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Quantitative Study on the Effect of Thermal Gradients on the Microstructure of Additively Manufactured Ti-6Al-4V Builds

Meiyue Shao[1], Chris Blackwell[1], Sriram Vijayan[1], Sabina Kumar[2], Sudarsanam S. Babu[2,3,4], Joerg R. Jinschek[1]

[1.] Department of Material Science and Engineering, The Ohio State University, Columbus, OH, USA.
[2.] Department of Material Science and Engineering, University of Tennessee, Knoxville, TN, USA.
[3.] Department of Mechanical Aerospace and Biomedical Engineering, U Tennessee, Knoxville, TN, USA.
[4.] Advanced Manufacturing Program, Energy and Environmental Sciences Division, ORNL, Knoxville, TN, USA.

Additive manufacturing (AM) can be defined as the broad class of methodology that produces components of a desired shape, size and composition by depositing material in 'layer by layer' method. By reducing the need for molds, dies, punches, expensive tooling, and several steps required to make a finished part, AM becomes more desirable, inexpensive and rapid route, to produce components with complex part geometries in small batches. Fusion based AM with Ti-6Al-4V (Ti64) alloy powders are now used to make high-performance custom-made parts for aerospace and biomedical applications. The layer by layer addition of powder, followed by melting and solidification over the 'previously melted' layer results in steep thermal gradients that causes repeated thermal cycling (heating and cooling) above or below critical phase transformation temperatures. The thermal gradient transients develop along the x, y and z build directions with reference to the underlying geometry of the component [1]. These thermal signatures are functions of several build parameters that include; beam power, scan velocity, scan pattern, layer thickness, and energy transfer, to name a few. The steep and alternating thermal gradients along with high heating- and cooling rates (10^4 K/s) across the three build directions may result in; metastable phases, residual stresses, volume defects, and mechanical anisotropy in the final AM part. As an example, mechanical anisotropy was measured in Ti64 alloy builds made by direct energy deposition and had been correlated to variations in the local microstructure brought about by the decomposition of β-phase to different α-phase morphologies [2]. However, the transients of phase transformation kinetics at α/β phase interface during complex cyclic heating and cooling are yet to be probed with multi-length scale and time-resolved characterization. Therefore, to understand the effects of cyclic thermal gradients on the microstructure evolution, there is a need for site-specific high-throughput characterization and data analysis methods. We propose to use large field-of-view scans using scanning electron microscopy (SEM) to quantify these variations in microstructure vs changes in thermal gradients in the AM build process.

Previously, researchers have developed stereological procedures to quantify the microstructure of a conventionally processed wrought α/β - Ti64 alloy using SEM [3]. Collins *et al.* [3] identified microstructural features such as: 1) size of equiaxed α, 2) volume fraction of equiaxed α, 3) volume fraction of total α and 4) the thickness of Widmanstätten α-laths. These features were observed to have the strongest influence on the mechanical properties of conventionally processed α/β - Ti64. Therefore, we adopt a similar approach to identify spatial variations of microstructural features in AM Ti64 builds, to quantify and correlate these variations to thermal conditions within the build plane and along the build direction of the AM build.

In this study, we characterized the bulk microstructure and phase distribution in Ti64 blocks with dimensions 15 x 15 x 25 mm, fabricated via electron beam melting (EBM) on a powder bed using three different beam scanning strategies. As shown in Figure 1a, a metallographic sample was prepared from a 15 x 15 x 1 mm section cut, 2 mm from the bottom of the AM Ti64 block. A 10 x 0.8 mm^2 region of interest (ROI) in the middle of XY build plane (Figure 1b) was imaged in an Apreo SEM (Thermo Fisher Scientific). A single SEM micrograph obtained from a small area within the ROI in Figure 1b revealed the α/β microstructure containing both basketweave and martensitic α-phase morphologies, as shown in Figure 1c. Over 400 individual, slightly overlapping SEM images were acquired to image the entire area with a spatial resolution of 25nm simultaneously enabling quantification of potential residual fraction of β phase. Figure 2 shows three representative columns of the SEM image montage that depict the observed variation in microstructure across the XY build plane. Results from the statistical analysis on these large-area scans, performed with the MIPAR™ software, will be presented and used to identify and quantify the microstructural features that are most strongly influenced by variations in thermal gradients [4].

References
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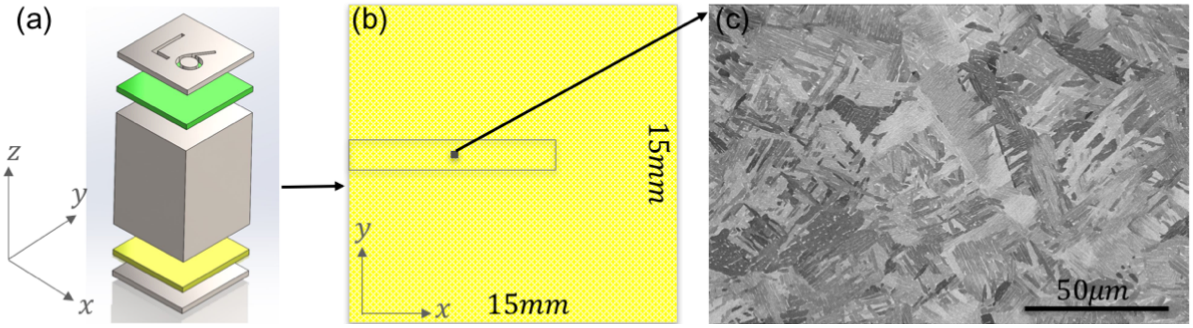

Figure 1. (a) scheme of AM Ti64 block, (b) large 10x0.8mm^2 area scan in the middle of XY build plane, (c) individual SEM image of the area marked with black square in (b).

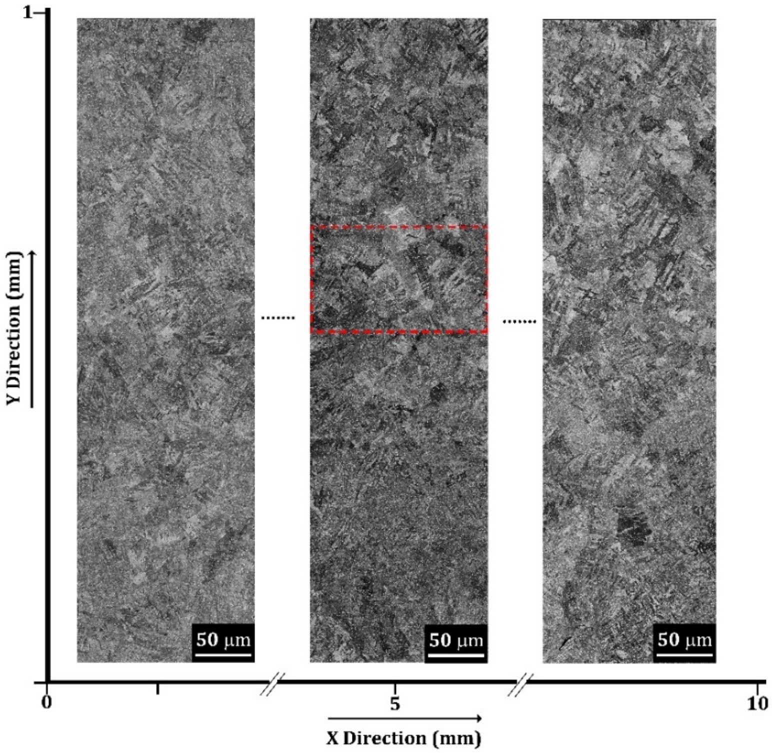

Figure 2. The montage of SEM micrographs obtained from specific areas across the 10x0.8mm^2 ROI of the AM-Ti64 sample. This figure depicts the variability in the microstructure across the XY build plane of the AM Ti-64 block. The red dashed rectangle outlines the region shown in Figure 1c.