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Direct visualization and three-dimensional reconstruction of structures formed by electrophotographic toner

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ABSTRACT

Materials or objects fabricated with solid particles, such as in additive manufacturing, can assume interior structures influenced by the arrangement of the particles. These structures will result in various porosities and directly impact the performance of the products constructed. It is difficult to image and visualize particle structures from dense powder samples.

We have determined particle positions in three-dimensions within toner powders. With these particle positions, a visualization of the particle structure can be reconstructed. The determination of particle positions involves imaging with a confocal laser scanning microscope to capture a stack of cross-sectional images of florescent particles and analyzing the resulting images. The feasibility of imaging sedimented particulate samples by using micron-sized poly-dispersed electrophotographic printing particles has been demonstrated. The XYZ co-ordinates and radii for these particles (which are assumed to be spherical) have been calculated in several selected sampling volumes. Consequently, a size distribution for the particles has also been obtained. The three-dimensional reconstruction of these particles illustrates a highly porous structure. This methodology of three-dimensional particle mapping and visualization can potentially lead to much needed materials and structural analyses for fine particles.

1. Introduction

Micron-size particles have been used in many industries for applications such as coating, sintered components, electrostatic printing, and most recently additive manufacturing. Additive manufacturing is a rapidly developing technology based on conventional digital printing for the purpose of improving manufacturing capability in form (shape, size, dimensions, mass, etc.), fit (relation to the entire assembly), and function (for which a product or material is designed to perform).

For powder-based printing applications, the quality of a product derives from the particle structure resulting from the print process and materials used. For instance, a missing placement of a particle aggregate will result in a missing "spot" in the manufactured product, which can consequently lead to a defect in the product and a potential failure in its application. The materials produced by particle-based additive manufacturing will assume properties corresponding to the powder employed. Microscopic structures formed within the fabricated material will thus be an influential factor in the resulting object's performance.

The objective of this work is to identify micron-size particle positions in real space and to produce a three-dimensional reconstruction from the particle positions, thus reproducing the particle structure. This work utilizes confocal laser scanning microscopy (CLSM) to identify the centroids of particles according to their pixelated values from planar images collected in stacks in the direction perpendicular to the CLSM imaging plane. This work shows the possibility of determining both the structures of the granular particles within a given volume as well as particle parameters. The study uses the resulting particle positions and radii to reproduce a three-dimensional representation of the structure formed by the particles. This work demonstrates the feasibility of using CLSM to three-dimensionally map and visualize interior structures of a granular particle system and offers a quantitative characterization of fine particle microstructures.

2. Material and methods

2.1. Material and imaging system

The model particles used for this study were micron-sized poly-dispersed electrophotographic (EP) toner (typically made out of styrene acrylate copolymers). EP toners were employed because of their fluorescent capability and because their particle sizes are of similar orders

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to those used in other particle additive manufacturing studies [1–7]. In this study, the yellow toner used was extracted from an HP3700 cartridge.

The samples for imaging were prepared by dropping a small quantity of toners onto a microscope glass slide using a spatula to form a powder sediment. The sampling region was barricaded with double-sided tape and a cover slide was placed on top to seal the sample from toner leakage.

The CLSM at the Rochester Institute of Technology is a Leica TCS SP-5 Biological Confocal Microscope with a reduced out-of-focus blur function. The imaging system used for this visualization had a lateral pixel size of approximately 0.048 μm × 0.048 μm and a Z axis sampling step of about 0.17 μm. The CLSM was imaged with a 40× objective (numerical aperture = 1.1) and with water as the refractive medium on the objective lens of the CLSM. The sample was imaged in the fluorescence mode with an excitation wavelength of 476 nm, generated from an Argon Laser. The scan mode was set to XYZ to obtain multiple XY images at predetermined Z increments. For this study, the XY imaging areas were 44.5 μm × 44.5 μm in dimension.

Z-depth range was determined based on the number of layers observed. The Z scanning (or the Z-stack) was set to 0.17 μm per sampling step. Multiple images obtained at this Z step increment were stacked together to cover the entire sample thickness. Several sampling volumes were selected and imaged. Images were stored in J-peg format for analysis.

2.2. Particle position determination

Fig. 1 shows the three-step procedure to obtain a particle's co-ordinates and radius. Step 1 selects a particle and marks this particle as the region of interest. Step 2 estimates the particle's Z value from the comparison of particle radius in different cross-sectional planes. In this process, the Z-cross-sectional imaging plane that contains the maximum particle radius for the particle of interest is identified. Step 3 locates XY coordinates for the particle in this maximum-radius cross-sectional plane and measures the XY planar radius for the particle (assuming spherical). This process is then repeated for all particles in a selected sampling volume.

The following further describes the three steps:

2.2.1. Step 1—identify a particle for analysis

Fig. 2 shows a CLSM image of an area covered with EP toners. A stack of images can be captured sequentially in the perpendicular direction into this viewing surface (Z axis). Various sampling areas (for example, the area boxed out by the square) have been selected for Z-stack imaging. In this work, nine such areas were randomly sampled.

Fig. 3 displays one cross-sectional plane from the sampling stack of a "boxed" area. At a higher magnification with respect to Fig. 2, the 44.5 μm × 44.5 μm imaging area shown in Fig. 3 illustrates particles of different diameters as the grey areas (indicating fluorescence). The diameter variation comes from 'cutting' through particles with centers at different "heights" (zero is the top surface of the glass-slide receiver) as well as from a distribution of particle sizes. A particle, marked by the white circle, is selected here to be the particle (or region) of interest and the XY position and radius analysis are then carried out for this particle in the next step.

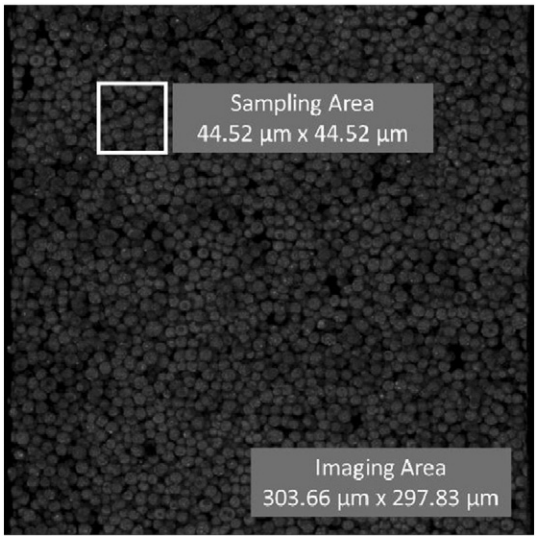

Fig. 2. Image of an area covered with toner particles. A sampling area is selected as shown by the boxed area.

2.2.2. Step 2—obtain the Z center frame

The Z position of the particle can be determined by the comparison of the radius for the particle of interest at different depths (This can also be done by marking the maximum of the fluorescence intensity profile, but this approach is not used here for a reason to be discussed in the discussion section). In this analysis, the particle 'starts' from the frame when it appears in the XY cross-sectional image and 'ends' at the frame where it disappears in the image at a particular depth. This method estimates the Z value for the particle centroid to be at the frame where the particle of interest has the maximum radius. Shown in Fig. 4 are cross-sectional images for a particle at three different depths to illustrate this radius change at different Z values.

Correspondingly, one can also observe other particles "appearing" or "disappearing" from each of the three views, revealing particles centered at various Z positions. As the size of a particle increases in the image stack, the number of fluorescing pixels increases, causing the particle to appear bigger and brighter. Beyond the center plane of the particle, the particle 'disappears' or blurs out of the image as the number of fluorescing pixels decreases.

2.2.3. Step 3—determine the particle's XY locations and radius

The maximum-radius z-position frame identified from Step 2 becomes the image frame for the analysis of X and Y values for the "particle-of-interest". To identify the X and Y co-ordinates and the radius for the particle of interest, the MatLab imaging function called 'imfindcircles' is used, which is based on the Circular Hough Transformation [8] algorithm. Fig. 5 illustrates the determination of these values for an example z-position frame for a particle of interest. MatLab 'imfindcircles' marks the particle (as a circle). The 'imfindcircles' function locates the X and Y co-ordinates for the center of the particle and radius, as shown in the figure.

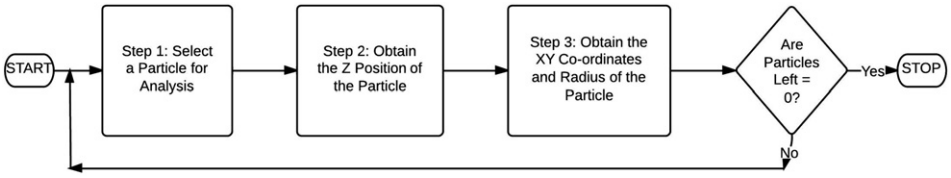

Fig. 1. A three-stepped process to obtain the particle co-ordinates and radii.