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Quantitative analysis of exposed grain surface area for multiphase particles using X-ray microtomography

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ABSTRACT

Direct determination of exposed grain surface area is a difficult task to achieve since the exposed surface area of grains in multiphase particles can only be accurately analyzed in three dimensions. Now, due to advances in high resolution X-ray microtomography (HRXMT), with a voxel resolution of ~1 μm it is possible to identify dispersed grains as small as 5 μm in multiphase particles and quantify their surface area exposure in 3D. In this paper, the development of procedures for detailed analysis to quantify the extent of grain surface area exposure using HRXMT is described. Image analysis procedures, including preprocessing of the 3D tomographic images, correction for the partial volume effect (PVE), and the use of a new algorithm for determination of exposed grain surface area measurement, are discussed.

Application of the procedure is illustrated with the analysis of flotation products from HydroFloat (HF) experiments for an auriferous pyrite ore. The results demonstrate that two levels of analysis are appropriate for understanding the flotation of locked particles. First, the particle distribution with respect to exposed grain surface area, expressed as a percentage of the total particle surface area, should be considered. Second, the grain distribution with respect to actual exposed surface area should be considered in order to account for the stability of attached bubbles and recovery of such multiphase particles in the concentrate.

1. Introduction

It is obvious that liberation/exposure analysis is of particular interest in the mineral processing industry, since such textural considerations will help define the limits of flotation efficiency. As known, the grain size distribution, texture/exposure, and spatial organization of valuable grains in the ore particles will determine flotation efficiency. If the relationship between mineral exposure and flotation efficiency can be established for different ore types, then the ultimate separation efficiency in the flotation process can be predicted for a specific ore type. It is therefore extremely important to determine the percentage of exposed valuable mineral grains in the ore to better understand the flotation fundamentals.

The first liberation model was reported by Gaudin [1], who described the degree of liberation as the percentage of a specific mineral phase occurring as free particles (single phase particles), in relation to the total content of that specific mineral phase in all particles. Mineral liberation analysis has been obtained from 2D image data after correction for stereological bias [2] and later in 3D with the development of X-ray tomography [3]. However, for many years, mineral exposure has been a big challenge since it can only be determined in 3D.

Now, however, X-ray microtomography can be applied for 3D mineral exposure analysis. The development of mineral exposure analysis for the determination of ultimate recovery from a given particle size distribution during heap leaching was presented by Miller and Lin [4–5]. Garcia et al. [6] calculated the interfacial area of mineral grains during breakage based on geometrical properties, including volume and surface area, of each mineral phase for each particle. Also, breakage of copper ore particles by slow compression was reported to determine if changes in specific interfacial area occurred under different breakage conditions [6].

In this paper, the image processing procedures for exposed grain surface area analysis of HRXMT data are reported. The analysis includes machine learning techniques, correction for the partial volume effect, and a new algorithm for 3D exposed surface area measurement. The flotation response of multiphase particles for an auriferous pyrite ore is well explained based on mineral exposure analysis.

2. Experimental procedure

2.1. Sample preparation

HydroFloat (HF) flotation products for an auriferous pyrite ore from the Western US were provided for exposed grain surface area analysis. A set of products including concentrate and tailing samples for the 850 × 500 micron size class was selected for analysis. In order to acquire

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the tomographic images of multiphase packed particle beds for each sample, a subsample was prepared by a rotary splitter to represent the original particle populations and then the subsample was placed in a 5 mm syringe tube. The particles were tightly packed for the tomographic scan. Choice of the syringe tube depends on the particle size (850 × 500 μm) and desired voxel resolution (4.59 μm).

2.2. Tomographic data acquisition

After the subsample was prepared, high resolution X-ray micro tomography (HRXMT) was used to acquire 3D tomographic data. The HRXMT system (Zeiss XCT-400) uses an X-ray detector having sub-micron resolution combined with a microfocus X-ray source. In this way, the voxel resolution can be extended to 1 μm. The basic schematic of the high-resolution X-ray micro tomography system is shown in Fig. 1.

3. Image processing procedure

3.1. Preprocessing of original 3D XMT images

Preprocessing is the treatment performed on the image that aims to improve image quality in order to increase the precision and accuracy of subsequent processing algorithms [7]. Generally, image denoising was first applied to remove the CT noises. Then, segmentation of particles from the background was done to identify the boundary regions between the particle phases and the background. Segmentation of the particles from the background is accomplished by traditional thresholding or feature based classification [8], depending on the particle characteristics.

3.2. Correction of partial volume effect (PVE)

The partial volume effect (PVE) is one of the important artifacts in CT images which impacts image quality, and usually makes intensity values at boundaries differ from what they really are. PVE refers to the blurring effect and sampling error of finite discrete voxels, which affect image intensities at particle and mineral phase boundaries.

When the voxel is near a boundary of two or more phases, the data acquisition process will combine the attenuation coefficients and the voxel value will represent an average attenuation coefficient. Because a packed bed of particles is really a continuous combination of different particles and phases, the PVE can have an important influence on the quantitative analysis of such images. As shown in Fig. 2, the attenuation coefficient of the boundary voxels between phases A and B will be a linear combination of the attenuation coefficient of each phase based on the volume occupied by each phase in the voxel. In this way, an attenuation coefficient value of a nonexistent material is obtained. This error will depend on the resolution or size of the voxels, phase dissemination in the material (grain size) and particle geometry.

Fig. 3 shows that the sharp edge and the boundary are blurred due to PVE. This effect is intrinsic to the system and cannot be avoided, which increases the difficulty of partial volume correction. The smaller the structures are, the more severe is the blurring and quantitative analysis becomes difficult [9–10].

The partial volume effect is present between any two phases in micro tomography images. Especially for analysis of multiphase packed particle beds, the partial volume effect between a high density mineral phase and air will underestimate the surface area of exposed grains since the boundary regions between the valuable mineral grains and the air background is misclassified as a thin layer of gangue mineral as shown in Fig. 4. The original CT image with a packed particle bed is shown in the top left image of Fig. 4, which shows the valuable minerals in white and gangue minerals in dark gray, based on the attenuation coefficients of the mineral phases. This original image was then segmented using traditional thresholding based on the CT number to visualize each mineral phase separately. The valuable mineral phase and gangue mineral phase are shown in the bottom left and right images, respectively. In order to compare the two mineral phases in one image, the composite image of the valuable mineral phase (white) and gangue mineral phase (gray) in the top right image of Fig. 4 is shown. As mentioned previously, the partial volume effect is always present between two phases. Therefore, the CT number at the boundaries between the mineral phase and air is always the average between the mineral phase and air and lower than the actual CT number of the mineral phase. In this regard, lower CT numbers for voxels in the boundary region are due to the partial volume effect and should be corrected. This effect is very obvious between high density mineral phases and air. The average CT number for boundary voxels composed of high density minerals and air is actually close, or equal, to the CT number of the gangue mineral. In this regard, the quantitative analysis of high density minerals will be underestimated and the partial volume effect must be corrected. As shown in the gangue mineral phase in the bottom right image of Fig. 4, the thin boundary lines are actually the partial volume effect between the high density mineral phase and air and need to be corrected.

In this study, the purpose of correction for the PVE is to find boundary regions between the high density minerals and the background. So the composite image at the top right of Fig. 4 was segmented to the high density mineral image and the whole particle image. Then outline filter [11] was used to find the boundary regions of high density minerals and whole particles, respectively. The partial volume effect between the high density minerals and air is actually the overlapping boundary regions between high density minerals and whole particles. In this regard, correction of the particle volume effect was accomplished by removing the overlapping boundary regions between the high density minerals and whole particles. Fig. 5 gives the zoomed views before

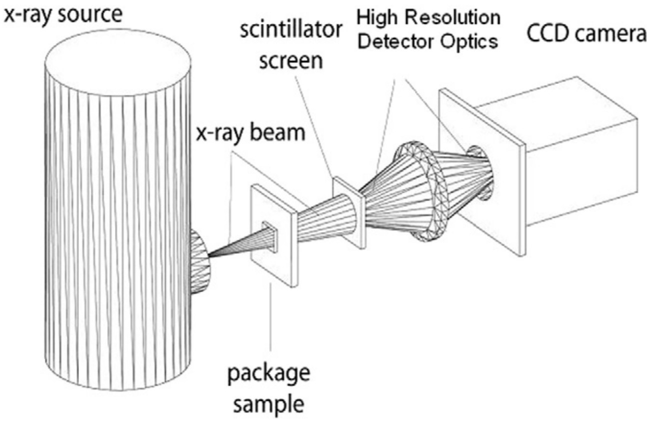

Fig. 1. Schematic of Xradia's (now Carl Zeiss Company) high resolution micro XCT-400.

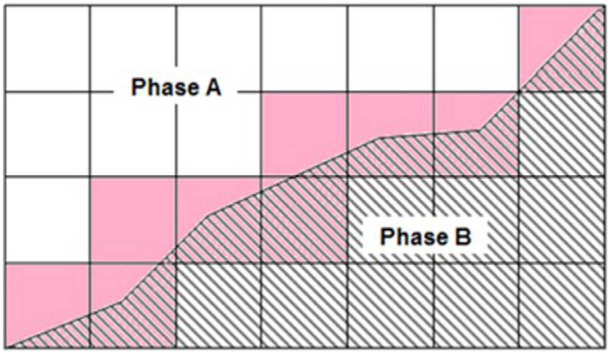

Fig. 2. Illustration of image error due to PVE. Phase A and phase B are combined together in the voxels at the phase boundary.