DIRECT THREE-DIMENSIONAL LIBERATION ANALYSIS BY CONE BEAM X-RAY MICROTOMOGRAPHY

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ABSTRACT

Liberation of valuable minerals during size reduction is an important aspect of mineral processing technology. In practice, most quantitative information on liberation is based on the application of stereological theorems for the analysis of image data from two-dimensional polished sections. On this basis an estimate of the volumetric grade distribution is made. Recently, a new method based on cone-beam xray microtomography has been used for direct determination of the three-dimensional liberation spectrum of multiphase particles 100 microns in size or less. Preliminary results for a packed bed of particles indicate that high spatial resolution (approximately 15 microns) and the direct processing of raw volumetric data are two important benefits offered by this new method.

Three dimensional liberation analysis by microtomography provides an excellent opportunity to overcome many of the limitations of currently used polished section techniques. For example, detailed textural information is provided. Of course microtomography provides an independent method to verify current procedures used for analysis and transformation of polished section data into an estimate of the volumetric grade distribution. More important, however, is the possibility that this method could be developed as a routine procedure for liberation analysis in the 21st century.

INTRODUCTION

Analysis of plant operations in the field of mineral processing often involves the characterization of irregularly shaped, multiphase particles of complex texture. Typically these particles are characterized with respect to size and composition using traditional analytical techniques. Other more detailed information regarding shape, liberation, grain size distribution, and texture can be estimated from the stereological analysis of two-dimensional polished section data. (Miller and Lin, 1988; Schneider et al., 1991; King, 1994) These measurements are tedious and the limitations are well known. For example, the most common method for determination of the volumetric grade distribution of a particle population, requires that a set of narrow-sized particles be prepared, each particle size be mounted in resin, the resin be hardened, the mount sectioned,/polished and the linear and/or area grade distributions determined by image analysis. Next stereological correction of the data must be done to estimate the volumetric grade distribution. It should be noted that assumptions must be made either based on textural information or based on geometrical probability in order to provide the stere(logical correction. Finally, extension of the stereological correction for more than 2 phases is limited.

X-ray computed tomography (CT) techniques (Kak and Slaney, 1987), originally developed for medical service, have an inherent advantage in providing detailed images of the internal structures of opaque materials in a nondestructive manner. Recently the application of x-ray CT in mineral processing technology was reviewed (Miller et al., 1990; Lin et al., 1992). For quantitative analysis of particulate systems such as coal washability analysis, a previous study (Lin, et al., 1991) done at the University of Utah indicated that a conventional medical x-ray CT scanner can provide sufficient information to construct the washability curve within minutes of sample collection. In fact, it now seems possible to design an on-line washability system for the control of coarse coal cleaning circuits (Lin et al. 1995). On this basis it is expected that x-ray microtomography can out-perform all existing stereological correction techniques based on sizing/separation and image analysis procedures. In such cases, CT techniques can be competitive with the most sophisticated microscopy techniques involving optical or electron microscopy equipped with automatic image analysis. X-ray CT analysis should be able to provide not only the volumetric grade distribution, but also a very detailed accounting for the multiphase particle population including grain size distribution, interfacial area, shape features, and textural information.

From the foregoing discussion, it can be realized that CT has the potential to characterize the mass density spectrum or the real three-dimensional grade distribution of a particle population. Information on the volumetric grade distribution of each process stream Is an important feature which is required to accurately model and/or control mineral processing operations. However, it is noted that the quality and utility of the CT data ultimately depends on the resolution of the machine employed. Medical x-ray CT systems have a beam width of a few millimeters and an energy source of about 110 Kev x-rays (Kak and Slaney, 1987). Generally such a system would not be adequate for liberation analysis, coal being an exception because of it low density. Currently in mineral processing operations, most of the process streams contain particles of a size less than several hundred microns and of a specific gravity exceeding 2.5 for which the medical scanners are not suitable. In this paper we describe a new method for the direct determination of the threedimensional mass density spectrum of particles with a size of a few hundred microns or less. The method combines high-resolution 3-D cone-beam x-ray microtomography techniques and a classification algorithm for the determination of particle composition and grain size distribution of the dispersed mineral phase inside each individual particle from three-dimensional data. Such a technique may provide the basis for more detailed and accurate liberation analysis in the 21 st century.

EXPERIMENTAL PROCEDURE

High Resolution Three-Dimensional X-Ray Microtomography

To determine the mass density distributions of particles from mineral processing streams, tomographic techniques which produce three-dimensional images of the internal structure of small particle samples with micrometer resolution will be required. In this regard, three-dimensional X-ray microtomography offers a unique imaging capability. In particular, accurate three-dimensional maps of density and mineral phase distribution can be measured for multiphase particles 100 microns in size or less.

Cone-beam geometry x-ray microtomography (Feldkamp et al., 1984, 1989; Kuhn et al. 1991) is well suited for the quantitative determination of the mass density distribution of the particles with a size of less than a few hundred microns. The CT system (Feldkamp et al., 1989) used in this study was originally designed for the detection of small structural defects in ceramic materials. Rather than rotating the x-ray source and detectors during data collection, as in medical CT technology, the specimen is rotated. Instead of generating a series of two-dimensional sliced images from one dimensional projectors, a three-dimensional reconstruction image array is created directly from two dimensional projectors. Details for the description of this micro-CT system and its corresponding reconstruction algorithm can be found in the literature (Feldkamp et al., 1984). Only a short overview is provided herein.

Fig. 1 shows a schematic diagram for the cone-beam geometry micro-CT system. X-rays from a microfocus x-ray generator are partially attenuated by a specimen that is made to rotate in equal steps in a full circle about a single axis close to its center. At each rotational position, the surviving x-ray photons are detected by a planar two-dimensional array (image intensifier) large enough to contain the shadow of the specimen. These two dimensional projection images are collected using conventional video technology. The video signal is then converted to a two-dimensional digital array by an image processing system. Finally, a three-dimensional image array is reconstructed from the collected set of projection images. This reconstruction algorithm is a generalization in three dimensions of the widely used convolution-back projection method.

Scanning a typical specimen takes about 20 to 50 minutes. Several hours were required for full threedimensional reconstruction with the use of Sun Ultra® Sparce system. The resolution of this system is approximately 15 microns for a standard specimen. Resolution limitations largely result from the finite resolution of the image intensifier.

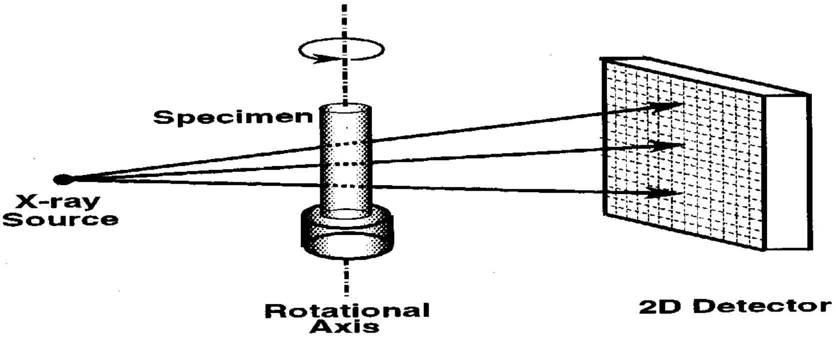

Figure 1. Schematic diagram of the cone-beam x-ray microtomography system.

Algorithms for Three-Dimensional Analysis of Multiphase Particle Populations

In addition to the three-dimensional reconstruction algorithm, several additional algorithms are needed to properly implement the three-dimensional mass density distribution analysis for the particle population. It is not a trivial exercise to automatically separate connected objects ffor both particles and dispersed grains inside each particle) for a 3-D digital image K the surfaces of the objects are not smooth, which is exactly the situation encountered in our case. Furthermore, large amounts of computer memory will be required to manipulate the reconstructed 3-D image array of CT data. The major data processing steps and their corresponding algorithms for mass-density distribution are given in Fig. 2. These algorithms include phase segmentation for data reduction, surface extraction to separate connected particles, labeling for particle classification, and volumetric grade classification for the three-dimensional CT image data set.

One of the problems faced for analysis of the three-dimensional spatial distribution of mineral phases in a multiphase particle population is the identHication and separation of contacted particles. Watershed technique commonly used in morphological analysis (Beucher and Meyer, 1993) was used in this study to separate these particles in contact with each other. The connected components

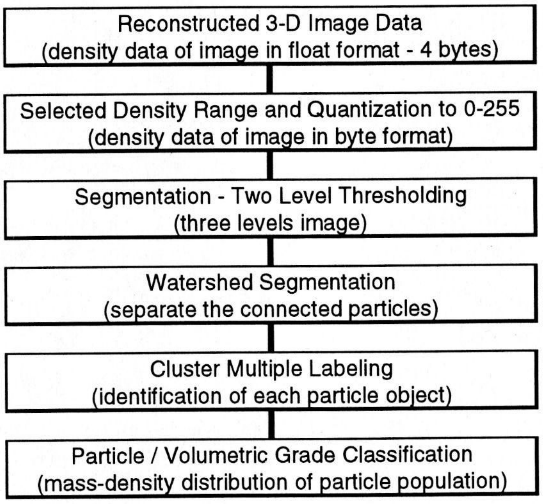

Figure 2. Major steps for the determination of mass-density distribution of particle population from 3-D image data from cone-beam x-ray microtomography.

labeling technique (Haralick and Shapiro, 1992) is widely used for applications involving images which consist of numerous objects. In this regard, the cluster multiple labeling algorithm (Hoshen and Kopelman, 1976) was used to label and classify particle size and grade by volume for the reconstructed three dimensional particles.

Sample Preparation

To test the effectiveness of the three-dimensional cone-beam CT measurement of volumetric grade distribution of multiphase particles, dolomite/sphalerite particles with a size less than 20 mesh (595 microns) were sent to the University of Michigan for CT analysis. The reconstructed three-dimensional image arrays were sent back to the University of Utah for volumetric grade distribution analysis as mentioned in previous section.

RESULTS AND DISCUSSION

Initial Evaluation of the Three-Dimensional Microtomography Images

Since this study represents the first attempt to directly measure the three dimensional grade distribution of multiphase particles, only preliminary data are presented to illustrate the potential of cone beam microtomography.

The three-dimensional reconstruction region for this study is a volume of 3.315 by 5.025 by 1.275 mm. The reconstruction set consists of 221 x 335 x 85 voxels (volume elements). Fig. 3 illustrates the coordinate system for the particulate sample. Three different cross sections (from a total of 85 sections) along the Z-direction as established from the three-dimensional reconstruction of the sample is also displayed in Fig. 2. It should be noted that these sections are taken from the three dimensional image and not used as such to construct the three dimensional image. The spacing between planes equals the resolution which in the Z-direction corresponds to 15 1lm. Here the gray scale levels of the images indicate the relative attenuation coefficient present in the bulk of the sample. The white features represent the sphalerite phase which has the higher mass absorbance. The gray regions in these planar images represent the dolomite phase which has a relatively lower mass absorbance. Reconstruction noise is also present in these images as a cloud of tiny dots with a relatively lower gray level than the dolomite phase. One way of removing the reconstruction errors is to form a gray level intensity (or density) histogram. The overall gray level intensity histogram calculated from the complete three-dimensional voxel array of the sample is shown in Fig. 4. By examination of the density histogram and from a priori knowledge of the noise spectrum (usually, the noise has a lower density than the object that produced it), density values below a certain reference point (in this case, a gray level of 100) can be construed to be noise and thus eliminated.

Volume visualization of the three-dimensional image data is a rapid growing field in the area of computer graphics. Three major approaches for volumetric visualization have been developed in the last decade. These techniques include surface-based, binary voxel, and semitransparent volume rendering methods. Details of these techniques can be found in the literature (Foley et al., 1989; Levoy et al., 1991). Volume visualization using the semi-transparent volume rendering technique is characterized by allowing a color and a partial opacity to be assigned to each voxel. Images are formed from the resulting colored semitransparent volume by blending together voxels projecting to the same pixel on the picture plane. First, to reveal the details of the dispersed grains of sphal~ rite inside the matrix of dolomite, semitransparent and opaque surfaces were assigned for dolomite and sphalerite phases, respectively. Then, based on

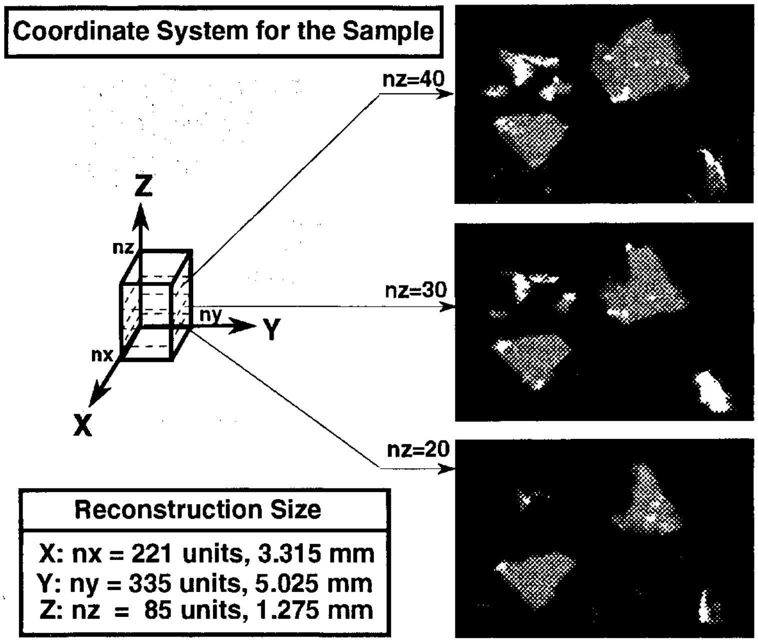

Figure 3. Coordinate system and cross sectional images from the three dimensional x-ray microtomography reconstruction of the locked dolomite/sphalerite particles.

the volume rendering technique, different views of the surface rendered particle images were generated from the reconstructed three-dimensional image array using the VolPack volume renderer (Lacroute and Levoy, 1994) as shown in Fig. 5.

Quantitative Volumetric Grade Measurements from Microtomography Images

For quantitative determination of the volumetric grade distribution, a particle classification algorithm has been developed to treat the three-dimensional array. This particle classification algorithm includes (1) a two-level threshold algorithm for phase segmentation, (2) labeling for particle and grain identification, and (3) classification and measurement of the volumetric grade for each particle. The purpose of segmentation is to separate the particle of interest from the background and from adjacent particles. Generally, a binary image containing white objects of interest and a black background will result from the threshold segmentation operation. The simplest form for thresholding is to select a specific gray level such that all the pixels (or voxels for the three-dimensional data set) with an intensity above or below the selected value are set as black (gray level = 0) and white (gray level = 255), respectively, or vice versa. For the multiphase case, such as ours, a two-level threshold technique based on the voxel intensity histogram (Fig. 4) is applied for phase segmentation. Gray levels of 100 and 200 were selected for dolomite and sphalerite segmentation.

A total of 152 particles and 92 grains of sphalerite within these particles were identified by the classification algorithm. Table 1 only shows the results for particles with a volume larger than 1.6875×10^{-4} mm^3 (50 voxels) which corresponds to a particle with an equivalent size of 55 microns. Table 2 shows the sphalerite grain size distribution inside each of the first six particles listed in Table 1. It is noted that the

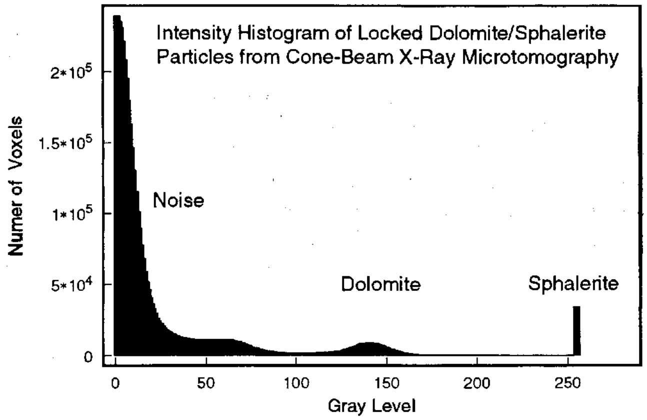

Figure 4. Intensity histogram from the complete three dimensional CT reconstruction of locked dolomite/sphalerite particles.

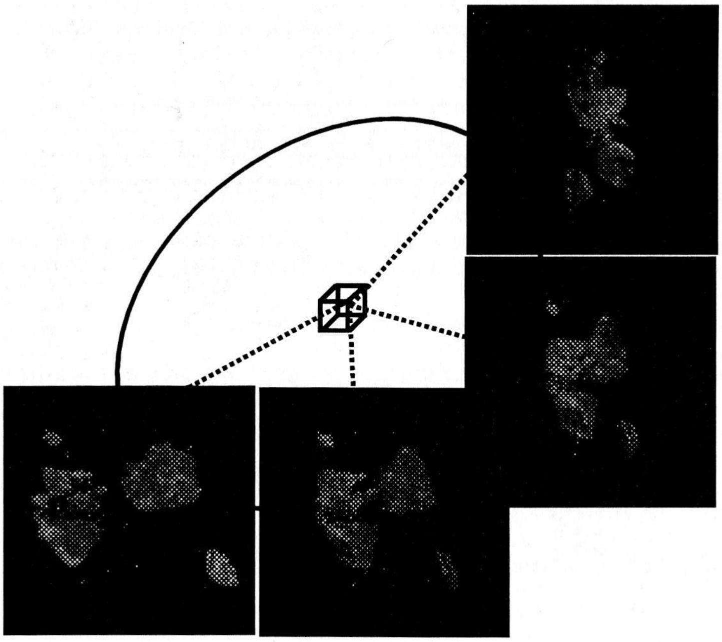

Figure 5. Dillerent views ol three dimensional semitransparent rendEred images of locked dolomite/sphalerite particles trom S-D x-raymicrotomography using VolPadc (Lacroute and Levoy, 1994) volume rendering software where the dolomite and sphalerite phases are distinguished by using semitransparent surlace lor the dolomite phase.

size and grade by volume of the largest particle for this sample, Particle No. 1, are 0.5645 mm^3 (826 microns) and 4.60%, respectively. This maximum size particle of the sample contains 31 sphalerite grains, the largest sphalerite grain having an equivalent size of 220 microns. In contrast, Particle No. 3, with an equivalent size of 500 microns, has only one sphalerite grain with an equivalent size of 363 microns.

Table 1. Size and sphalerite grade by volume tor selected locked dolomite/sphalerite particles as measured by three dimensional x-ray microtomography.

Particle No.	Volume, mm^3 x 10^4	Equivalent Size, µm	Volumetric Grade,%
1	5645.30	826.47	4.60
2	3562.55	708.90	4.79
3	1252.43	500.32	49.89
4	723.26	416.64	66.41
5	558.63	382.27	18.20
6	166.12	255.16	25.68
7	101.01	216.17	21.35
8	48.06	168.76	0.00
9	8.94	96.33	4.91
10	8.64	95.24	0.78
11	6.65	87.29	19.80
12	6.55	86.84	0.52
13	5.84	83.59	0.00
14	5.77	83.25	1.17
15	5.40	81.43	0.00
16	5.30	80.93	20.38
17	5.03	79.53	25.50
18	4.73	77.91	15.71
19	4.66	77.53	2.90
20	4.46	76.40	37.12
21	4.39	76.00	0.00
22	3.92	73.19	0.00
23	3.51	70.54	31.73
24	2.84	65.73	20.23
25	2.63	64.07	30.77
26	1.76	56.04	1.92

Table 2. Grain sizes of dispersed sphabrite inside the first six particles listed in Table 1 as measured by three-dimensional x-ray microtomography.

Grain	Particle No.					
	Grain Size, volume in voxels[a] (equivalent size, μm)					
No.	1	2	3	4	5	6
1	3168(220.3)	4283(243.6)	14232(363.5)	18425(396.2)	1458(170.1)	1264(162.2)
2	749(136.2)	307(101.2)		42(52.1)	762(137.0)	
3	652(130.1)	158(81.1)		29(46.1)	186(85.6)	
4	614(127.5)	108(71.4)		12(34.3)	148(79.3)	
5	339(104.6)	56(57.4)		3(21.6)	148(79.3)	
6	224(91.1)	51(55.6)		1(15.0)	80(64.6)	
7	215(89.9)	17(38.6)			75(63.3)	
8	195(87.0)	14(36.2)			49(54.9)	
9	170(83.1)	14(36.2)			31(47.1)	
10	146(79.0)	13(35.3)			20(40.7)	
11	139(77.7)	12(34.3)			17(38.6)	
12	131(76.2)	7(28.7)			15(37.0)	
13	125(75.0)	6(27.3)			13(35.3)	
14	119(73.8)	4(23.8)			6(27.3)	
15	114(72.7)	3(21.6)			4(23.8)	
16	82(65.2)	1(15.0)				
17	71(62.1)	1(15.0)				
18	69(61.5)					
19	66(60.6)					
20	64(60.0)					
21	55(57.0)					
22	38(50.4)					
23	33(48.1)					
24	32(47.6)					
25	26(44.4)					
26	24(43.3)					
27	22(42.0)					
28	14(36.2)					
29	2(18.9)					
30	1(15.0)					
31	1(15.0)					

a. 1 voxel = 3375 μm^3

SUMMARY AND CONCLUSIONS

For detailed liberation analysis, the volumetric grade distribution of multiphase mineral particles, 100 microns in size or less, can be measured directly by cone-beam x-ray microtomography as described in this study. High spatial resolution (approximately 15 ,ur 1) and the direct processing of raw volumetric data are the two important benefits offered by this new method. Three dimensional liberation analysis by microtomography provides an excellent opportunity to overcome many of the limitations of currently used polished section techniques. Although only preliminary results are reported, it is expected that this analytical approach will provide the basis for more accurate detailed liberation analysis in the 21st century. With the advanced system, complete accounting of the spatial distribution of mineral phases in each particle is possible, including grain size distribution, interfacial area, shape features and textual information.

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