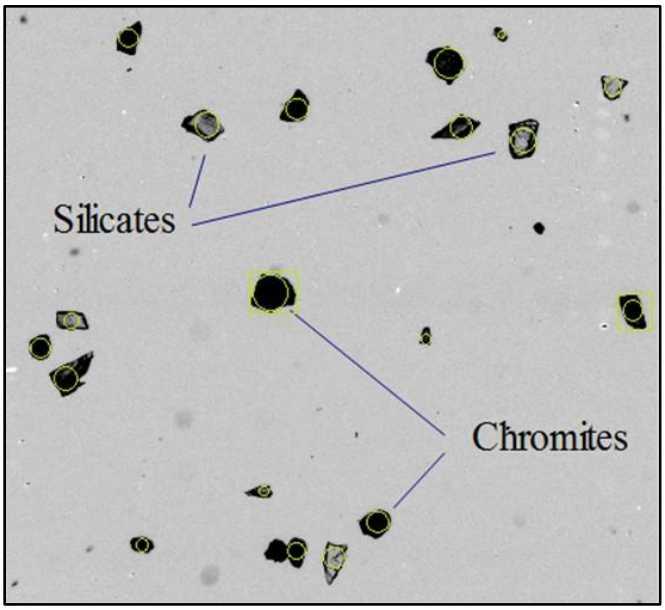

Figure 2. Typical image of UG-2 gangue acquired with the Occhio FC 200 (38-75 µm fraction)

The images are then segmented with a Matlab routine to obtain two sub-sets containing only chromite or only silicate particles respectively. Each sub-set is then processed with Callisto software to extract both size and shape data. Each particle is analyzed in terms of elongation, bluntness (with the calypter) (Pirard, 1994) and circularity. After the particle size and shape analysis, filtering operations are applied to exclude the touching particles on both silicate and chromite sub-sets.

RESULTS

Extended PSD

Considering that approximately 65 percent mass of the mill discharge (MD) consists of <38µm particles, the preliminary four classes PSD analysis is meaningless. So, extended particle size distribution (PSD) analysis is conducted on a selection of mill discharge samples. The additional sieves used are 11µm and 20µm. For each size fraction obtained, a chrome assay (atomic absorption) is prepared to examine the chromite distribution compared to total mass distribution. For coarse fractions (>38µm), the chrome assays show good correlation with the image-based chromite content analysis (refer Figure 3).

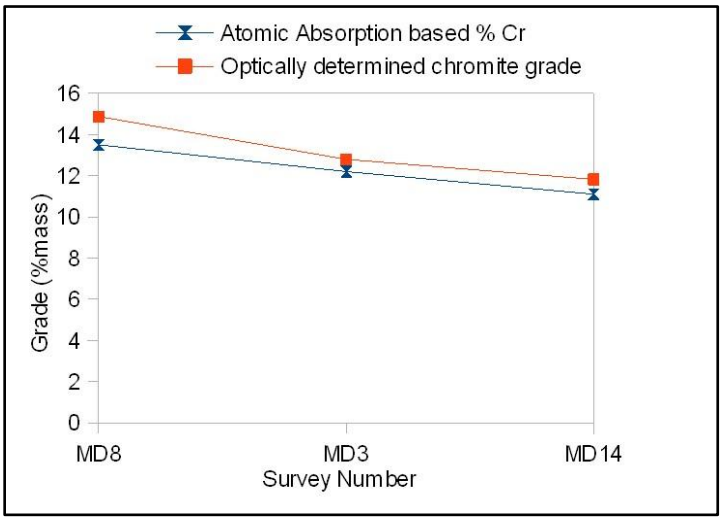

Figure 3. Estimation of chromite content through image segmentation towards atomic absorption chrome assays. Error bars represent the standard error of imaged-based assays (standard deviation of imaged-based assays divided by the root square of the number analyses)

The extended sieving analysis show that the PSD at the mill feed is quite stable in spite of the percent solids variation that affects the cyclone operation (mainly the 38-75 µm fractions); however the chromite proportion is clearly impacted by this variation. It is thus necessary to apprehend the chromite grinding problem and at the same time considering the feed composition and the mill discharge composition.

Concerning the particle size analysis results, the predominance of <10µm size fraction, which represents a least 25 percent in mass for all the tested samples, is to be noted (Figure 2).

However, chrome assays (by atomic absorption) on the <11µm, 11-20µm and 20-38µm size fractions allow to demonstrate that the chrome content at the mill discharge is usually 10 percent lower in the <11µm compare to 11-20µm size fraction and higher.

Similar sieving procedure and chromite assays on high grade and low grade concentrates show that more than 60 percent mass of the chromite particles entrained in the concentrate are <11 µm size.

Chromite Content Analysis

First several test on 38-75 µm and 75-106 µm fractions allow to demonstrate that chromite content evaluation based on particle image discrimination through opacity are consistent with chemical chromite assays (by atomic absorption) with a correlation coefficient higher than 0.95(unit) for around 1500 particles analyzed (refer Figure 3).

The results of chromite assays were primary interpreted as useless because the chrome grade at the mill discharge was found to divert a lot from the chrome grade at the mill feed. The sampling procedure was suspected to have failed as chromite content does not appear to be conserved throughout the mill. However, as already noted, it is important to apprehend the grinding considering at the same time the feed and the discharge.

In view of the mill size and of the high density contrast between chromite and silicate, the mill is suspected to behave as a classifier and thus to retain chromite particles more longer than silicates. Thus it become relevant to

look at the difference between chrome grade at the feed and at the discharge. Moreover, in view of the variations of chromite head grade at the feed, the difference between the feed and the discharge grade must be normalized by the feed grade in order to compare the surveys with each other. The definition is given below.

$$Accumulation_i = \frac{(\%Cr_{(DU,i)} - \%Cr_{(MD,i)})}{\%Cr_{(DU,i)}} \quad (1)$$

Where i stands for the number of the survey.

This parameter is called accumulation, since a positive value corresponds to a physical accumulation of chromite within the mill. This definition is first applied to the head grades and the values obtained for each survey are displayed as a function of the percent solids set for the survey (refer Fig 4). This allows to bring to line a strong linear correlation between accumulation and percentage solids (R^2 = 0.87) that confirms the hypothesis of segregation occurring in the mill.

In order to examine the segregation effect for the separate size fractions, the same definition cannot be applied because normalization no longer makes sense (as size reduction occurs in the mill). Nevertheless, the deviation of chrome grade (see below) can at least be measured. Indeed, if the breakage rates of the chromite and silicates were the same, the chrome grade (% mass) would shown no deviation for a given size fraction.

$$Grade\ Deviation_{(i,s)} = GD_{(i,s)} = \%Cr_{(DU,i,s)} - \%Cr_{(MD,i,} \quad (2)$$

Where i and s respectively stand for the number of the survey and the size fraction.

However, when apply only to the >106µm size fraction, deviation values reveal that coarse chromite particles become comparatively sparser in the mill discharge when the per cent solids is lower. This shows that the accumulation phenomenon is size dependant and mainly affect >106µm particles (refer Figure 4). This observation was previously pointed by Napier et al. (1996) that particles >100 µm do not behave like water in a ball mill.

For fine size fractions (<38µm), it is less intuitive since size reduction makes mass of <38µm particles in the mill inlet small towards the mass of <38µm particles in the mill discharge. Nevertheless, the percentage chrome at the feed and at the mill discharge can be compared. The evolution of the percent chrome in the <38µm seems opposite to the evolution of the per cent chrome in the >106µm (refer Figure 4 and Figure 5). No clear tendency could be isolated for particles in the range of 106 to 38µm.

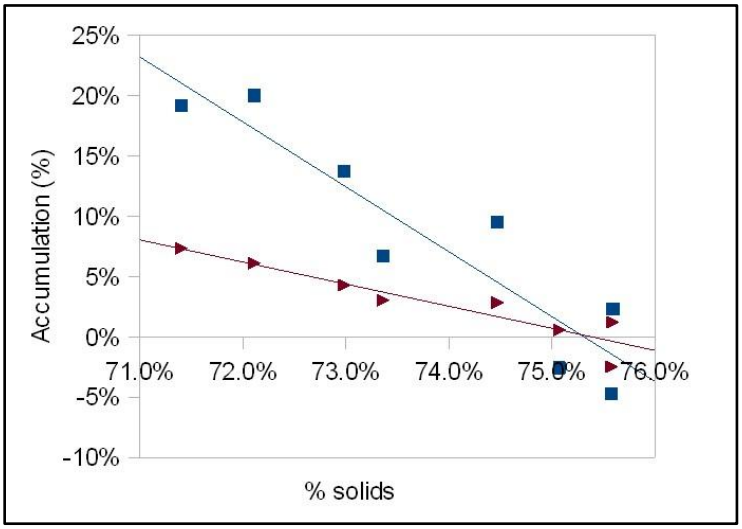

Figure 4. Accumulation and chromite grade deviation for particles >106µm (GD_ >106 µm) as a function of pulp percent solids in the mill

Shape Analysis

Due to the high degree of confidence achieved for chromite segmentation, the particular shape characteristics of both gangue minerals could be examined separately. This distinction between chromite and silicate is essential since otherwise shape analysis results would have been strongly related to the chromite content. So far, shape analysis have been restricted to >38 µm fractions.

Silicate and chromite particles exhibit slightly different shape characteristics. However, up to now, the specific variations of chromite and silicates shapes could not be immediately related to macroscopic operating parameters (percent solids, filling degree).

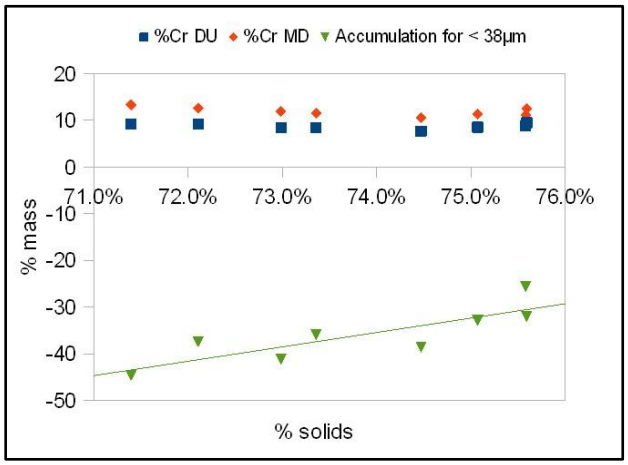

Figure 5. Chromite grade deviation values and variables for particles < 38µm

DISCUSSION

The assays on extended size fraction first demonstrate that chromite better resists to extra-fine (<10µm) grinding compared to the silicates. Indeed the percentage chrome in the <10µm size fraction is systematically lower than in the all the coarser fraction (except >150µm size fraction). Another observation is that the final chromite grades in the concentrate are still significantly lower than at mill discharge which means that certain drainage still happens and helps to lower chromite grade even at very fine size.

The noticeable bi-modal character of the PSD probably indicate that the grinding mechanisms are different at coarse and fine scales, which was already observed in stirred mill by other authors (Tromans and Meech, 2002; Jankovic and Sinclair, 2006). On the other hand, it is well established that the PSD of a ground rock is often linked to its mineralogical structure. Here, chromite, being unaltered, is suspected to better resist to grinding than silicates, that would explain the lower chromite content in <10 µm. Chromite could actually act as a skeleton that controls the general shape of the PSD. In other words the PSD shape for fraction larger than 20µm is constrained by the presence of the chromite grains dispersed in the silicate matrix. On the contrary, as no fine chromite grains are naturally present in the ore, the PSD shape under 20µm should be controlled by the PSD of silicates grains minerals only.

On a dynamic point of view, the bulk chromite accumulation observed in the mill as the percent solids decreased from 76 percent to 71 percent should be linked to the increase of the residence time of large chromite particle (>106µm). As a consequence the >106 µm chromite particles becomes sparser while at the same time, more <38 µm are produced. These two phenomenons are linked to segregation which becomes predominant towards mechanical entrainment while percent solids are low.

At high density, as the percent solids increases, the segregation decreases. Indeed, when considering only the linear motion of the particles inside the mill, the forces applying can be identified as either,

- Mechanical forces (linked to the others particles motion and lifter design)
- Hydrological forces (linked to the fluid movement)

At high density, mechanical forces are predominant and no segregation effect can be observed. On the contrary, when the percent solids decreases the hydrological forces generate a certain segregation linked to the density contrast between chromite and silicates which causes chromite accumulation.

Concerning the percent chrome measurements on <38µm, they are interpreted as a consequence of the increase of the residence time of coarse chromite. So the importance of attrition phenomenon would be mainly linked to the residence time.

Last, it should be noticed that the behavior of the <38 µm particles is mainly controlled by the <11µm particles which represent the main part of it. At very low density (around 65 percent solids), most of the assays show a negative accumulation value (results not shown) which means that the percent chrome is higher at the mill discharge than in the feed. These negative values are interpreted as kind of a washing phenomenon consecutive to preliminary accumulation of chromite at higher density.

The great stability of shape parameters tends to indicate that the percent solids have no significant effect on particle shapes. However, it could be interesting to investigate <38 µm particle shapes and especially ultra fine particle shapes (<11µm) as they account for the main part of <38 µm and are the most sensitive to entrainment. The >106 µm particle shape could be studied as well since they seem to be the more impacted by attrition due to their higher residence time.

CONCLUSIONS

A methodology was established to study the particle size and shape distribution of an ore with contrasted gangue mineralogy. The predominant importance of the residence time against mechanical grinding modes is demonstrated. It is also demonstrated that it is possible to monitor the chromite content in a UG-2 ore by mean of image analysis techniques on diluted pulp sample for particles >11 µm.

Another important fact is the difficulty to maintain stable operating conditions in a ball mill. Indeed, for the surveys performed here, the mill was supposed to process at steady state. However, the instability of the feed and the high density contrast of gangue materials prevent to reach the equilibrium even several hours after the operating conditions for the surveys were set.

This study reaffirmed the need to consider the ore characteristics at every processing step and so to tend to a fully-integrated geometallurgical approach for plant design and operation. As a consequence, grinding models should be developed in a way that takes into account mineralogical characteristics. Grinding efficiency measurement should take into account the by-effect of the grinding process. As per the UG-2 processing, fine grinding is necessary to recover fines disseminated platinoïds and so fine grinding of chromite cannot be avoided. However, fine chromite generation can be minimized when working at optimum percent solids. Last, if UG-2 is milled with low percent solids, it will probably result in an increase of the global mass of the charge in the mill and thus increase the power draw.

PERSPECTIVES

The data obtained from image analysis should be reconciled with macroscopic parameters recorded with the Sensomag®. The particle shape distribution of <11µm chromite in the concentrate should be examined to determine its influence in dragging phenomenon. From the results exposed, it seems essential to take into account mineral density to model the grinding of an ore with contrasted gangue densities. The approach using accumulation rate could be a simple way to calibrate this kind of model.

In view of the influence of segregation effect, it should be interesting to investigate the shape of the >106 µm particles to see if chromite attrition could be monitored this way.

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