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Quantifying mineral liberation by particle grade and surface exposure using X-ray microCT

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ABSTRACT

Liberation is a key driver in all mineral separation processes as it limits the maximum possible grade for a given recovery. In flotation, this is further complicated by the fact that it is surface exposure of the floatable minerals that determines the ultimate performance. Liberation, grade and surface exposure are commonly quantified using Scanning Electron Microscopy coupled to Energy Dispersive X-ray spectroscopy (SEM/EDX) analysis of polished sections. The intrinsically 2D nature of this technique can result in significant sampling errors and stereological effects that can affect the quantification of the ore's textural characteristics. X-ray microCT (XMT) is an imaging method that can non-invasively and non-destructively delineate ore fragments in 3D, thus providing an alternative method that eliminates the need for stereological corrections and readily provides surface exposure. A methodology and automated algorithm were developed for extracting this information from images of closely packed particles. By dividing these particles into classes based on both their surface exposure and grade, the extent to which there is preferential breakage of the particles can be assessed—an important consideration if sufficient surface liberation for good flotation performance is to be achieved at coarser particle sizes. Using low energy scanning simple 3D mineral maps can be obtained via XMT, allowing for the assessment of liberation and surface exposure for each mineral species. The methodology was tested on low grade porphyry copper ore as this is representative of the most commonly treated ore types for copper production.

1. Introduction

Liberation is one of the two fundamental operations—alongside concentration—in mineral processing (Wills and Napier Munn, 2005). Its importance resides in the fact that it limits the maximum possible grade for a given recovery of downstream processes (Leiβner et al., 2013; Carrasco et al., 2016). For the specific case of concentration by flotation, this is further complicated due to the dependence of flotation performance on the achieved surface exposure of the floatable minerals. This is especially crucial for coarse particle flotation where the amount of available surface exposure is often the limiting factor. Furthermore, the relationship between liberation and surface exposure is a complex function of the mineral texture as liberation of the valuable minerals from the gangue is normally carried out by comminution (Mariano et al., 2016; Ozcan and Benzer, 2013; Yin et al., 2017).

Liberation and surface exposure are commonly quantified using automated mineral analysers equipped with Scanning Electron Microscopy and Energy Dispersive X-ray Spectrometry analysis from particle's polished sections (Leiβner et al., 2016; Little et al., 2016). Little et al. (2017) assessed the effect of different mill types on the resultant particle shapes and mineral liberation, with the aim of understanding how these parameters may affect flotation performance. The authors concluded that, for the specific ore and particle size used, both shape and liberation were predominantly a function of ore texture and not whether milling was carried out in a ball or stirred mill.

The main issue with this kind of analysis is that the intrinsically 2D nature of automated mineralogy techniques results in significant stereological effects. Correcting for these effects is challenging as it requires knowledge of grain shape, often erroneously assumed to be spherical or ellipsoidal (Reyes et al., 2017). Early attempts to correct for stereology were proposed by Miller and Lin (1988) using simulation tools to understand the relationship between 1D (linear grade) and 2D (area grade) information in order to estimate the 3D (volume grade) distribution. Recent work using simulated ore has been proposed by Ueda et al. (2016) and Van der Wielen and Rollinson (2016). On the other hand, Fandrich et al. (1998) and King and Schneider (1998) attempted to correct grade distributions using experimental data from real ores. However, the method requires a narrow grade and size fraction distribution and was only validated in 3D by macroscopic mass balance between two species. Zhang and Subasinghe (2013) presented

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an updated model that directly uses image analysis information in order to account for the ore texture and lifted assumptions that made the previous models unsuitable for high grade ore. Yet again the models were not validated against real 3D measurements. In the case of surface exposure there is still no accepted methodology for stereologically correcting the surface exposure obtained from 2D automated analysis into an accurate 3D exposure.

X-ray micro-CT (XMT) is an imaging method that can non-invasively and non-destructively delineate the rock and the mineral grains in 3D (Lin and Miller, 2005; Lin et al., 2016). This provides an alternative method to directly image the full 3D particle, eliminating the need for stereological corrections and readily providing surface exposure. Lin and Miller (1996) used the information provided by XMT to obtain 3D grade distributions in a Sphalerite/Dolomite system using a two-level threshold and a connected components labelling technique. Miller et al. (2009) used an updated algorithm to construct grade/recovery curves and compared the results between the 3D and 2D information, showing that the latter overestimates the extent of liberation. Recently, Wang et al. (2017) presented a methodology for the quantification of mineral grains surface exposure using XMT. The methodology includes image processing operations for compensating for known artefacts and meshing the voxelised XMT output data. Due to the nature of XMT scans, unlike SEM/EDX analysis, mineralogy cannot be easily measured. Reyes et al. (2017) presented a methodology for combining the 3D X-ray attenuation map obtained from XMT with 2D mineralogy obtained from SEM/EDX in order to produce a calibrated 3D mineralogical map, thus allowing for extension of many of the traditional mineralogy analysis techniques into 3D.

In this paper we proposed a similar approach to the one presented by Wang et al. (2017) with a more extensive analysis. We incorporate particle size, mineralogy and extent of liberation into the analysis. This allows us to further understand the nature of the comminution that is achieved for a given ore, such as the existence of preferential breakage, and impact that this has on surface exposure and thus, ultimately, on the flotation response. A generic low-grade porphyry copper ore is used to demonstrate the methodology.

2. Materials and methods

2.1. Ore samples

A porphyry copper ore with a grade of 0.8 wt% copper was used to illustrate the capabilities of this method. Table 1 summarises the mineral composition as obtained from a Mineral Liberation Analysis assessment of the larger particles before comminution. A total of 33 representative fragments were sliced, polished and scanned. These particles were representative of those subsequently crushed and were in the size range +8 mm–12 mm. The main non-sulphide gangue mineral is quartz, with pyrite being the main sulphide constituent. The main copper mineral is chalcopyrite, though accompanied by a range of other copper containing species. The authors are aware of the limitations of the present analysis and sample size, well described in the literature (Evans and Napier-Munn, 2013; Ueda et al., 2016), but producing a fully representative mineralogical analysis of the ore is beyond the scope of the paper. Table 1 thus only gives an indicative mineralogy for the ore used in this study.

Table 1
Main mineral composition of the ore sample. Main minerals are primary copper sulphides, pyrite and a gangue consisting of mainly quartz. Error shows the inter-particle standard deviation.

Mineral type	Weight%
Copper containing species	**2.01 ± 0.47**
Chalcopyrite	1.26
Tennantite	0.48
Other Cu Minerals	0.27
Pyrite	**7.00 ± 2.74**
Gangue minerals	**90.69 ± 2.73**

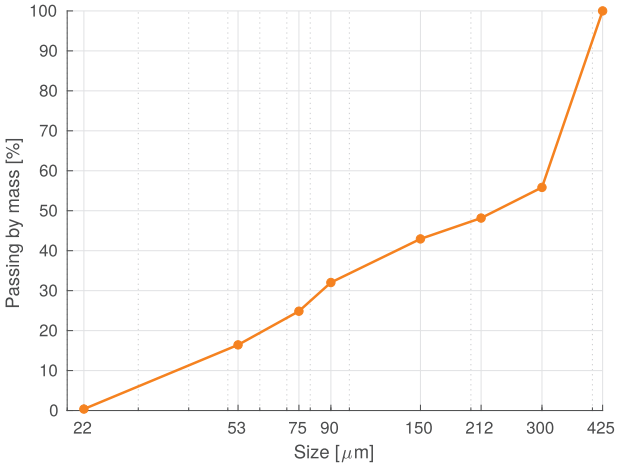

Fig. 1. Particle size distribution of crushed ore. Sizes are 300, 212, 150, 90, 75, 53 and 22 μm.

Another representative sample of fragments were crushed in four stages using a Fritsch lab jaw crusher Pulverisette 1. The crushed material was sieved into eight size classes (particle size distribution shown in Fig. 1). The procedure involved the repeated crushing of different size intervals of material in order to have similar amounts of material in each interval. The material that remained above 212 μm was not included in the analysis as this is beyond typical flotation sizes and we wished to investigate the microCT performance at finer sizes (we already know that it performs well with larger particles).

Sample preparation for scanning was performed by taking representative samples of each size class via coning and quartering. These samples were placed in layers in a 6 mm perplex column as shown in Fig. 2. The width of the column plays a key role, as it defines the resolution of the images when the field of view is set as the column width. For this imaging equipment, the resolution is 1000th of the width of the field of view, which gives a resolution (voxel size) of 6.21 μm/px when imaging the whole column.

2.2. X-ray microCT

The sample was scanned using a Zeiss Xradia 510 Versa system. Three different energy levels (50, 60 and 70 kV) were tested together with different resolutions (1, 2.01, 3.1 and 6.2 μm). This was done in order to ascertain the best scanning conditions, as well as the best compromise between accuracy and scanning time. High energy scans can be carried out more quickly than low energy ones, but result in less contrast between different sulphide minerals, while lower resolution scans allow larger sample sizes to be scanned in a given time, but contain less spatial information. It was found that for this particular ore the highest energy level provided a good contrast between the gangue and the sulphide minerals. Spatial resolution was selected as the lowest value that provided no significant change in the results with a further increase in the resolution, so that scanning time is minimised, and the

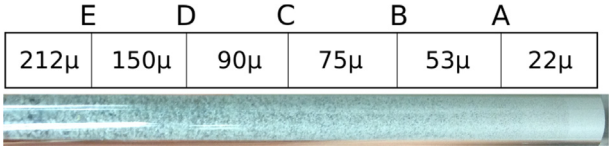

Fig. 2. Sample preparation. Coning and quartering was used to sample each size class and placed in ascending size order in a 6 mm column.