Study on the Effect of Thermal Gradients on the Microstructure of Additively Manufactured Ti-6Al-4V by Optical Microscopy Image Analysis

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Additive Manufacturing (AM) of Ti64 Alloy

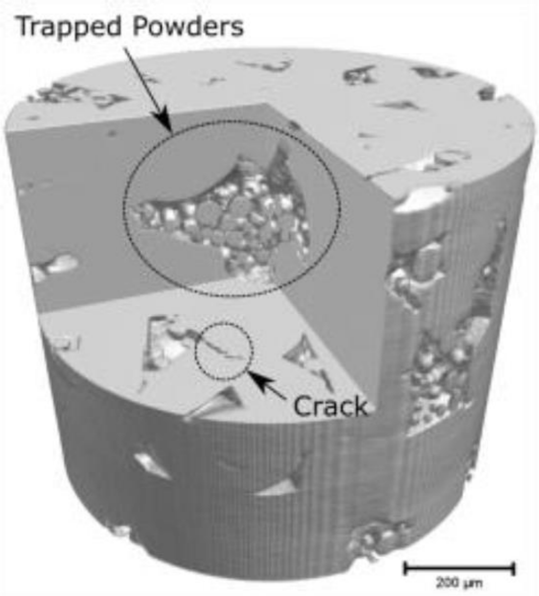
Opportunity

Relevant for complex design and functional performance of parts

Investigate the effect of AM beam scan strategies

- to control complex thermal conditions and fast cooling rate
- thereby the effect on number of defects in the AM part
- Trapped power creates lack of fusion defects
- Defect conditions and characteristics are quantifiable using optical microscopy

Challenges



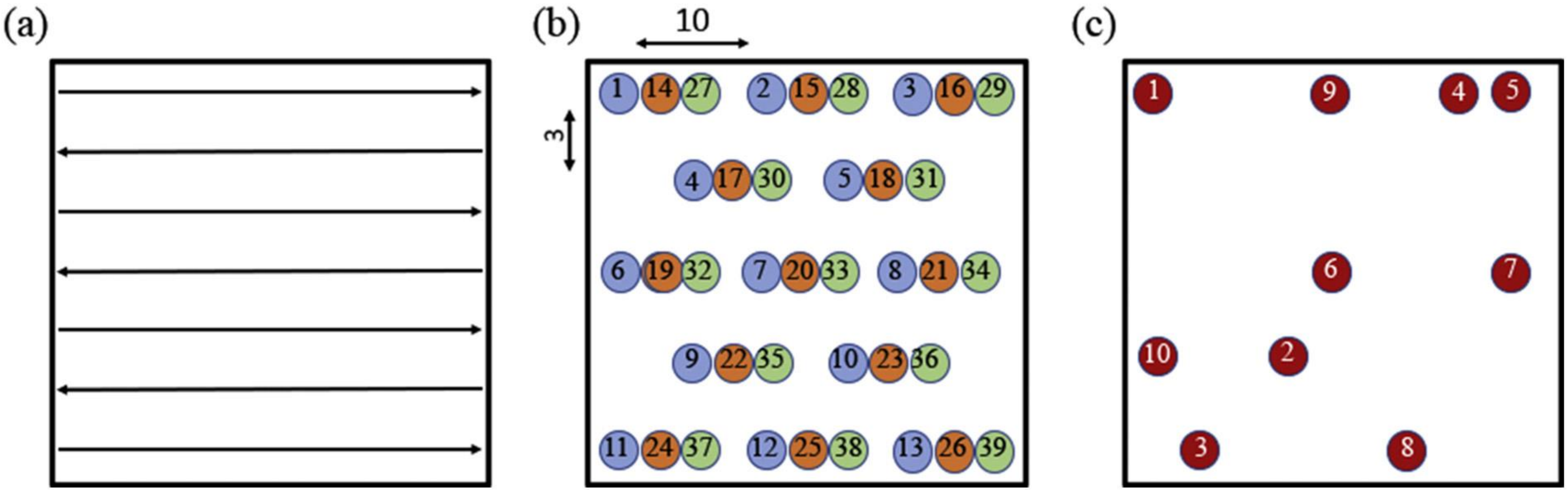
Various defects in an AM metal component [1].

[1] Kim, F., et al. (2017)

AM Processing Parameters

EBM Electron Beam Scan Strategies

Linear raster scan (**LS**) | Ordered spot scan (**OS**) | Random spot scan (**RS**)



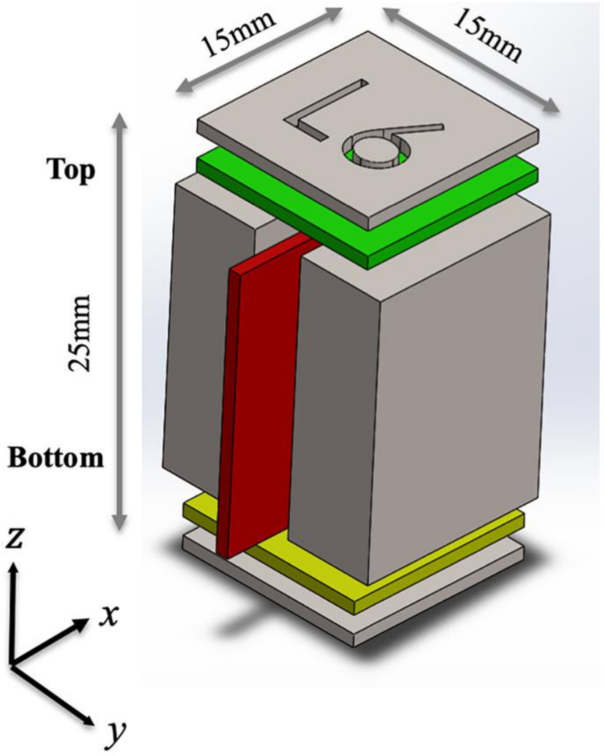
Bi-directionally continuous scan

Spot melt each 11th point in a line, skip 3 lines and repeat

Randomly spot melt each point with equal probability

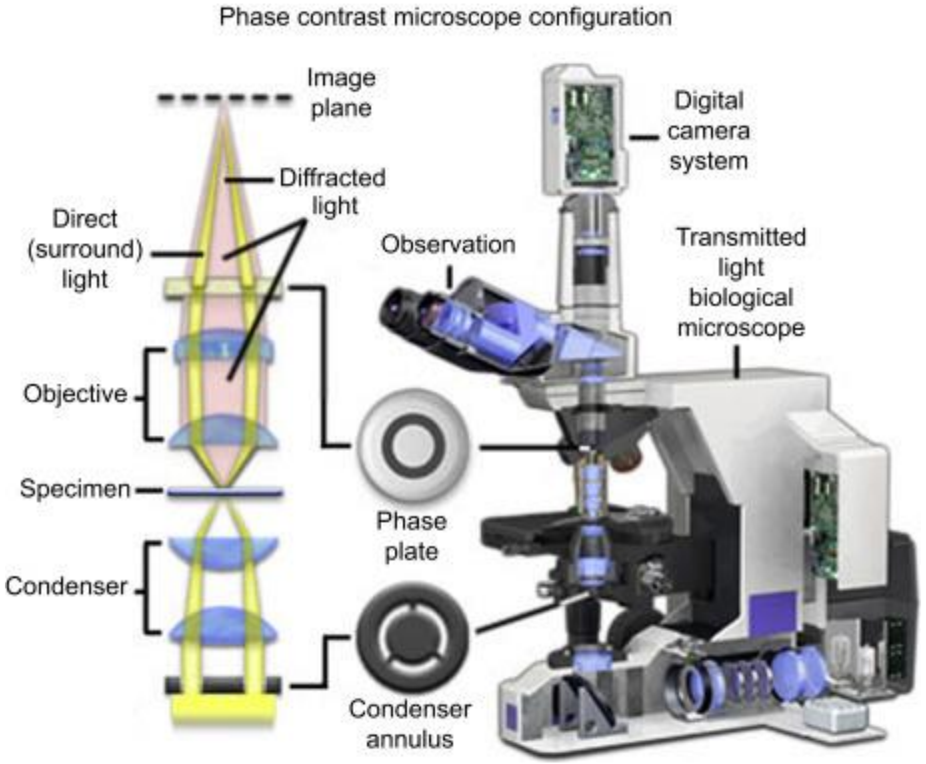
M. Shao, et al. *Materials & Design* 196: 109165 (2020).

Location and Description of OM Analysis in AM Ti64 Build



Schematic of AM metal part, indicating the location cut for OM characterization [1].

- AM sample is cut along the build direction
- Sample surface is polished according to standard metallography techniques
- An optical microscope (OM) is used to characterize the sample surface and to identify AM build defects



Standard Optical Microscope System [2].

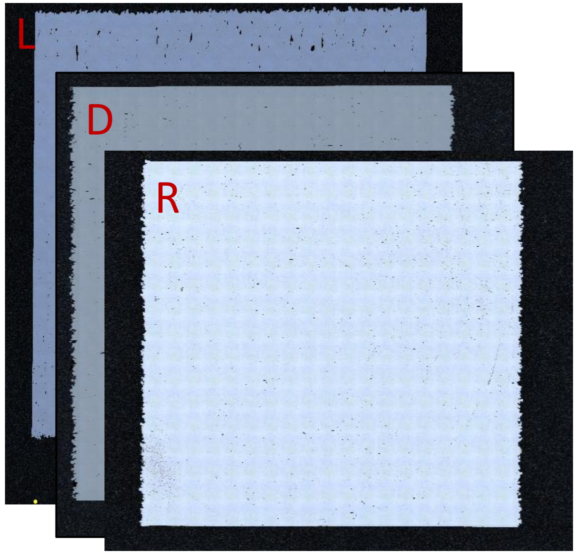
Optical microscopes work via a light source and an objective lens to magnify the specimen surface.

[1] M. Shao, et al. *Materials & Design* 196: 109165 (2020).

[2] A. Di Gianfrancesco, Materials for Ultra-Supercritical and Advanced Ultra-Supercritical Power Plants, 197-245, (2017).

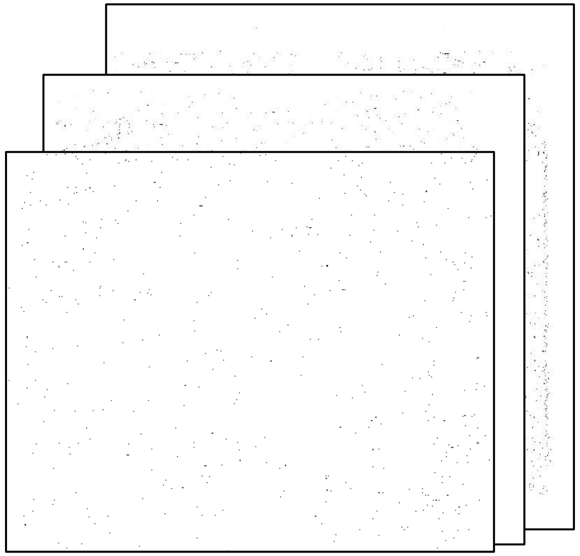
Background

Unprocessed



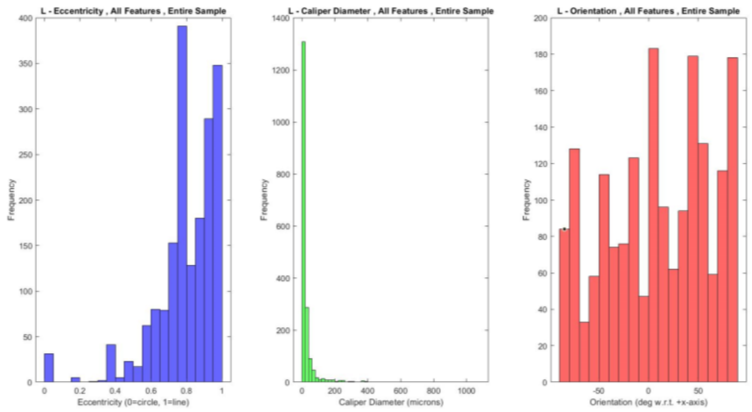
[1]

Processed



Features with area <4 pixels filtered out as noise

[2]



Processed to analyze:
- Size
- Orientation
- Distribution

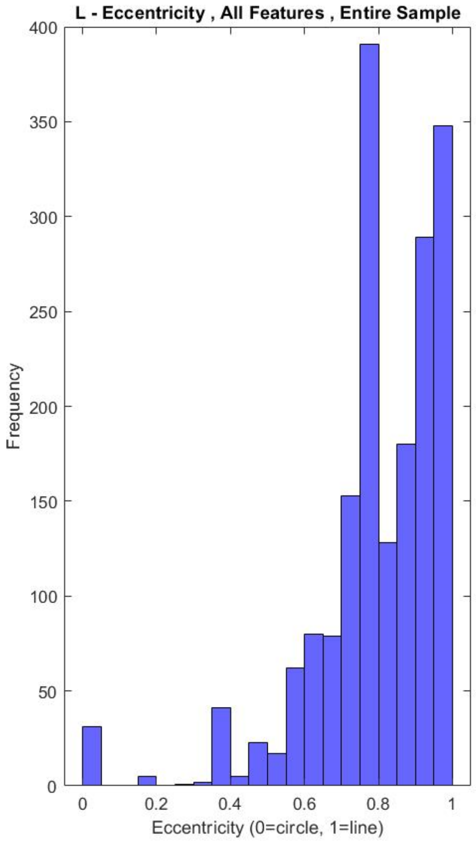
Transformed into graphical representation

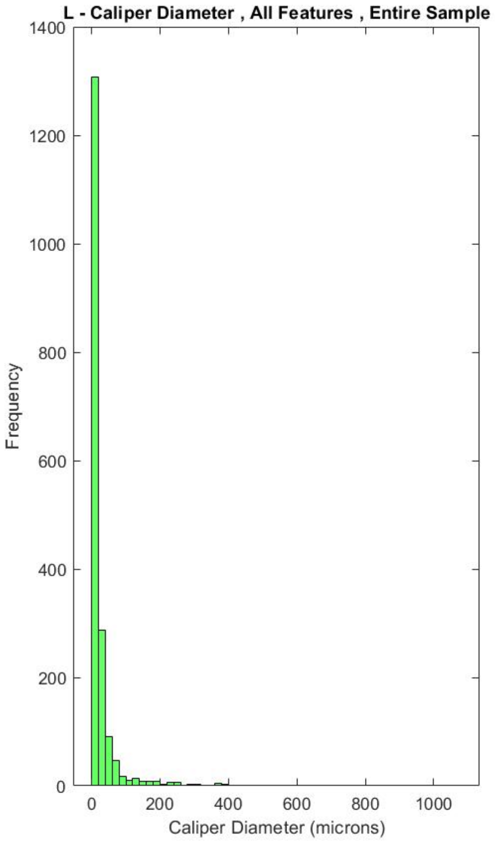
[1] https://www.mipar.us/
[2]https://www.mathworks.com/products/matlab.html

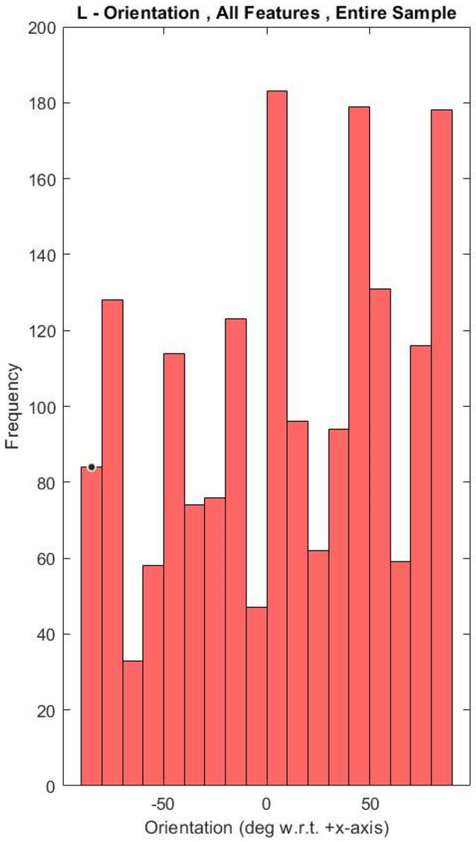
Linear Scan Strategy

- Large fraction of high eccentricity defects
  - Elongated features
- Corresponding small mean caliper diameter
- Broad distribution of orientation throughout sample

Linear Scan Strategy			
Mean Caliper Diameter (µm)	Caliper Diameter Standard Deviation (µm)	Mean Orientation (° from + x-axis)	Orientation Standard Deviation (° from + x-axis)
28.3	64.3	8.74	52.4



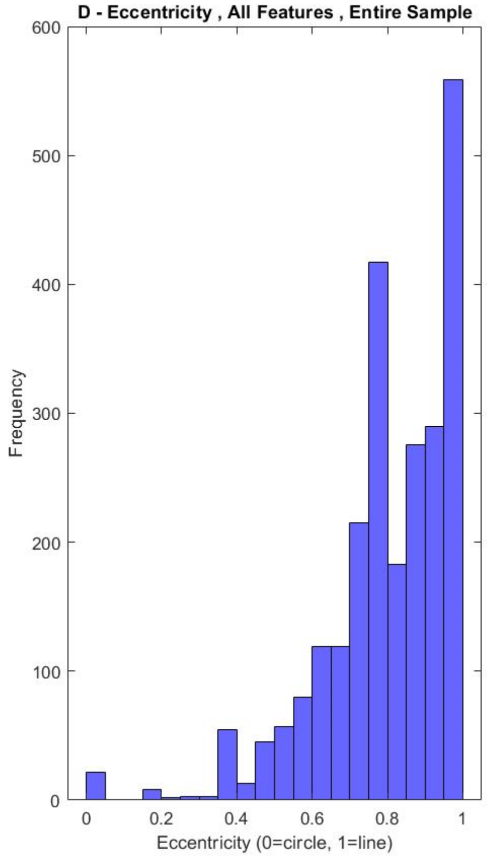


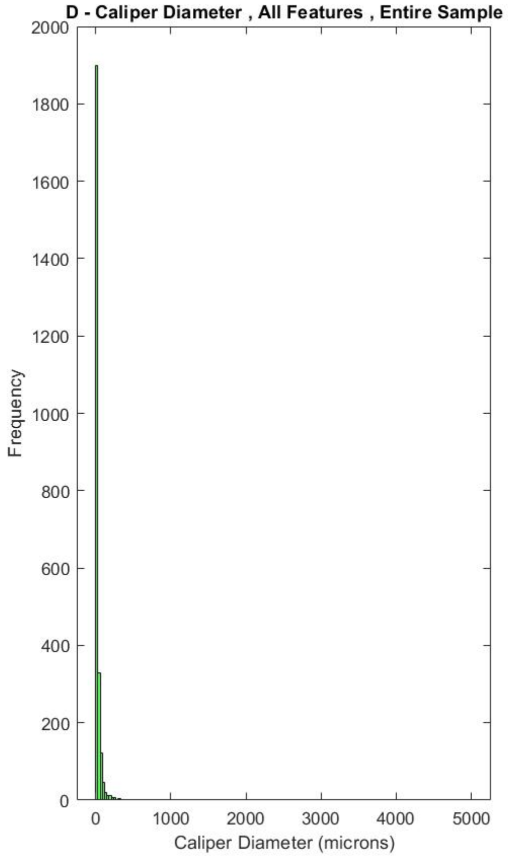


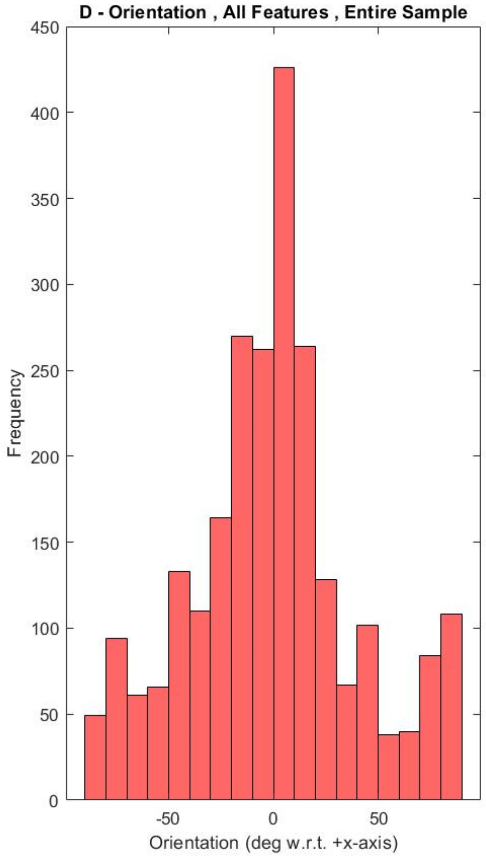
Dehoff Scan Strategy

- Similar to linear scan strategy
- Still a significant fraction of high eccentricity defects
  - Elongated features with an increased circular feature density
- Small increase in mean caliper diameter
- Low angle features dominant

Dehoff Scan Strategy			
Mean Caliper Diameter (µm)	Caliper Diameter Standard Deviation (µm)	Mean Orientation (° from + x-axis)	Orientation Standard Deviation (° from + x-axis)
30.2	109.7	-0.932	39.8



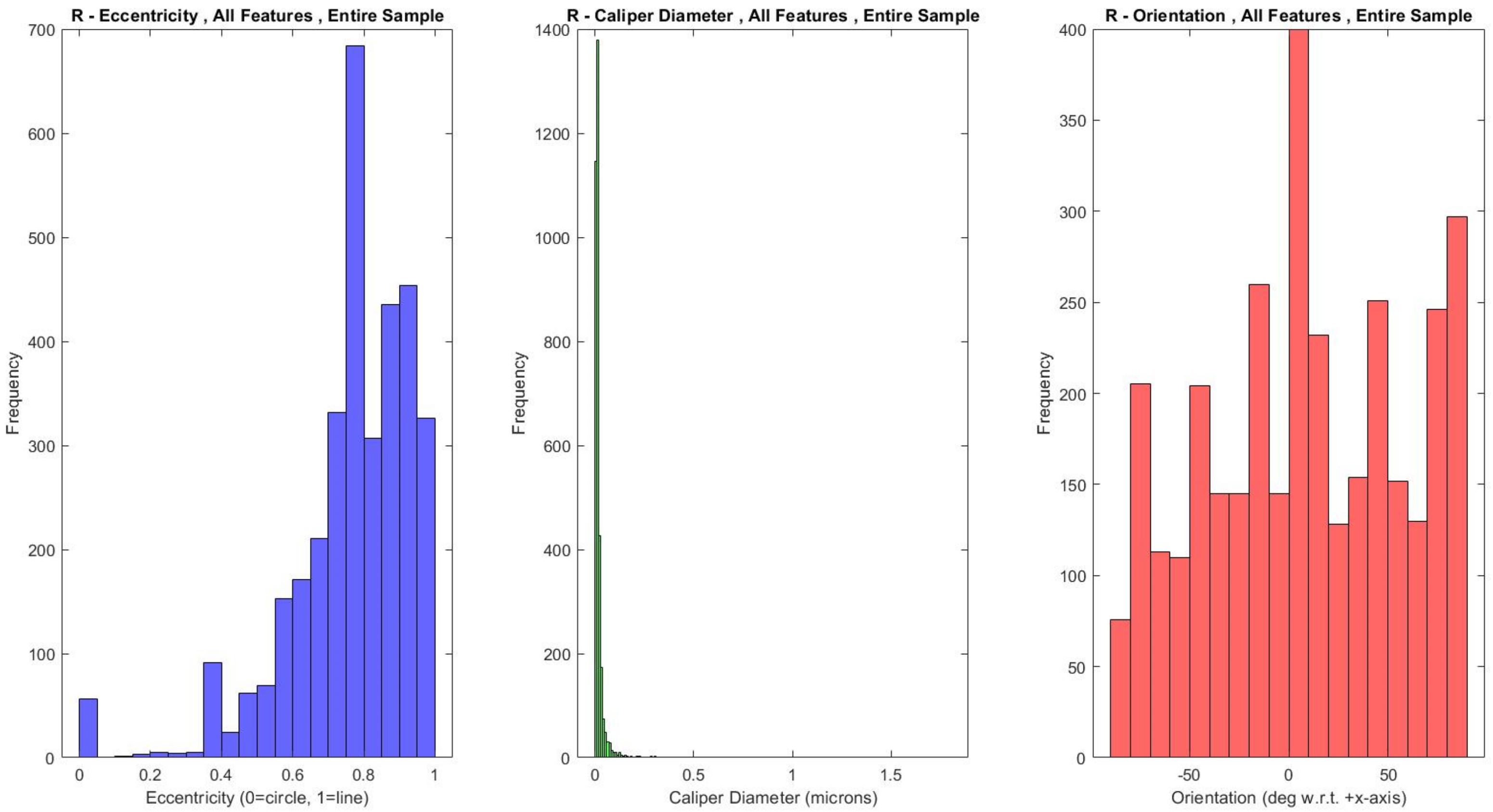




Random Scan Strategy

- Less significant trend shown within eccentricity
  - Elongated features slightly dominate over circular
- Smallest mean caliper diameter of all three scan strategies
- Broad distribution of orientation with significant density of low angle features

Random Scan Strategy			
Mean Caliper Diameter (µm)	Caliper Diameter Standard Deviation (µm)	Mean Orientation (° from + x-axis)	Orientation Standard Deviation (° from + x-axis)
21.4	56.9	8.00	49.3



Conclusion

- Microstructure; in relation to lack of fusion defects are highly influenced by electron beam scan strategy
- Linear and Dehoff scan strategies demonstrate high fractions of large eccentricity defects
- Caliper diameter changed minimally between samples likely due to the subsequent changes in eccentricity.
- Defect orientation consistently maintained a low angle spike
  - Likely due to the defects following the build layers out towards the edges
  - High angle feature likely smaller porous features

- The random scan strategy presents the largest number of defects at the greatest density within the microstructure of Ti-64

	Dehoff Scan Strategy	Linear Scan Strategy	Random Scan Strategy
Total Number of Defects	2466	1835	3925
Defect Density per square mm	11.8	8.6	17.9

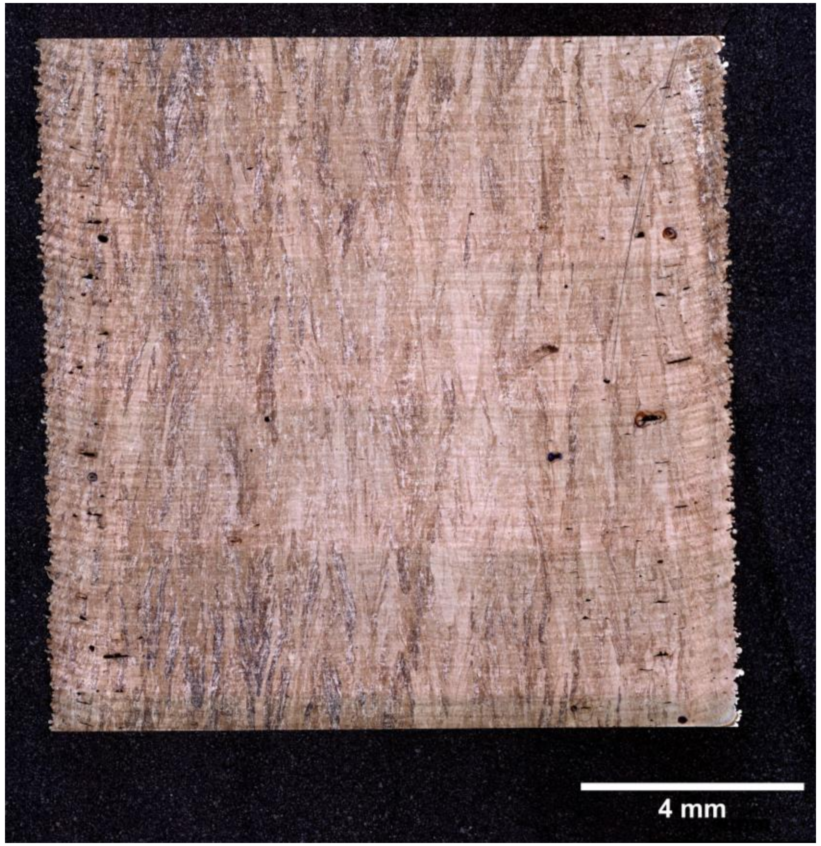
Next Steps

- Etch the sample surfaces to reveal grain structure
- Compare to EBSD for each scan strategy
- Understand if we can identify grain structures in OM as it can be seen in EBSD
- Advantage Optical Microscopy:
  - faster, easier
  - Identify potential correlation between lack of fusion defects and underlying microstructure

Optical Microscopy
(etched sample surface)

↔

Electron Backscatter Diffraction (EBSD)
(IPF figure of reconstructed β grains)



Example: linear scan sample