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Ultrasonic Inspection of Additive Manufactured Components

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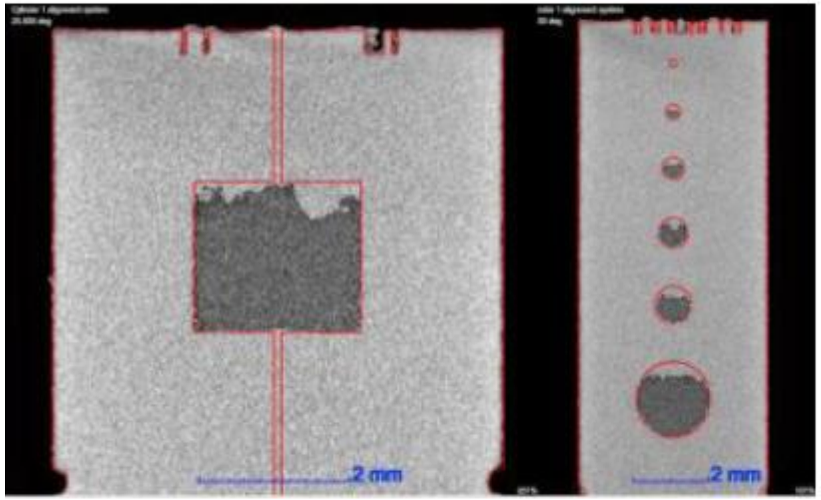
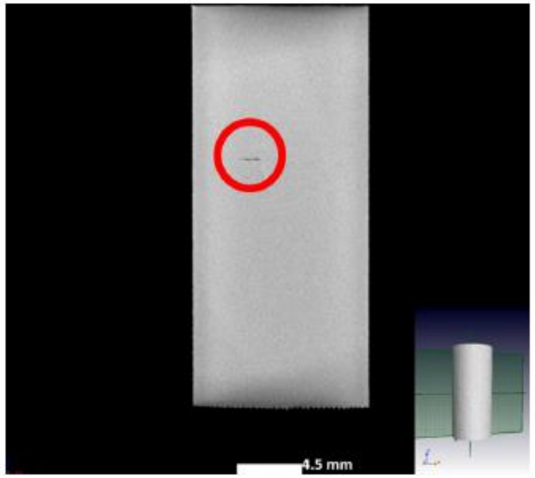
Background and motivation

- Additive Manufacturing (AM) is moving towards production of highly complex, low volume functional metallic components.
- This introduces new challenges related to quality assurance of the mechanical properties and homogeneity of the manufactured parts.
- Defects that arise during AM might be undetectable without the use of NDT techniques.



[1] **Kim et al.**

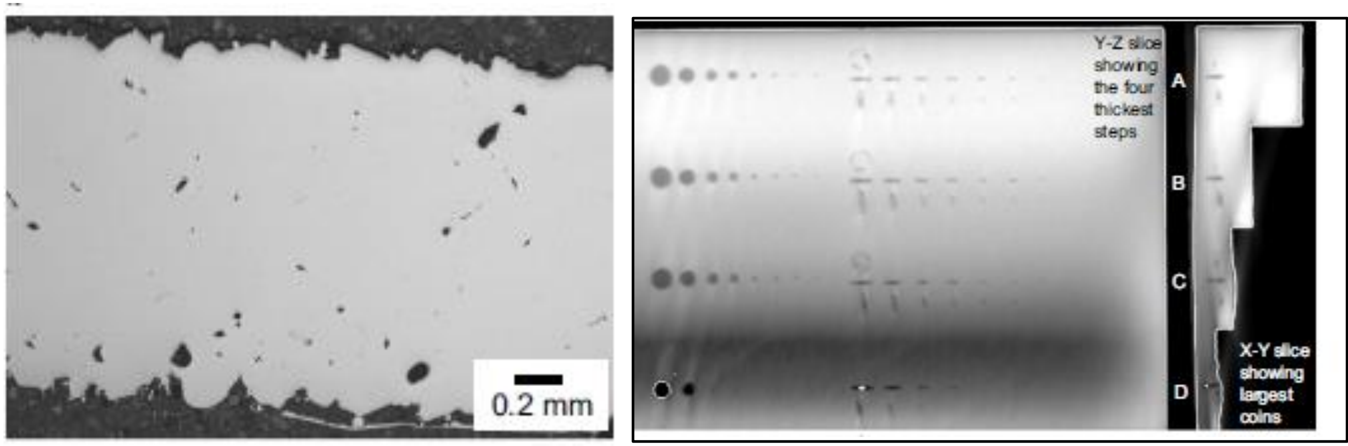


[2] **Plessis et al.**

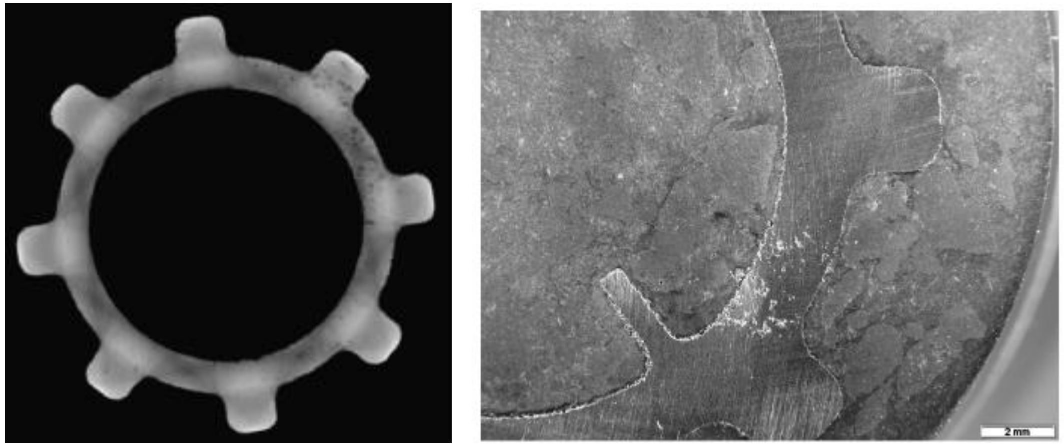
[1] F. H. Kim, H. Villarraga-Gomez, and S. P. Moylan, in *Proceedings of the American Society for Precision Engineering*, Raleigh, NC, Jun. 2016, vol. 64, p. 6.
[2] A. du Plessis and S. G. le Roux, *Additive Manufacturing*, vol. 24, pp. 125–136, Dec. 2018.

Background and motivation

- X-ray Computed Tomography (XCT) is the state-of-the-art NDT technique to identify defects in AM parts.
  - It is useful for accurately studying the internal structure of the part.
  - X-rays have trouble penetrating large parts made of dense alloys.
  - It is expensive to use for ongoing quality control purposes and requires elevated safety precautions.
- Ultrasonic NDT is investigated as a cost effective and safe alternative for defect detection in AM parts.
  - Ultrasonic imaging resolution is usually lower than XCT.
  - It is sufficient for detecting flaws for quality control purposes.



[1] **Rometsch et al.**

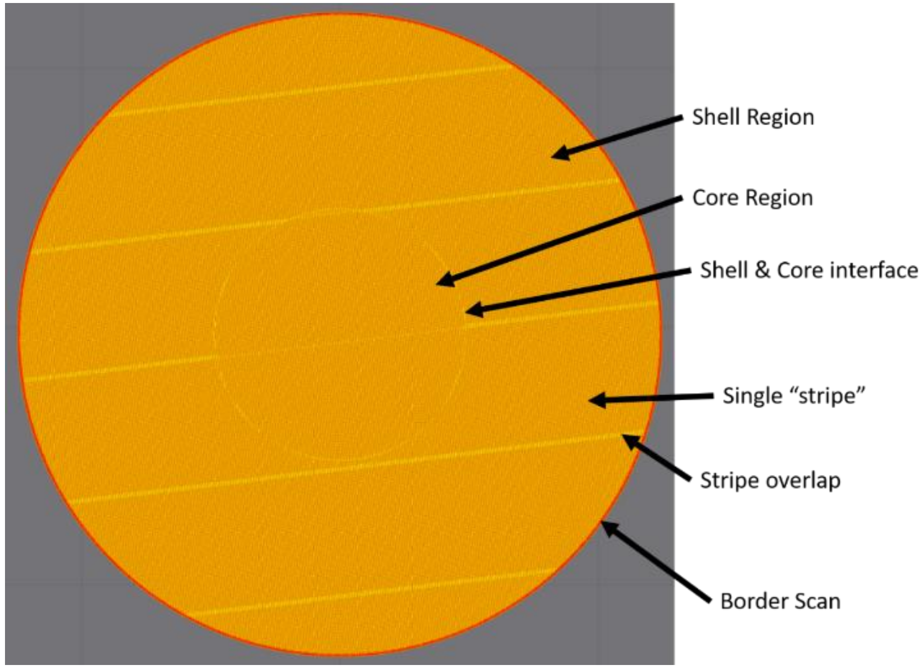


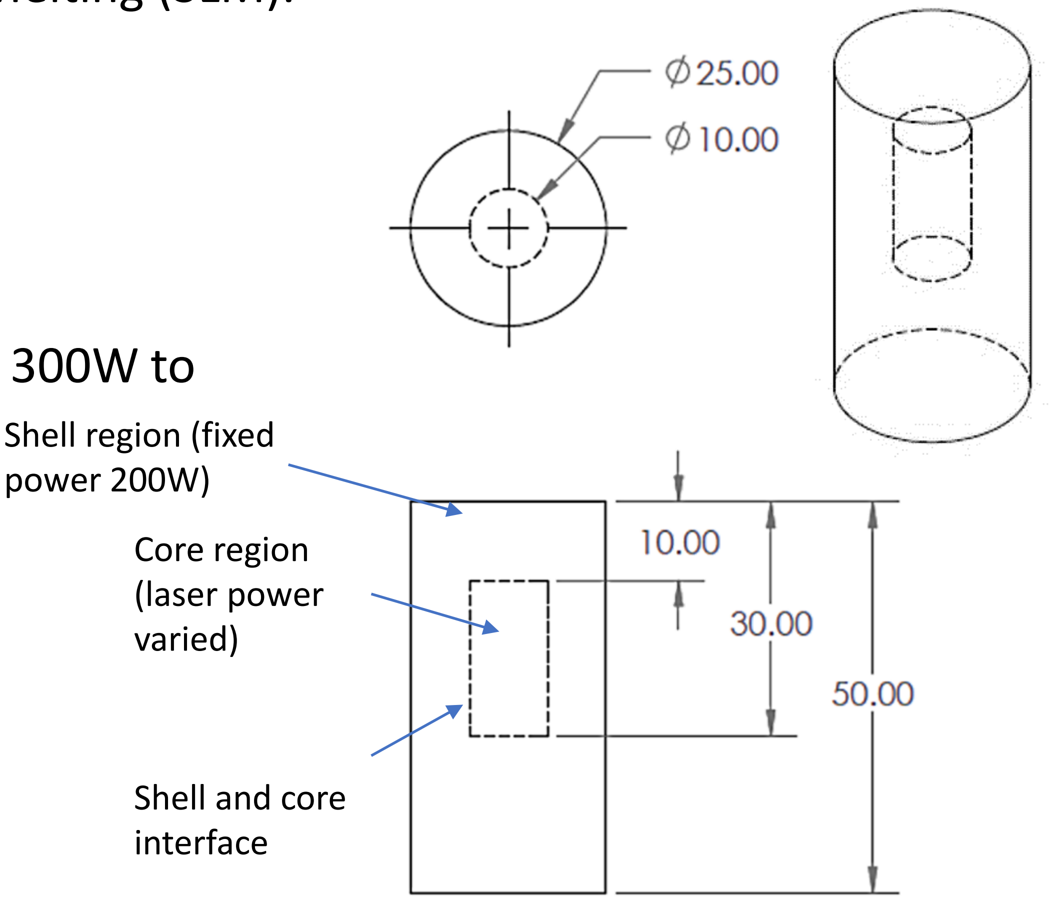
[2] **Plessis et al.**

[1] P. A. Rometsch, D. Pelliccia, D. Tomus, and X. Wu, *NDT & E International*, vol. 62, pp. 184–192, Mar. 2014.
[2] A. du Plessis, S. G. le Roux, J. Els, G. Booysen, and D. C. Blaine, *Case Studies in Nondestructive Testing and Evaluation*, vol. 4, pp. 1–7, Nov. 2015.

AM samples

- 6 cylindrical samples were 3D printed using Selective Laser Melting (SLM).
- Print details:
  - Machine: Renishaw RenAM 500Q, Material: Inconel 625
  - Layer thickness: 30µm, Point Distance: 70µm
  - Stripe Size: 5mm, Stripe Offset: 0.1mm
  - Exposure Time: 70 µs
- The laser power was varied at the core region from 100W to 300W to generate systematic defects in each cylinder.

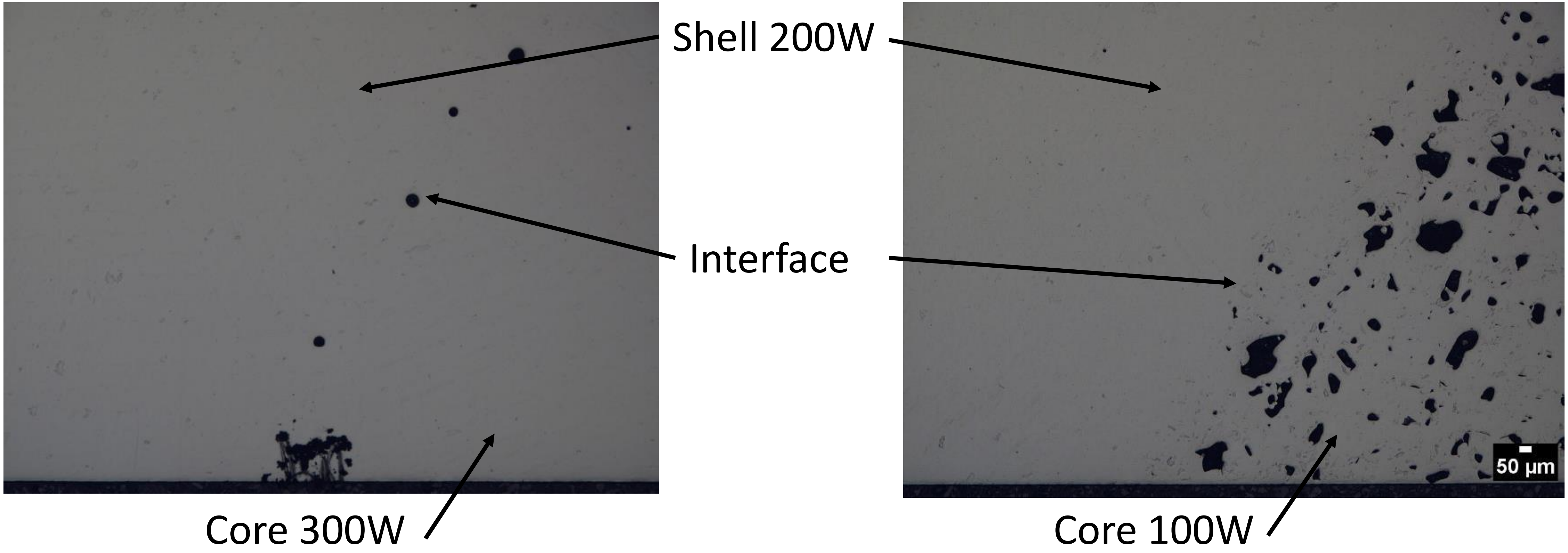




*Dimensions are in mm

Optical micrographs of the printed cylinders

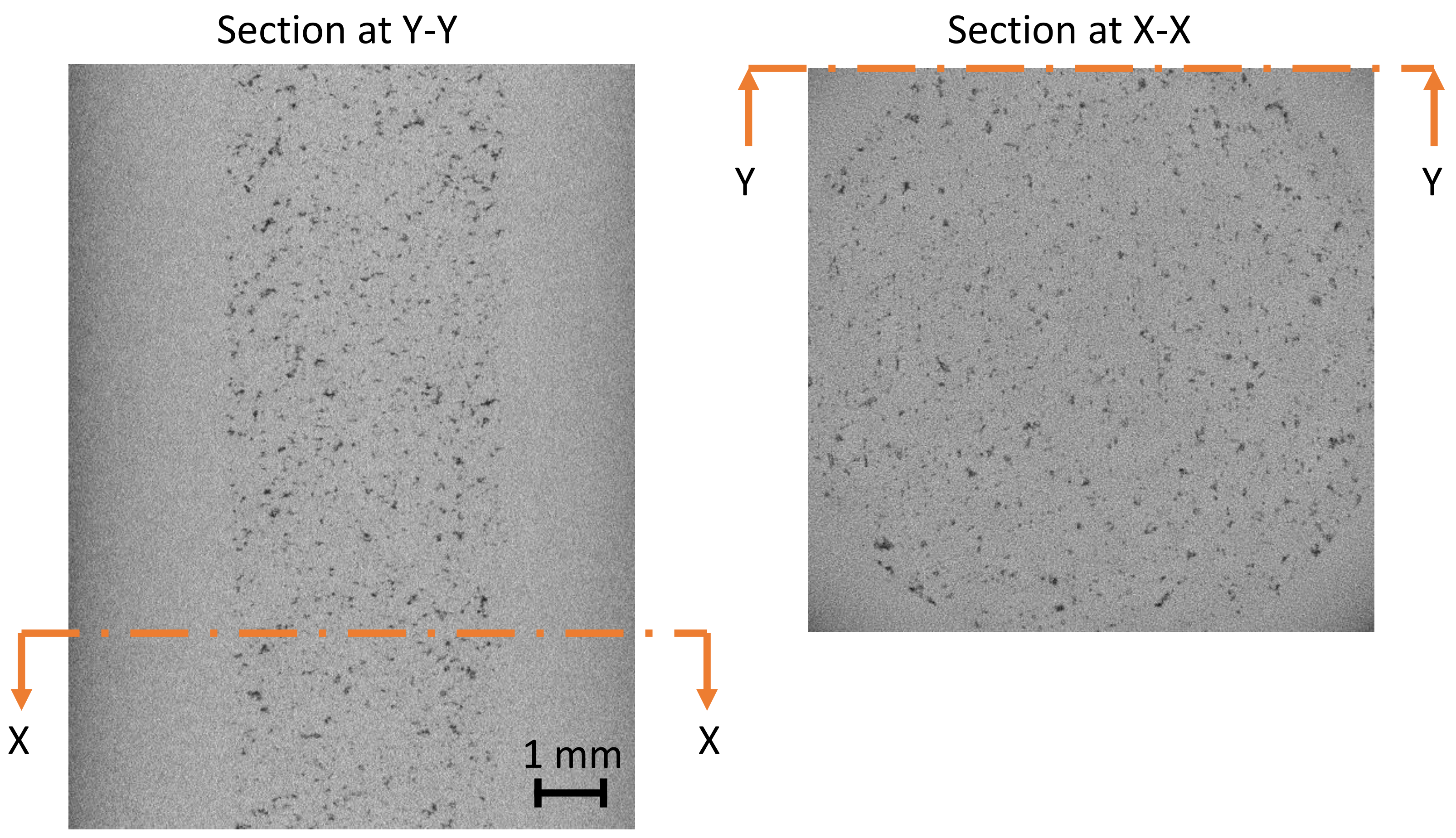
- The printed cylinders were sectioned, polished and optical micrographs were captured for the core and shell regions.



- Two main types of defects were observed:
  - Interface defects due to high laser power
  - Lack of fusion defects due to insufficient laser power

XCT scanning of 3D printed Inconel cylinders

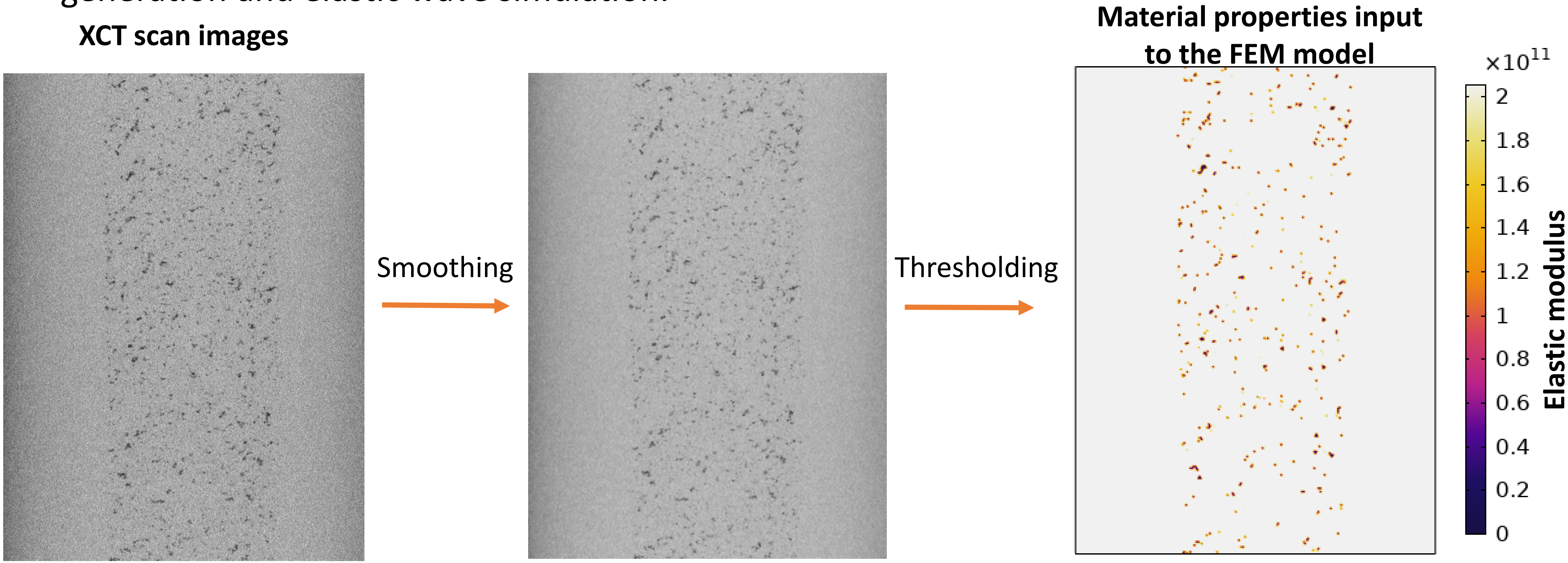
- Samples with the largest defect density (core 100W) were X-ray CT scanned with a voxel size of 4.5 μm to accurately identify defect size and distribution in the core region.
- The scanning results show a uniform distribution of the defects in the core region caused by lack of fusion due to insufficient laser power.



CT scanning resolution: 4.5 μm

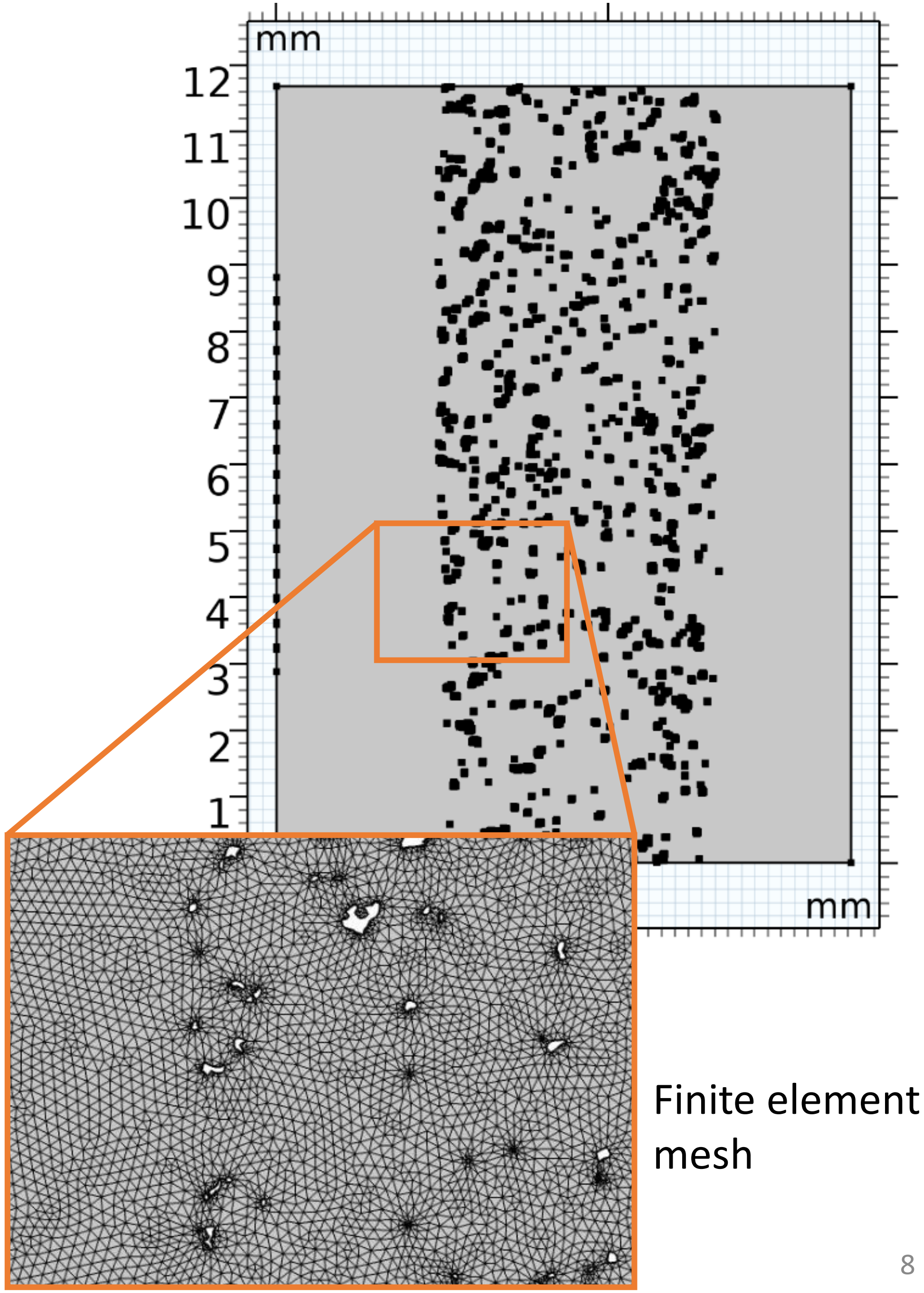
Preparing XCT scan images for wave propagation simulations

- XCT images were used to generate material property distribution and 2D geometries for wave propagation simulations using the Finite Element Method (FEM).
- The generated 2D geometries were imported into Comsol Multiphysics software for mesh generation and elastic wave simulation.



Finite element model

- Elastic waves generated from a phased array are simulated using a 2D elastic finite element model.
- The model is discretized with elements smaller than $\lambda_p/5$ (λ_p is P-wave wavelength in homogeneous Inconel 625)
- The phased array consists of 16 elements ($\lambda_p/2$ spacing) operating @ 10 MHz with 50% bandwidth.
- Each element was excited with a gaussian pulse and the reflected signal was recorded for all elements to form the full matrix of the array i.e. Full Matrix Capture (FMC) method.



Finite element mesh

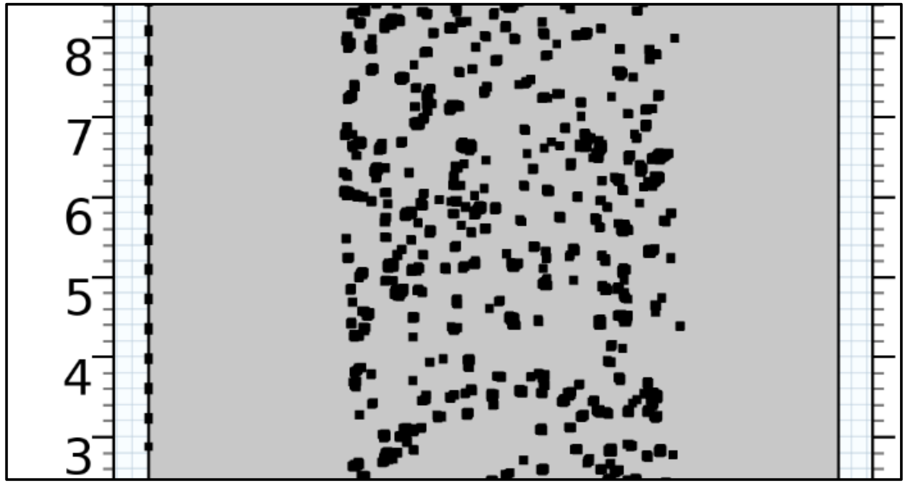
B-scan imaging results

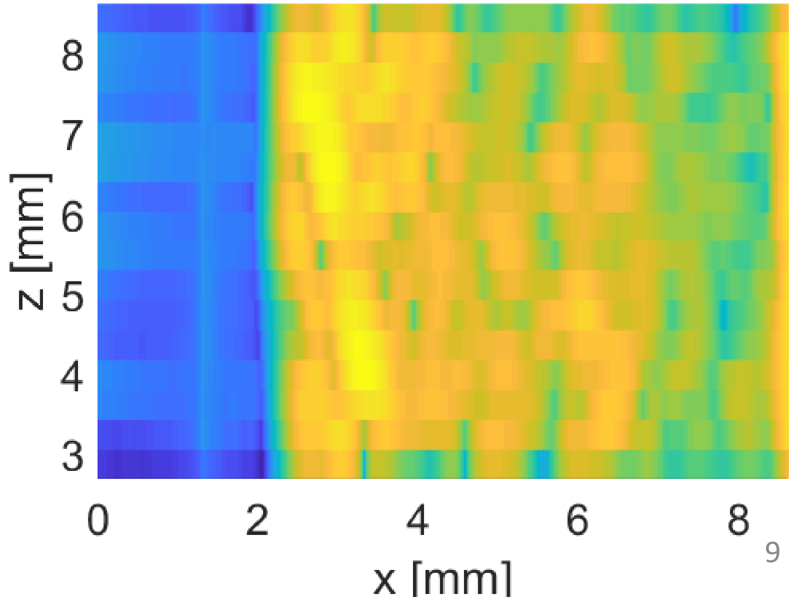
- B-scan results were generated from the full matrix data using the relation*:

$$I(x,z) = \left| \sum h_{tx,rx}\left(\frac{2x}{c_p}\right) \right|$$

  where $h_{tx,rx}$ is the Hilbert transform of the full matrix and c_p is the P-wave speed in Inconel

- The B-scan results captures the interface between the core region (defect region)
- The individual defects are not resolved since they are much smaller than the wavelength of P-waves in Inconel (570 μm)

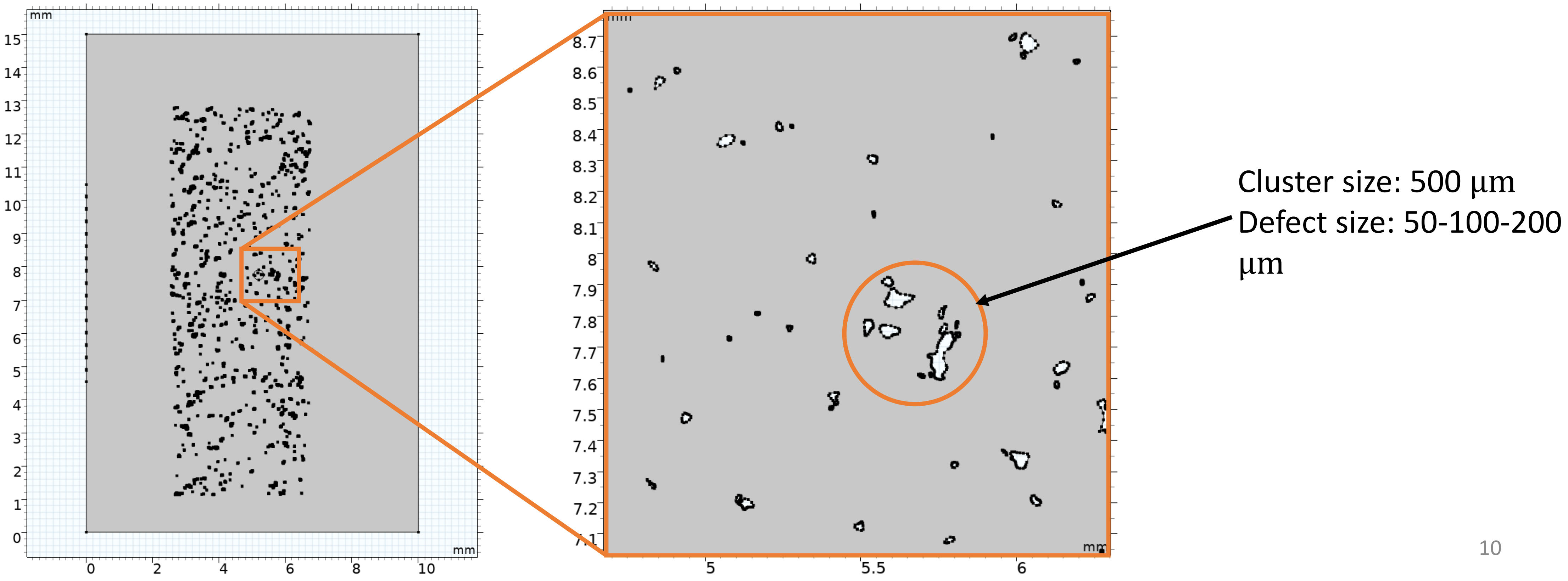




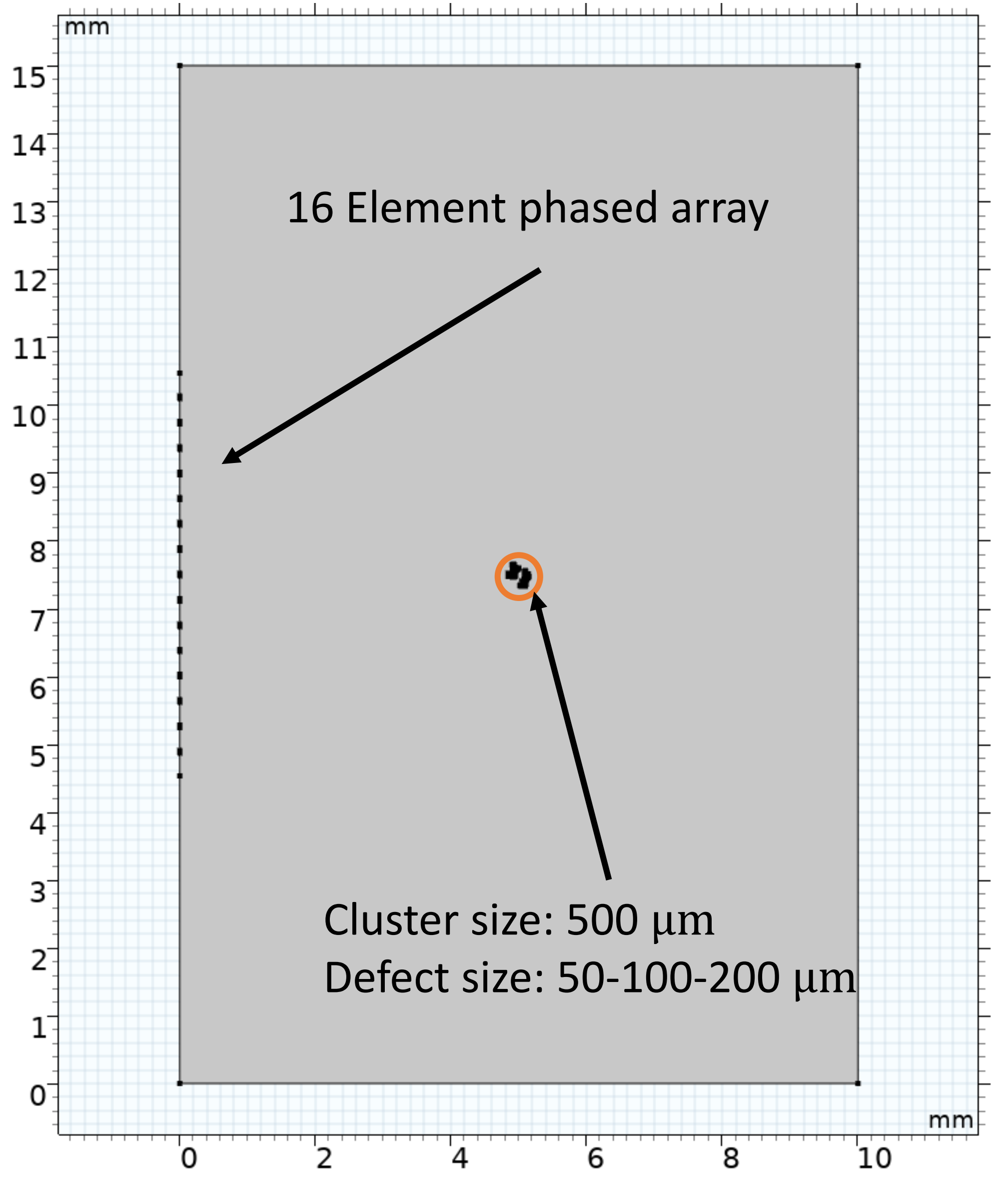
* C. Holmes, B. W. Drinkwater, and P. D. Wilcox, *NDT & E International*, vol. 38, no. 8, pp. 701–711, Dec. 2005

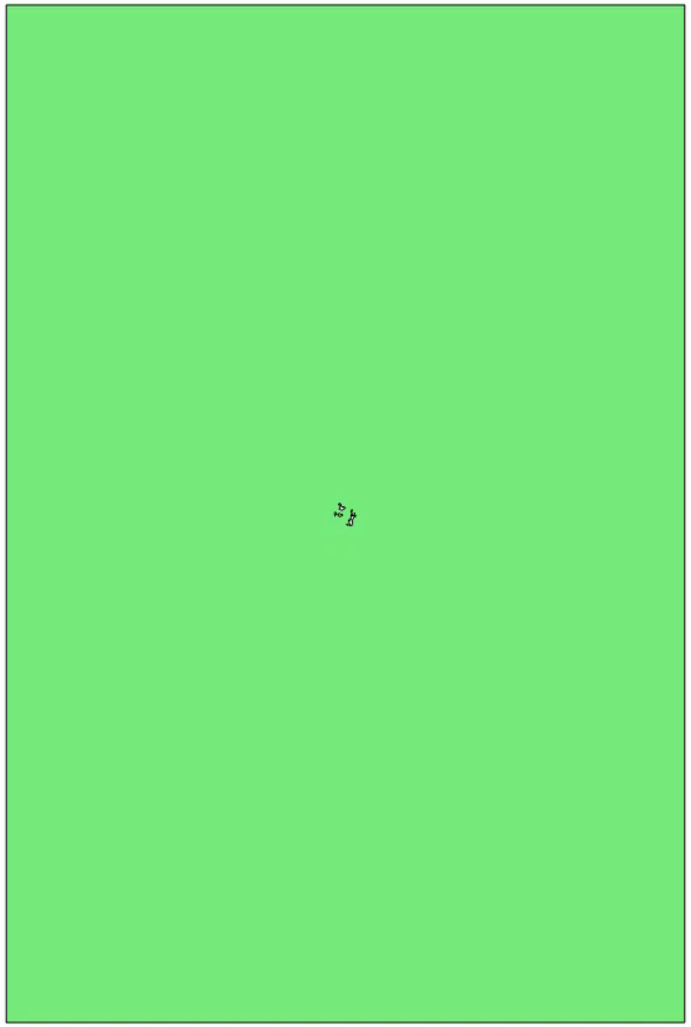
Isolated defects

- In a normal print, the variation of the laser power is expected to be minimal.
- Clusters of smaller defects are more likely to occur than continuous large domains of defects.
- Isolated clusters of defects were simulated separately to assess their detectability.

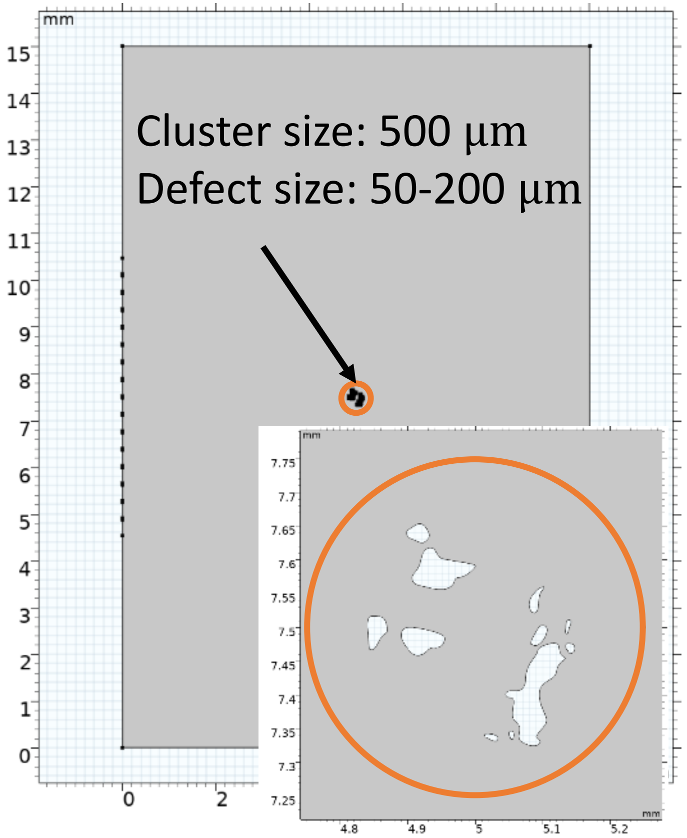


P-wave scattering from an isolated defect

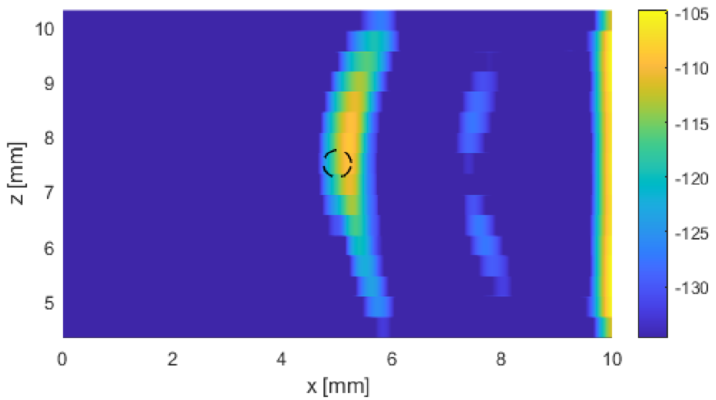




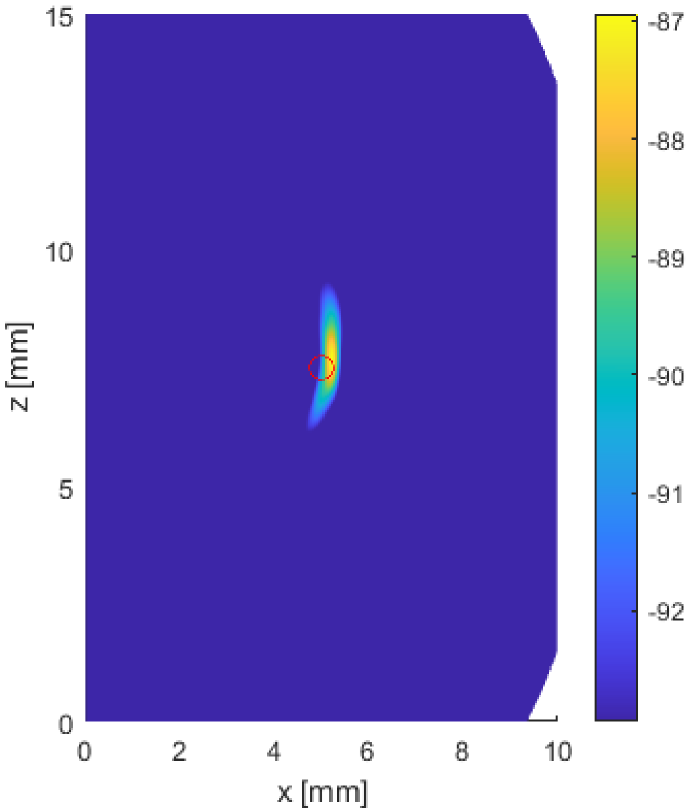
Imaging results for an isolated defect



B-Scan



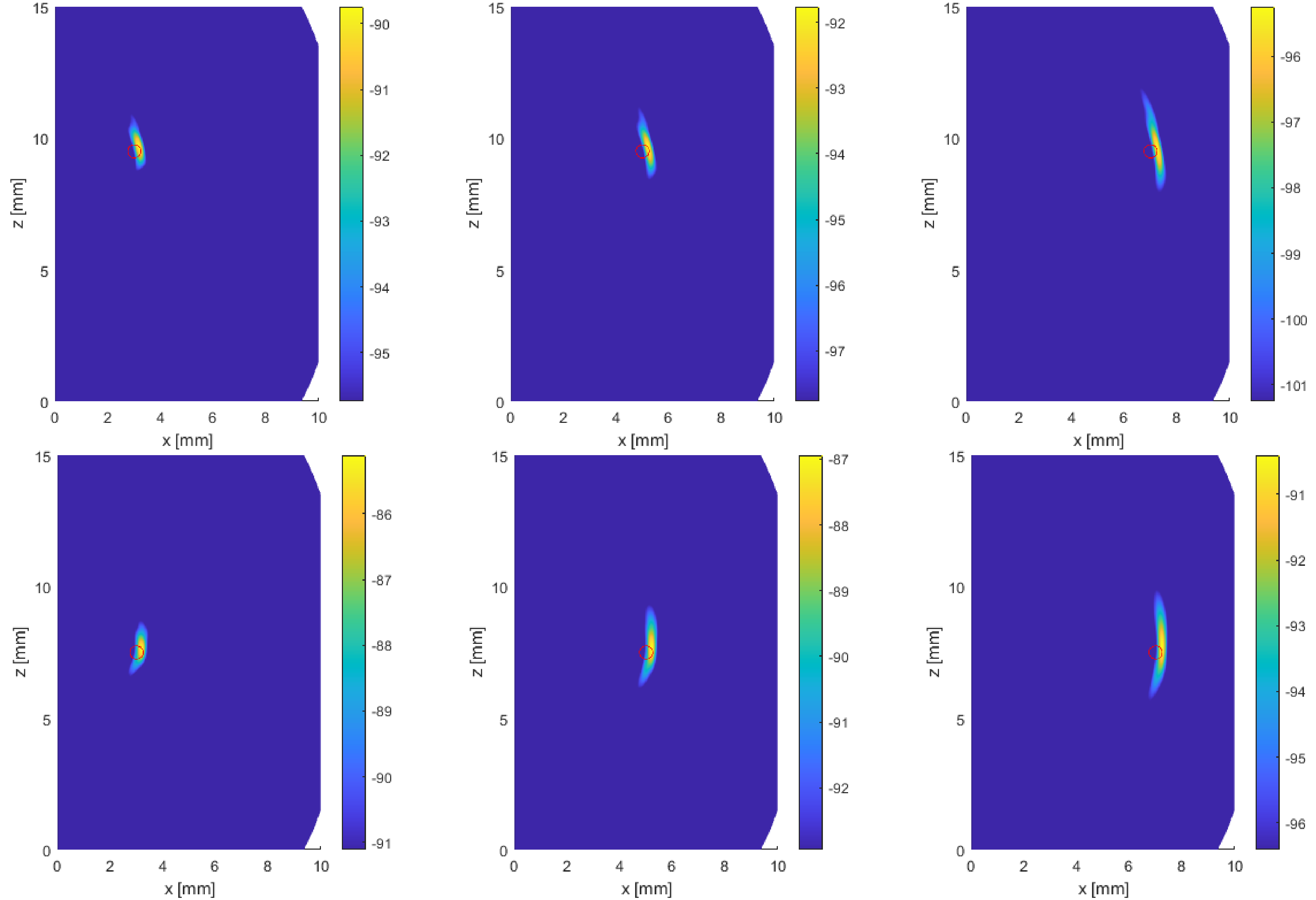
Total focusing

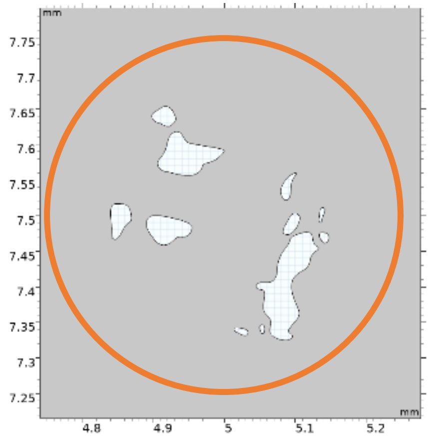


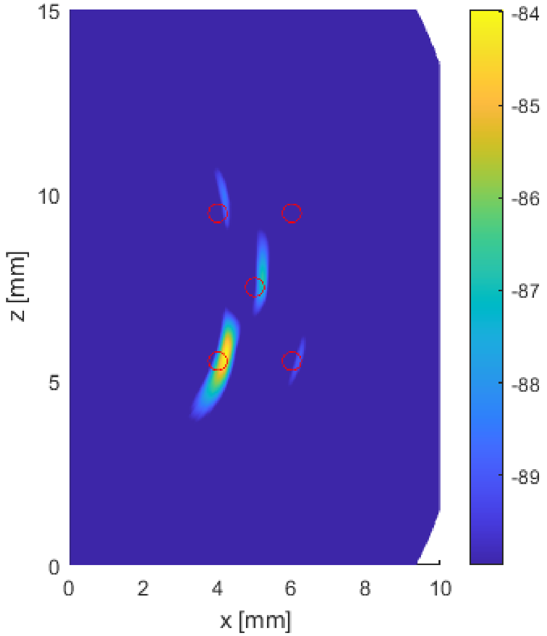
- The total focusing image was generated from the full matrix data using the relation:

$$I(x,z) = \left| \sum h_{tx,rx} \left(\frac{\sqrt{x^2 + (z_{tx} - z)^2} + \sqrt{x^2 + (z_{rx} - z)^2}}{c_p} \right) \right|$$

Effect of defect location on the image quality







Conclusion

- We propose Ultrasonic NDT for quality assurance of AM parts.
- We have studied the defects generated by varying laser power in SLM using optical micrographs and XCT.
- XCT images was used to simulate the propagation of elastic waves in the AM samples and their interaction with the generated defects.
- FEM simulations were used to outline the effect of the defect size, location, distribution and material properties on the ultrasonic image and the detectability of the defect.
- The results show that ultrasonic imaging could be used to qualitatively detect common flaws generated in the presence of laser power fluctuation during SLM processing.