INVESTIGATION OF PORE STRUCTURE AND DEFECTS OF METAL ADDITIVE MANUFACTURING COMPONENTS USING X-RAY COMPUTED TOMOGRAPHY

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Summary: X-ray Computed Tomography (XCT) revealed pore structure and defects of additively manufactured metal parts produced with various processing parameters. A thresholding procedure involving a local thresholding algorithm was developed where the local thresholding parameter was found from the image itself. Qualitative analysis of Additive Manufacturing (AM) pore structure and quantitative measurements of engineering parameters were carried out based on the thresholded images.

1. INTRODUCTION

Additive Manufacturing (AM) is a revolutionary manufacturing technique for creating complex geometry parts. The metal-based AM has great potential in a wide range of industries including aerospace, automotive, and medical implants. For widespread adoption of this technology, however, thorough characterization of microstructure as related to performance is needed. Quantification of pore structure can be for the purpose of quality control in eliminating pores, or for quality control in producing a desired pore structure and/or pore size distribution, for example in porous biological implants. Pores are commonly observed in AM parts, which occur due to incomplete melting or gas entrapment. Critical pore size and structure are yet to be determined for AM, and of course will depend on expected mechanical properties in service, but are thought to be on the order of 100 μm for typical applications, which need to be screened out before putting into service. While porosity is typically measured with gravimetric techniques or Archimedes' method, the actual pore structure and pore distribution have not been thoroughly considered. Characterization of pore structure in 3D is crucial for determining macroscopic properties for any heterogeneous material, including AM materials. In this paper, we used X-ray Computed Tomography (XCT) to study the pore structure of AM parts, including the effect of AM processing parameters. This study is also presented as an example of how to carefully select image processing parameters and image segmentation algorithms, which are required for valid quantitative analysis, based on aspects of the images themselves. It is hoped that this paper can serve as a basis for developing standardized analysis of XCT images of AM parts.

2. EXPERIMENTAL METHOD

Cobalt-chrome alloy disks were produced using laser-based powder bed fusion (PBF) processes (EOS M270 Direct Metal Laser Sintering System (DMLS)†) with varying scan speed (v, straight line speed of laser), varying hatch spacing (h, the distance between adjacent laser scanning tracks), a constant laser power of 195 W, and a nominal distance between build layers of 20 μm. Six disks with varying processing parameters were produced. Pre-alloyed and gas-atomized CoCr powders, with size, as measured by laser diffraction, between 5 μm and 80 μm, with a peak around 30 μm, were used. Cylinders with 5 mm diameter and 10 mm height were cored out of the disks (about 2 mm from the disk edge), and measured with the ZEISS Versa XRM500 system available at

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† Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

NIST. Two settings were used to achieve images with pixel sizes ≈ 2.44 μm and ≈ 0.87 μm.

3. RESULTS

XCT provided qualitative information of the microstructure produced with different AM processing parameters, as shown in Figure 1a. Gravimetric measurements of porosity (φ) are also shown in Figure 1a. The image of sample 1 (v = 800 mm/s, h = 0.1 mm, and φ = 0 %) is not shown as there was no visible pore. In some cases, a part can have large enough pore spaces to trap raw metal powders, as shown in Figure 1b. Such trapped powders can mislead gravimetric density-based mechanical performance estimation as they provide little mechanical support if the part is loaded in tension. For a quantitative analysis, a local thresholding algorithm (Bernsen's method [2]) was studied carefully and used to threshold images. The local thresholding algorithm parameter was found based on the standard deviation of image intensity within homogenous areas as it provides noise characteristics. Global thresholding algorithms (Figure 2b and c) were not reliable due to non-uniform image intensity in this case. In this paper, we developed a procedure to more accurately segment XCT images based on the information of the images themselves to find a suitable input parameter of the local thresholding algorithm (Figure 2d) without using proprietary commercial software codes. The thresholding technique was successfully applied to all data sets to acquire quantitative information including porosity, pore size distribution, virtual removal of trapped powders, powder size distribution (Figure. 2e), porosity over height of the sample, and powder size distribution. XCT-based dimensional measurement, determination of the effects of AM defects, and image-based prediction of mechanical property are also on-going projects.

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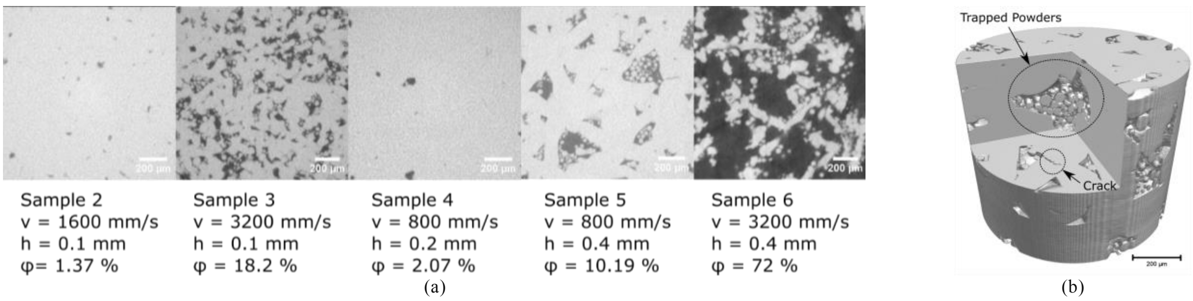

Figure 1: (a) Microstructure comparison of samples produced with different AM processing parameters. (b) Three-dimensional view of Sample 5 with trapped powders in pore spaces and cracks.

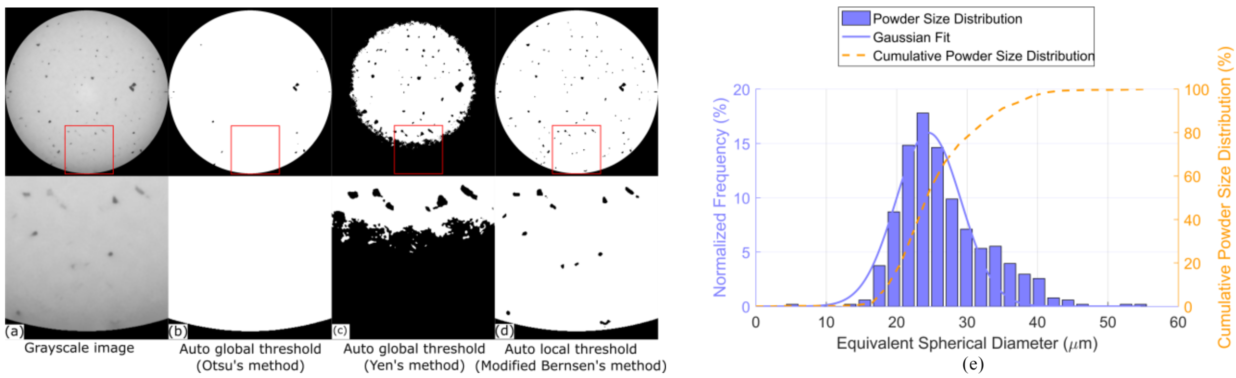

Figure 2: (a) Original grayscale image of Sample 2, and image thresholding results based on automatic global ((b) Otsu's and (c) Yen's method) and local thresholding algorithms ((d) modified Bernsen's method). (e) The powder size distribution of trapped powders measured based on the thresholded images of Sample 5