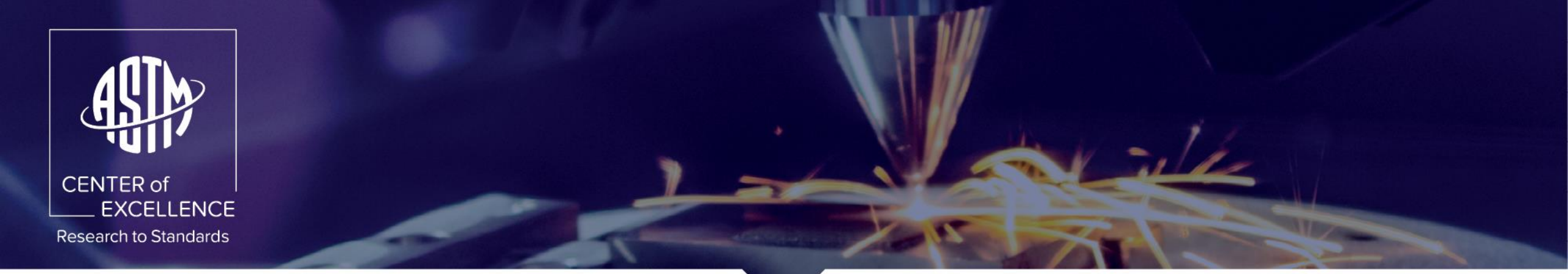

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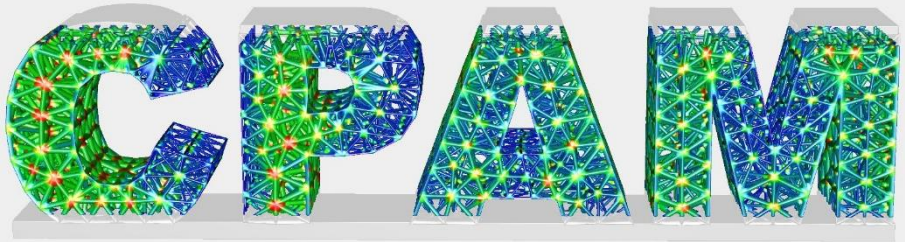
X-ray computed tomography inspection in metal additive manufacturing: the role of witness specimens

Prof Anton du Plessis, Stellenbosch University, South Africa

Invited talk, 4th Symposium on Structural Integrity of Additive Manufactured Materials and Parts, Washington, 9 Oct 2019

www.amcoe.org



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Research group
3D INNOVATION

In this talk

What will I talk about?

- X-ray CT in AM
- Porosity in metal PBF
  - Process parameter induced porosity
  - Non-process porosity and build flaws
- AM Round robin test: typical flaws and porosity in final parts
- Value of witness specimens analyzed by CT
- MicroCT round robin test
- Conclusions

X-ray tomography in AM

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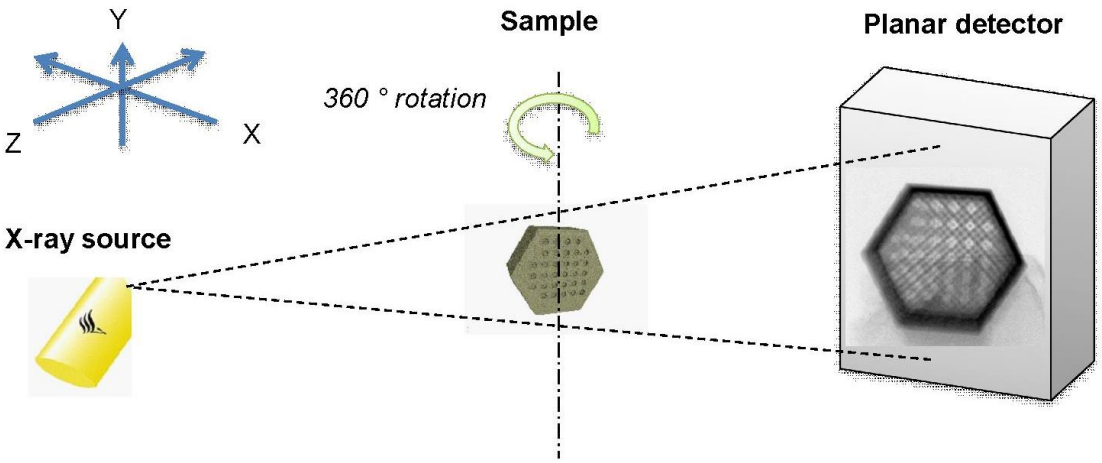
Widely known already for:

- Porosity measurement
- Dimensional measurement / metrology



Other newer uses:

- Analysis of powder feedstock for quality – size, shape and porosity
- Density
- Time-lapse CT (or 4D CT)
- Surface roughness
- Multiscale CT, etc.
- Simulations – FEM

*** X-ray microcomputed tomography in additive manufacturing: a review of the current technology and applications. *3D Printing and Additive Manufacturing*, *5*(3), pp.227-247. Du Plessis, A., Yadroitsev, I., Yadroitsava, I. and Le Roux, S.G., 2018. https://www.liebertpub.com/doi/abs/10.1089/3dp.2018.0060**

Porosity in metal AM

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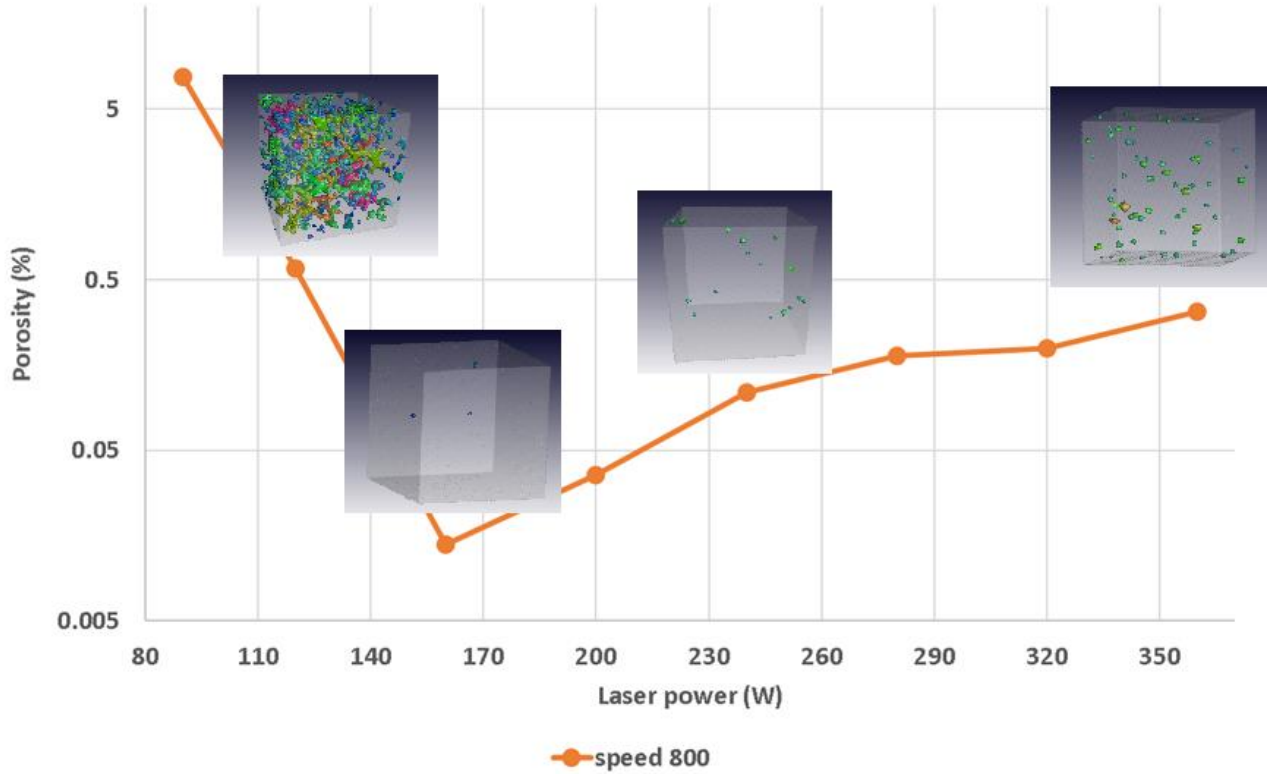
Major cause of porosity is wrong process parameters

- By using high resolution X-ray tomography, it is possible to visualize and quantify LoF vs keyhole mode pores and other forms of typical pore formations and distributions resulting in final parts
- Used small cubes and quantification of porosity from <0.05% to >5%
- Found sharp transition from “ideal” to LoF, with decreasing power



*** Effects of process parameters on porosity in laser powder bed fusion revealed by X-ray tomography. Du Plessis, A. https://doi.org/10.1016/j.addma.2019.100871**

Porosity in metal AM

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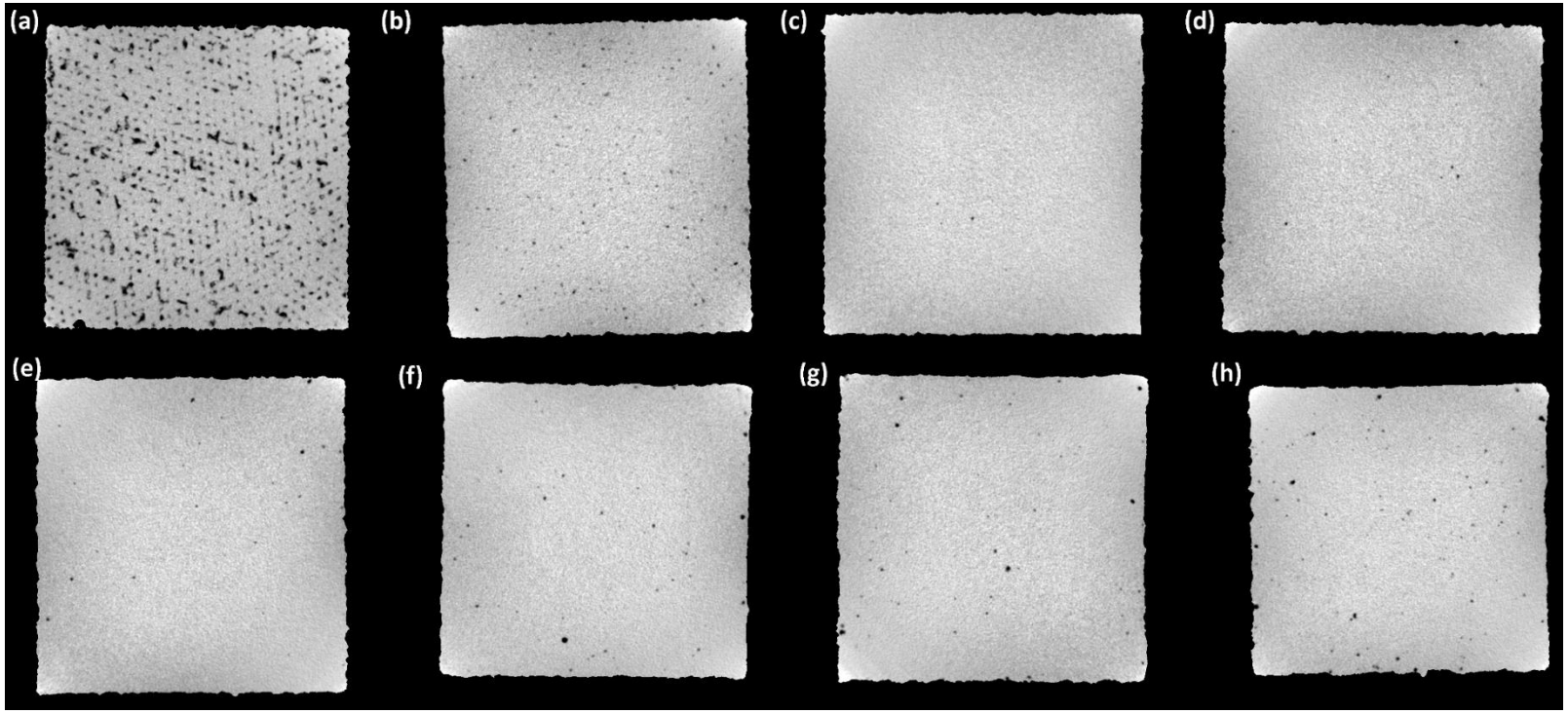
Morphology and distribution of pores

- Excessive LoF causes regular spaced pores, with irregular morphology
- Keyhole is rounded and randomly distributed



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Porosity in metal AM

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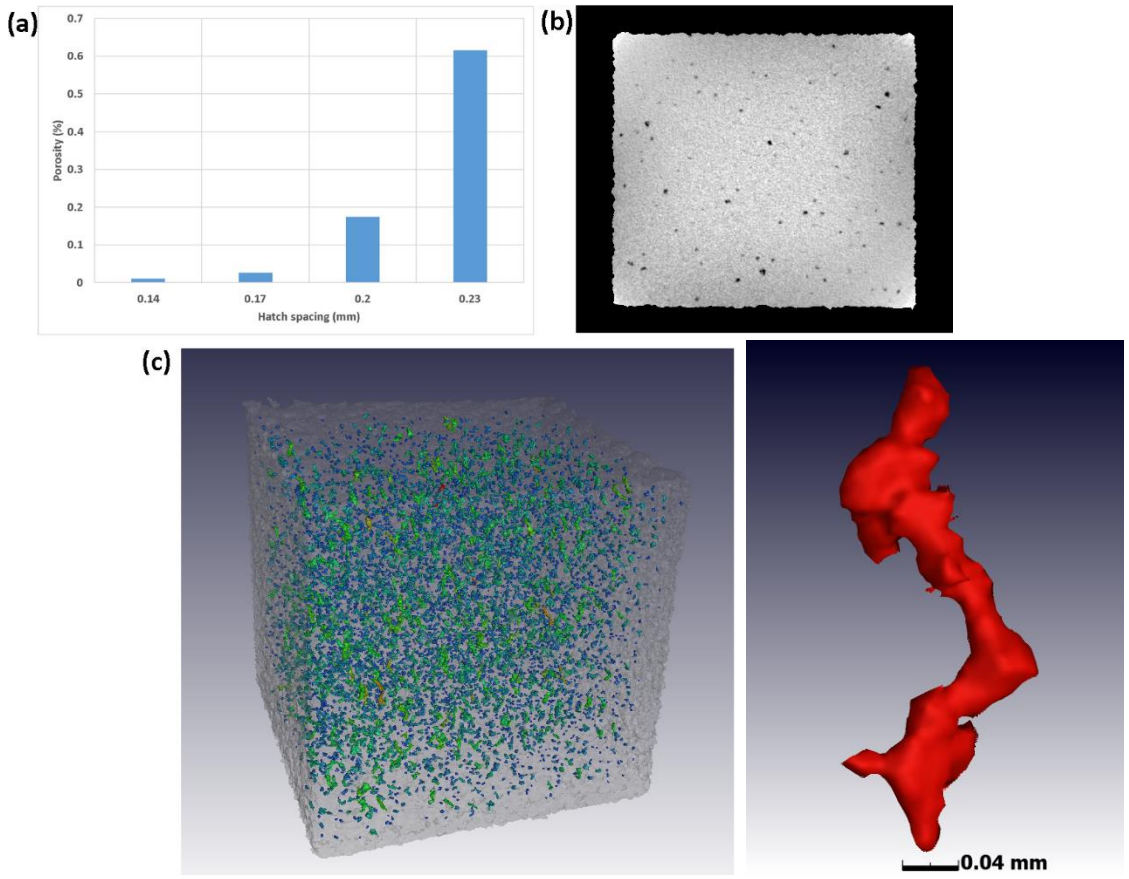
Hatch spacing increase

– Vertically oriented LoF pores



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Porosity in metal AM

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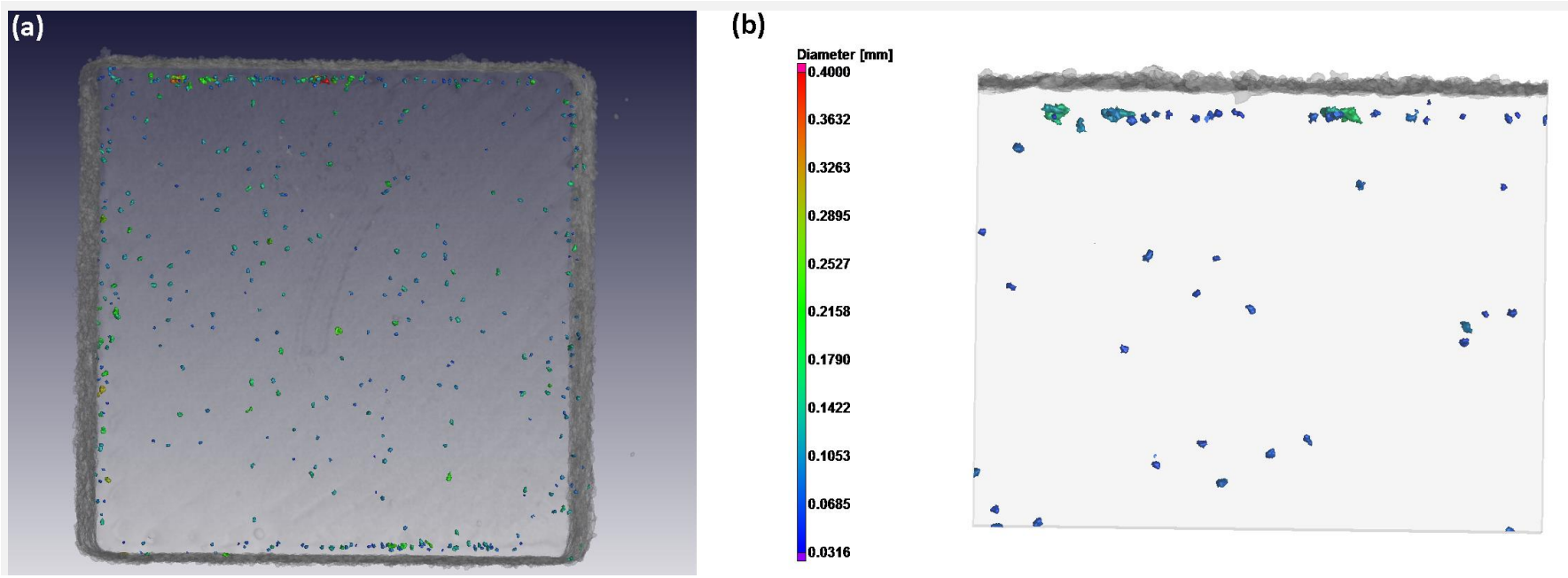
Contour-hatch track spacing

– Pores mainly near surfaces



*** Effects of process parameters on porosity in laser powder bed fusion revealed by X-ray tomography. Du Plessis, A. https://doi.org/10.1016/j.addma.2019.100871**

Porosity in AM

Process induced porosity

- Lack of fusion: different forms
- Keyhole
- Contour pores
- Upskin pores
- Inclusions and powder contamination
- Etc.

Other build porosity and flaws

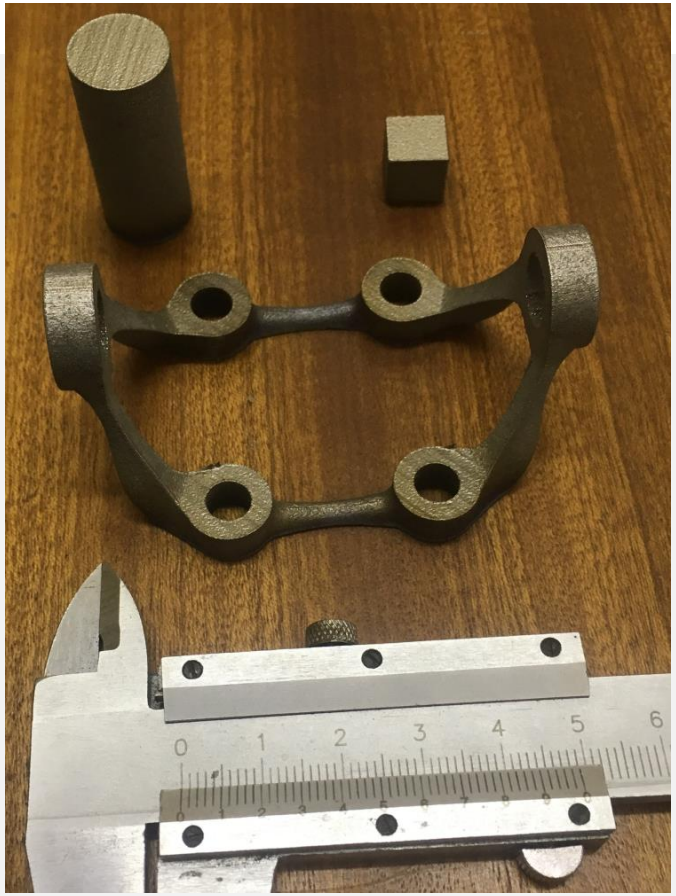
- Layered lack of fusion
- Stop-start flaw
- Recoater blade damage causing irregular powder spreading and flaws

- Etc.

AM round robin test (RR1)

Goal of the AM round robin tests

- Aim was to demo “prescribed CT scan parameters & image analysis recipes” – towards standardization
- Commercial systems used at service centers and R&D labs across 3 continents: ID confidential
- All Ti6Al4V, no post processing besides support removal
- All built with > 99.8% density, with aim to be good parts
- Typical errors are highlighted which are still present often in AM parts

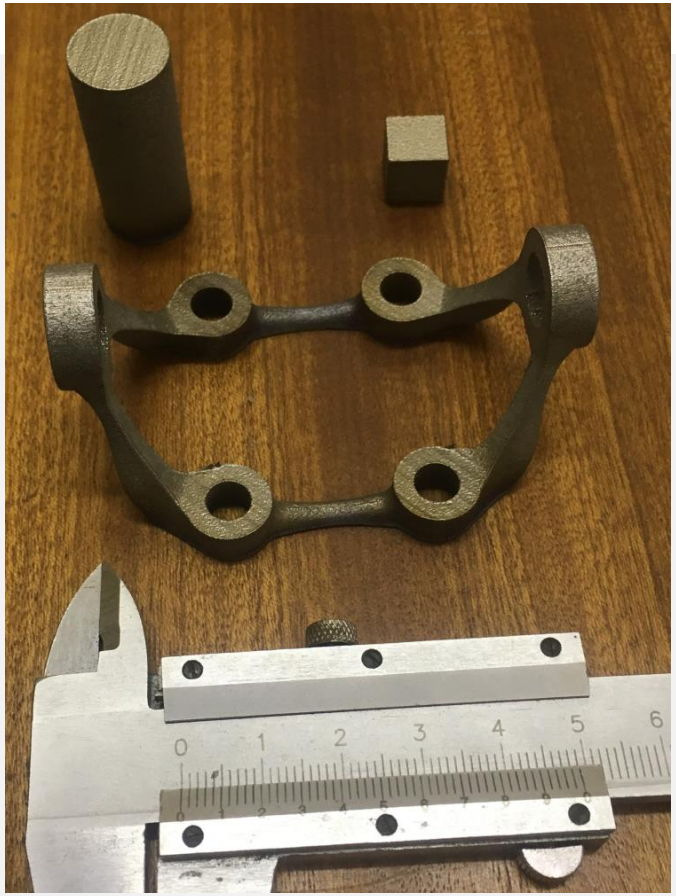


* Standardized X-ray tomography testing of additively manufactured parts: A round robin test. Du Plessis & Le Roux 2018. https://doi.org/10.1016/j.addma.2018.09.014

AM round robin test (RR1)

Same parts built on various L-PBF systems

- 10 mm cube coupon sample for porosity quantification and visualization
- Topology optimized bracket = example of complex part of interest
- Witness specimen (cylinder) built alongside bracket

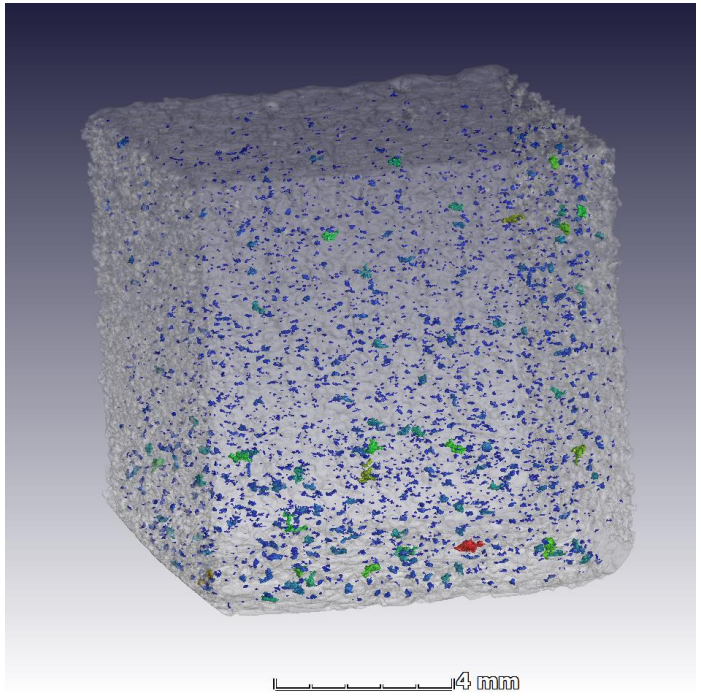


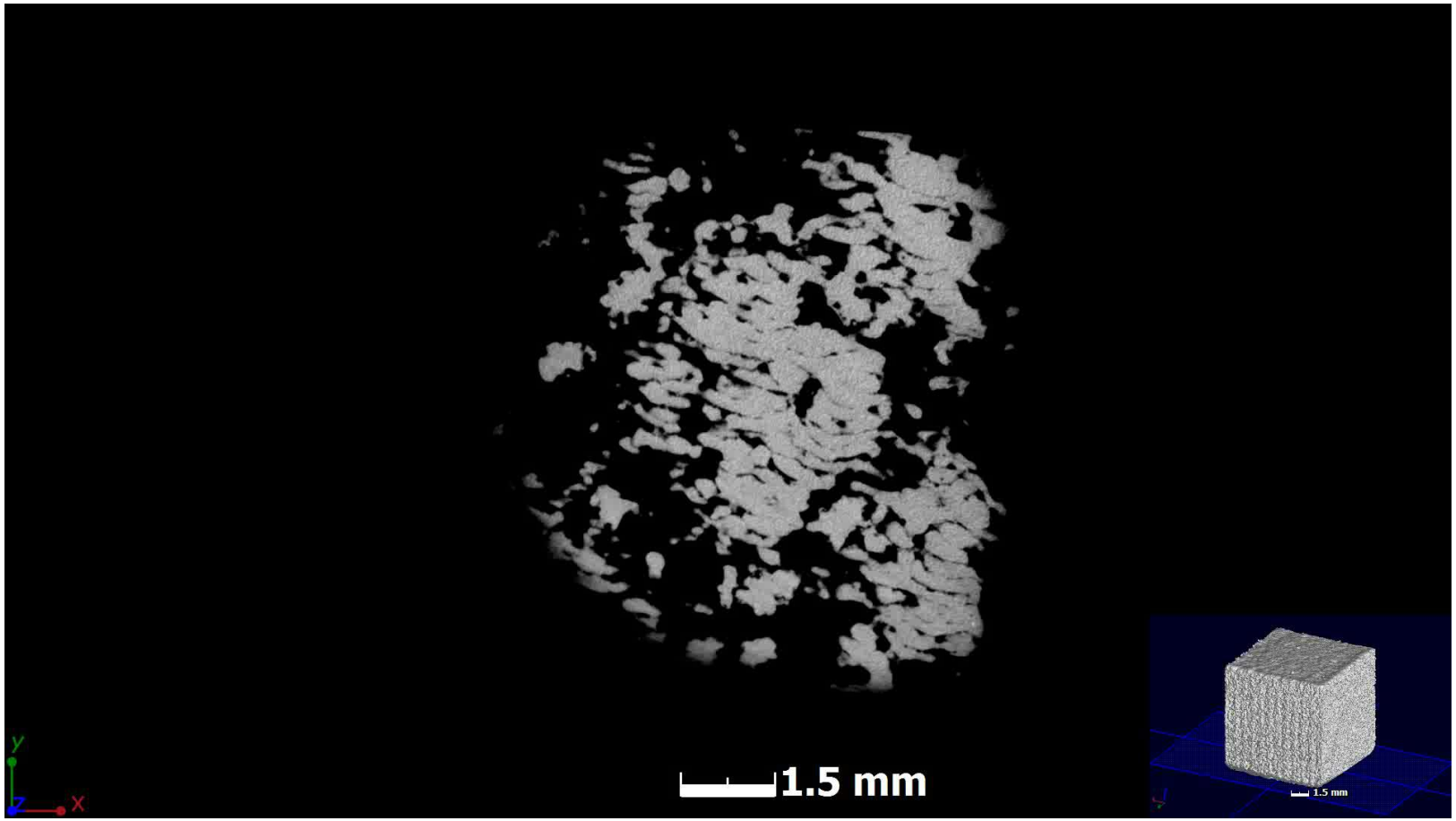
* Standardized X-ray tomography testing of additively manufactured parts: A round robin test. Du Plessis & Le Roux 2018. https://doi.org/10.1016/j.addma.2018.09.014

AM round robin test

Example of LoF porosity

– This example is the most extreme case of 0.13% porosity

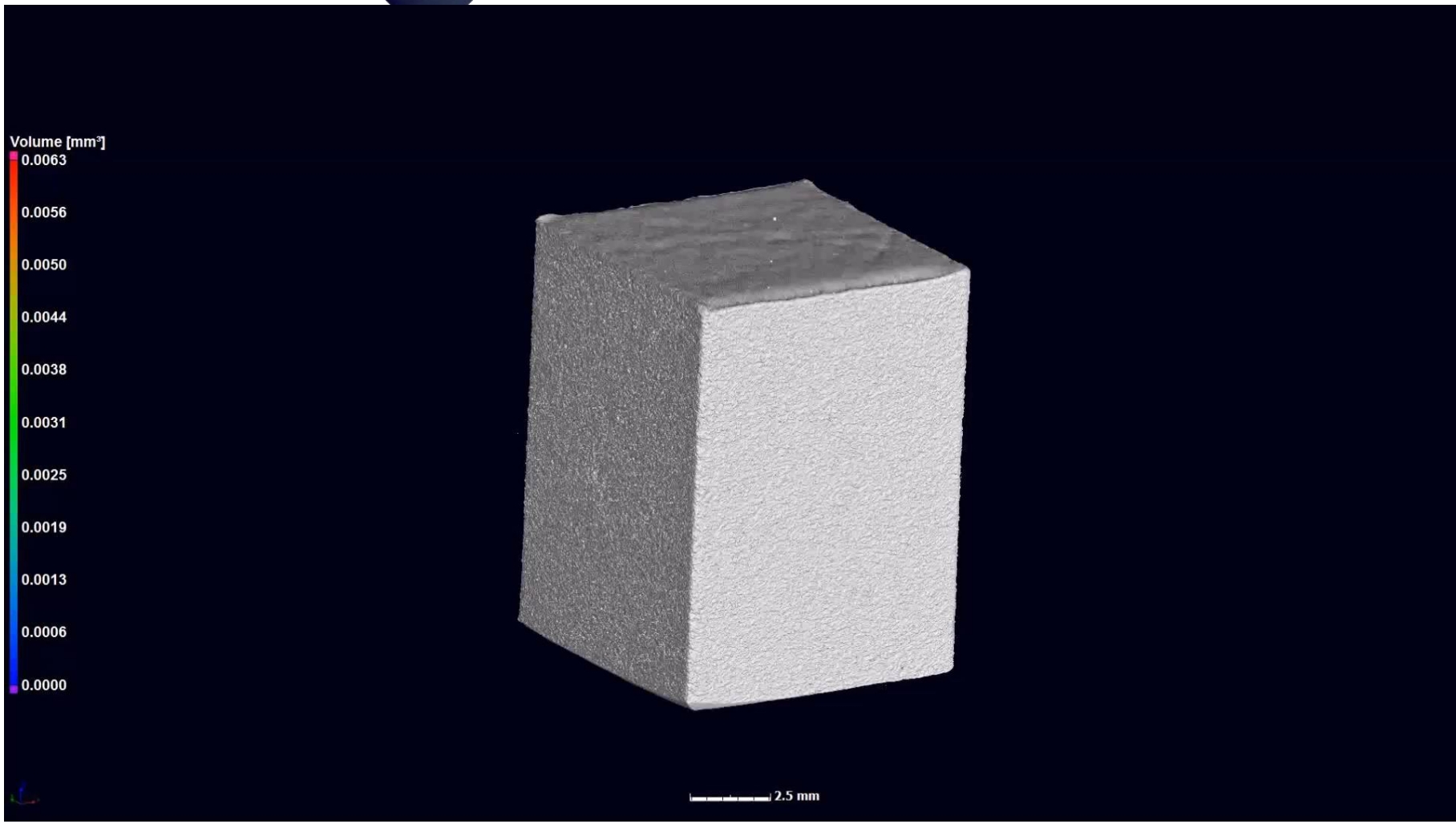




AM round robin test

Example of contour porosity

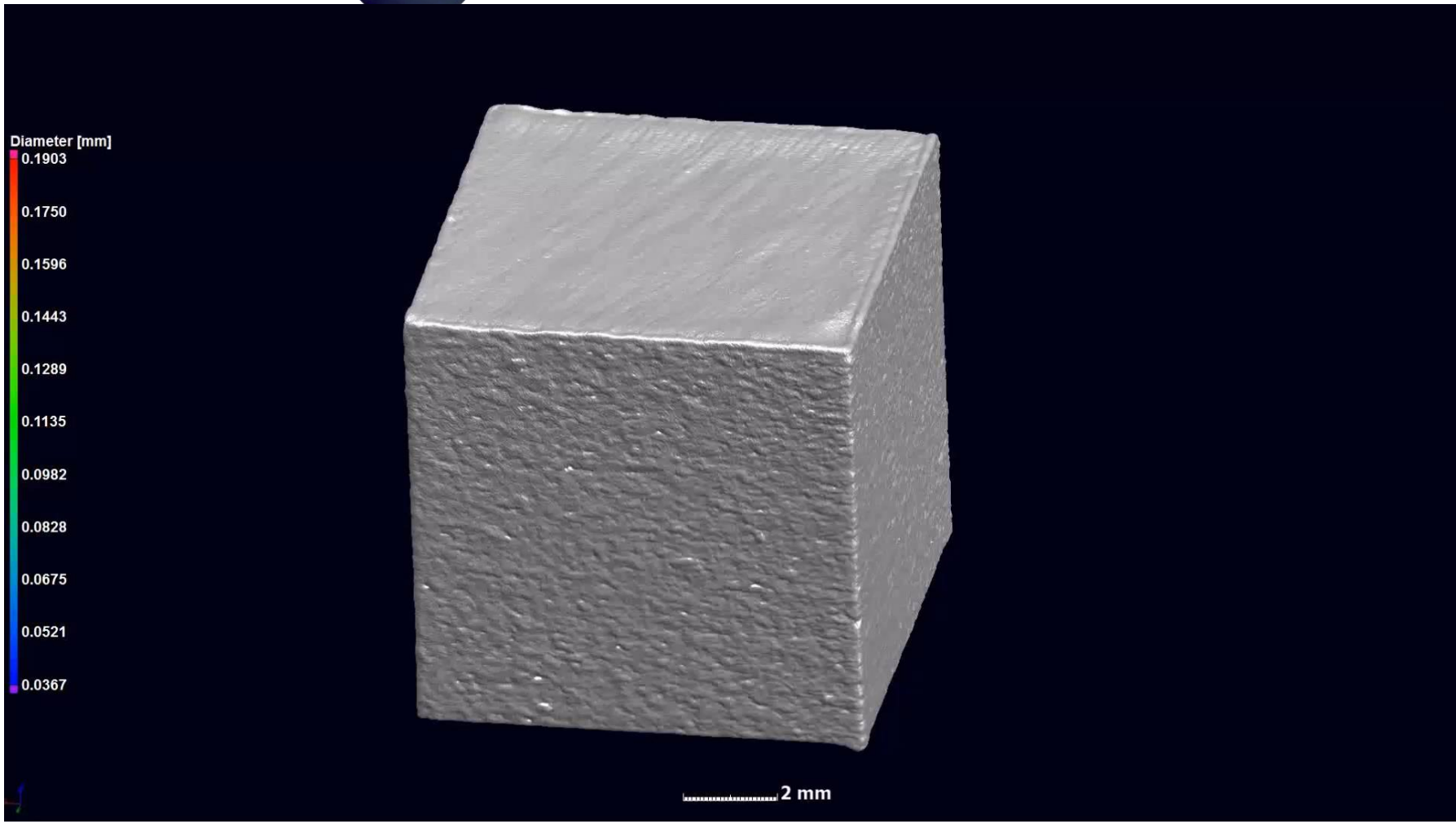
– Only at contours



AM round robin test

Example of upskin porosity

– Only at top surface



AM round robin test (RR1)

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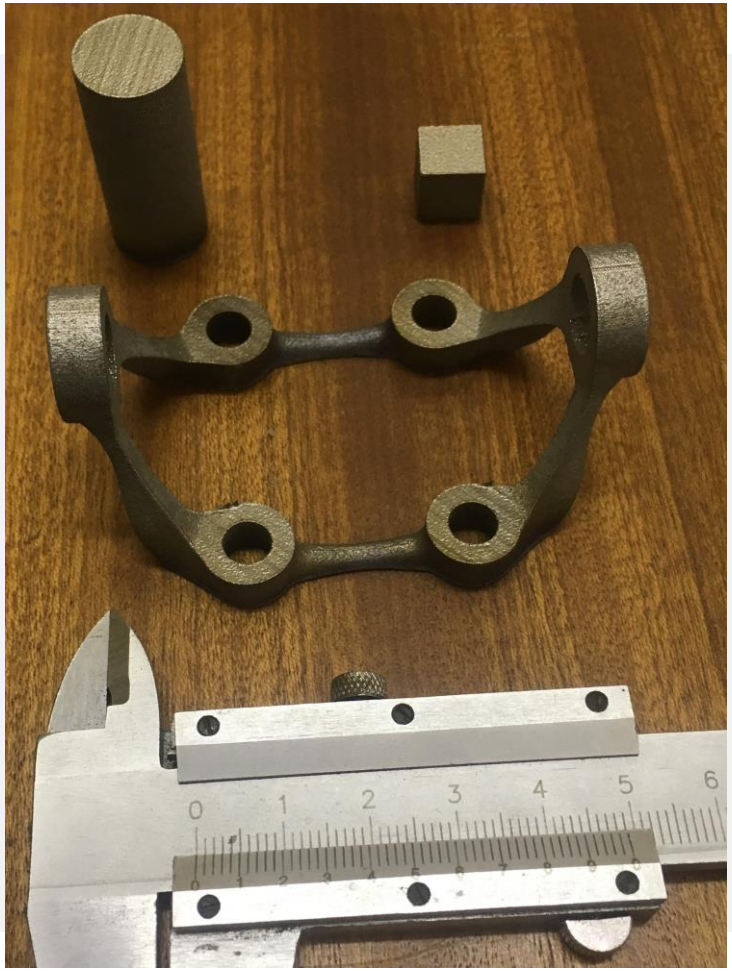
What do we learn?

- Some small issues remain in L-PBF parts, with small pores of different morphologies and due to different causes
- Coupon samples with high resolution CT very useful to highlight and visualize these issues
- This can be used to improve processes

Questions remain:

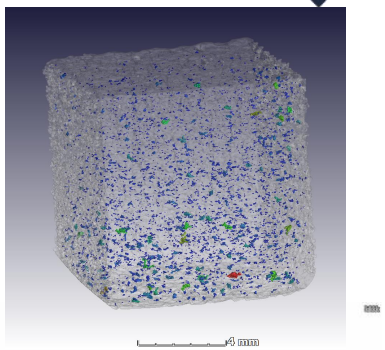
- Do these porosity distributions transfer to the complex part?
- And are they also present in the witness cylinder?

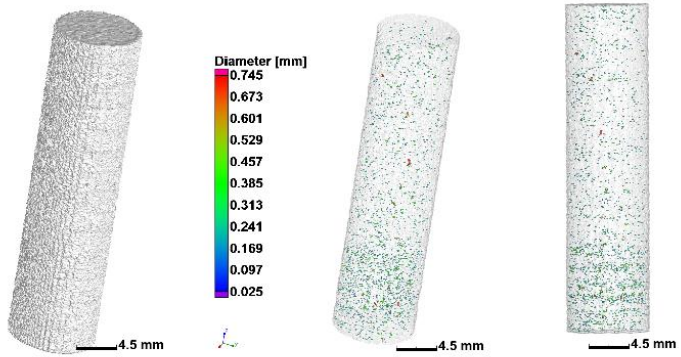


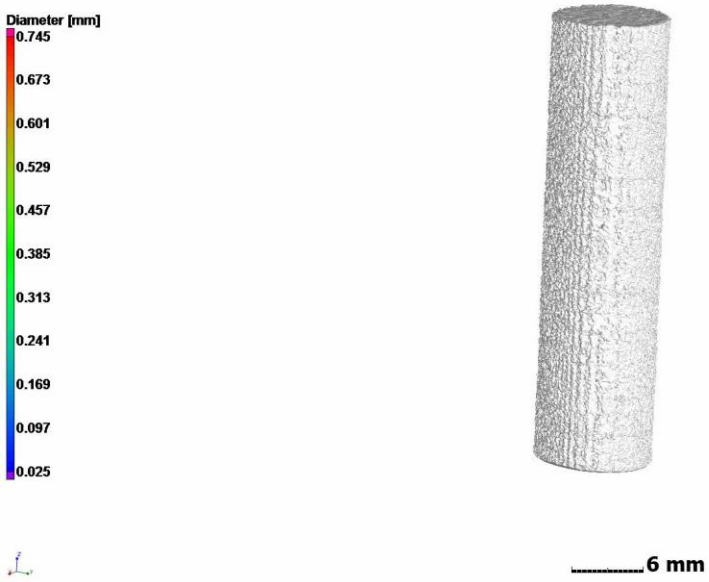
AM round robin test

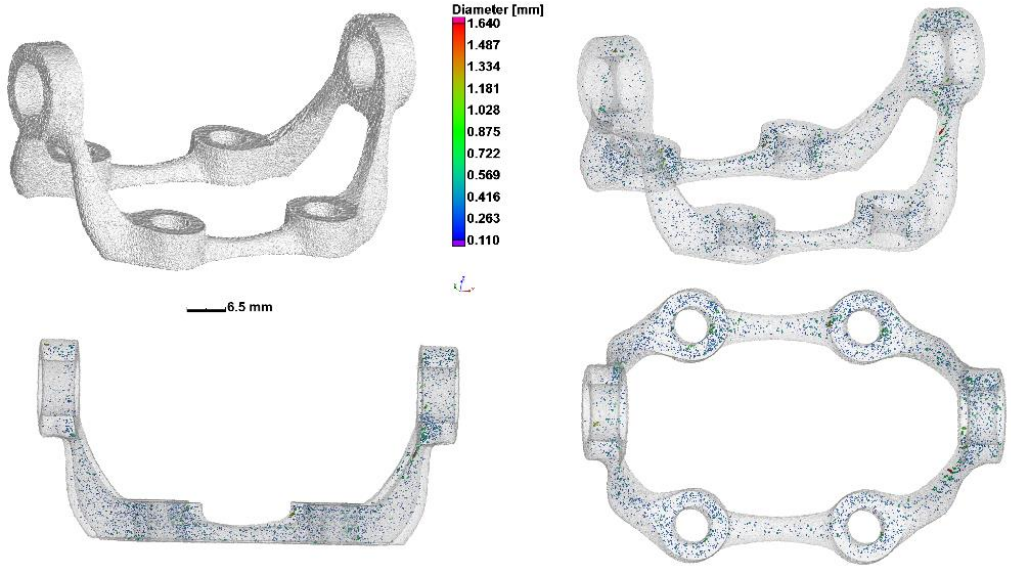
Lack of fusion pores

- Can be seen in witness
- And also present in complex part





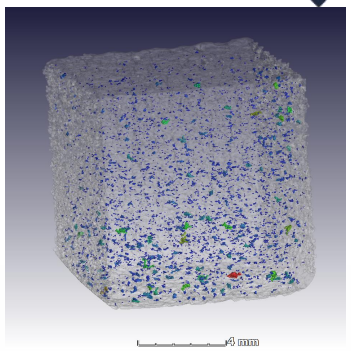


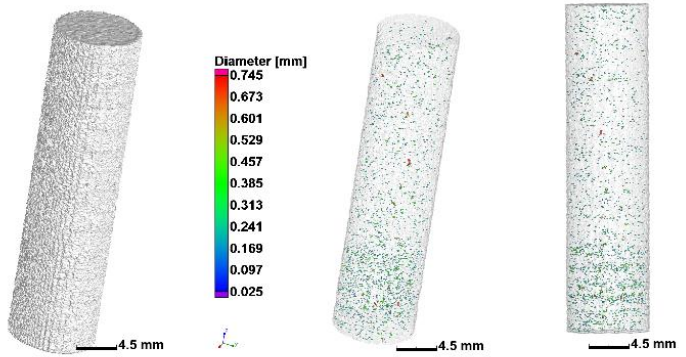


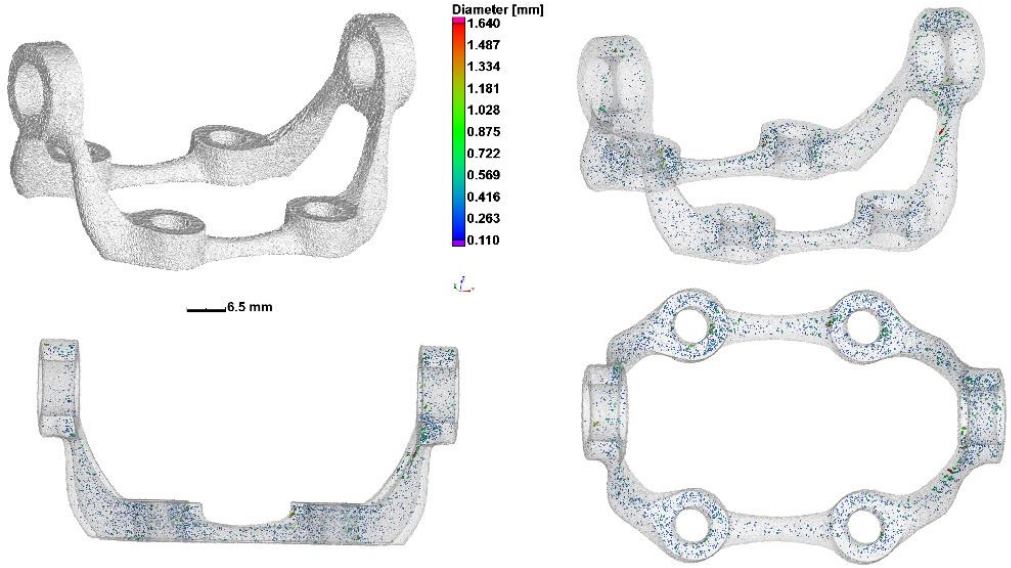
AM round robin test

Lack of fusion pores

- Can be seen in witness
- And also present in complex part



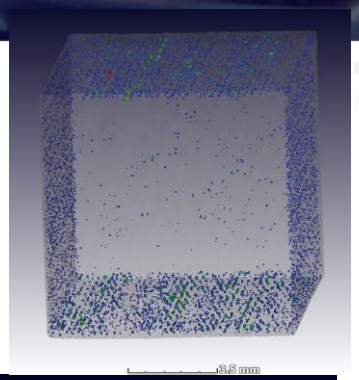


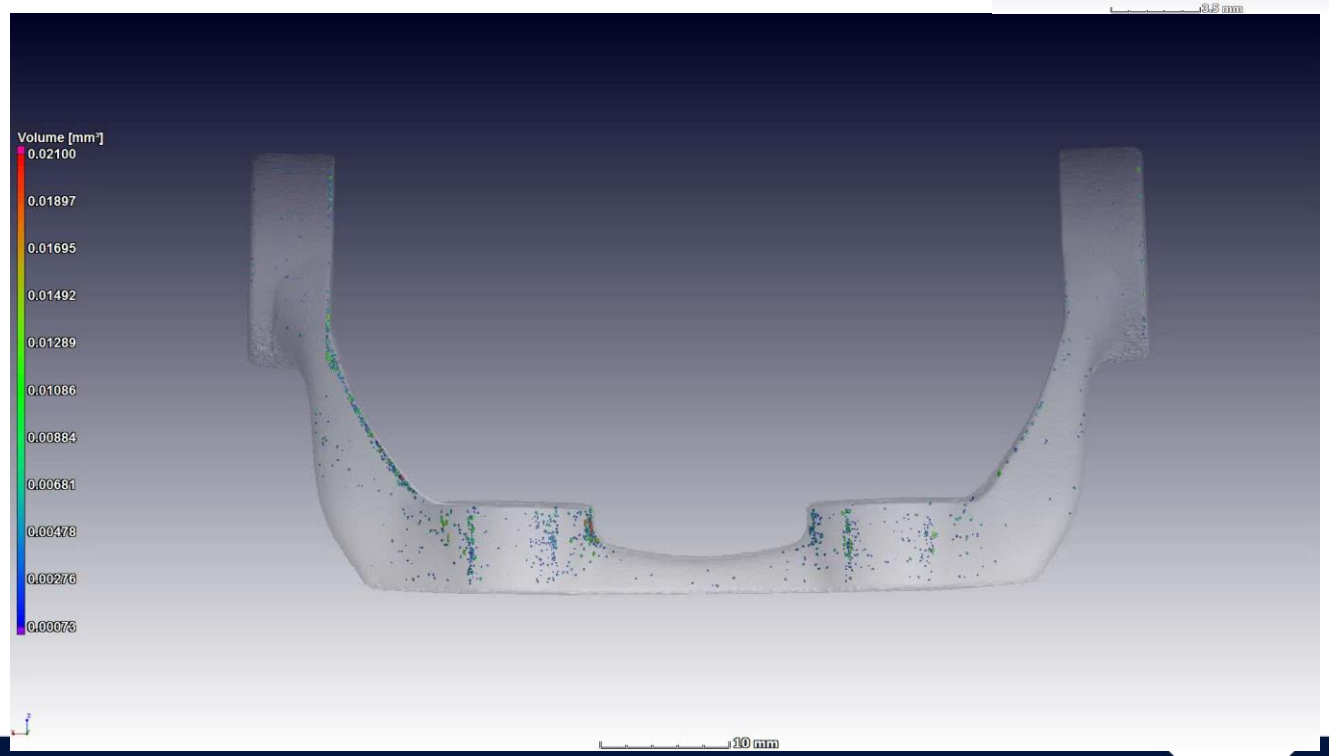


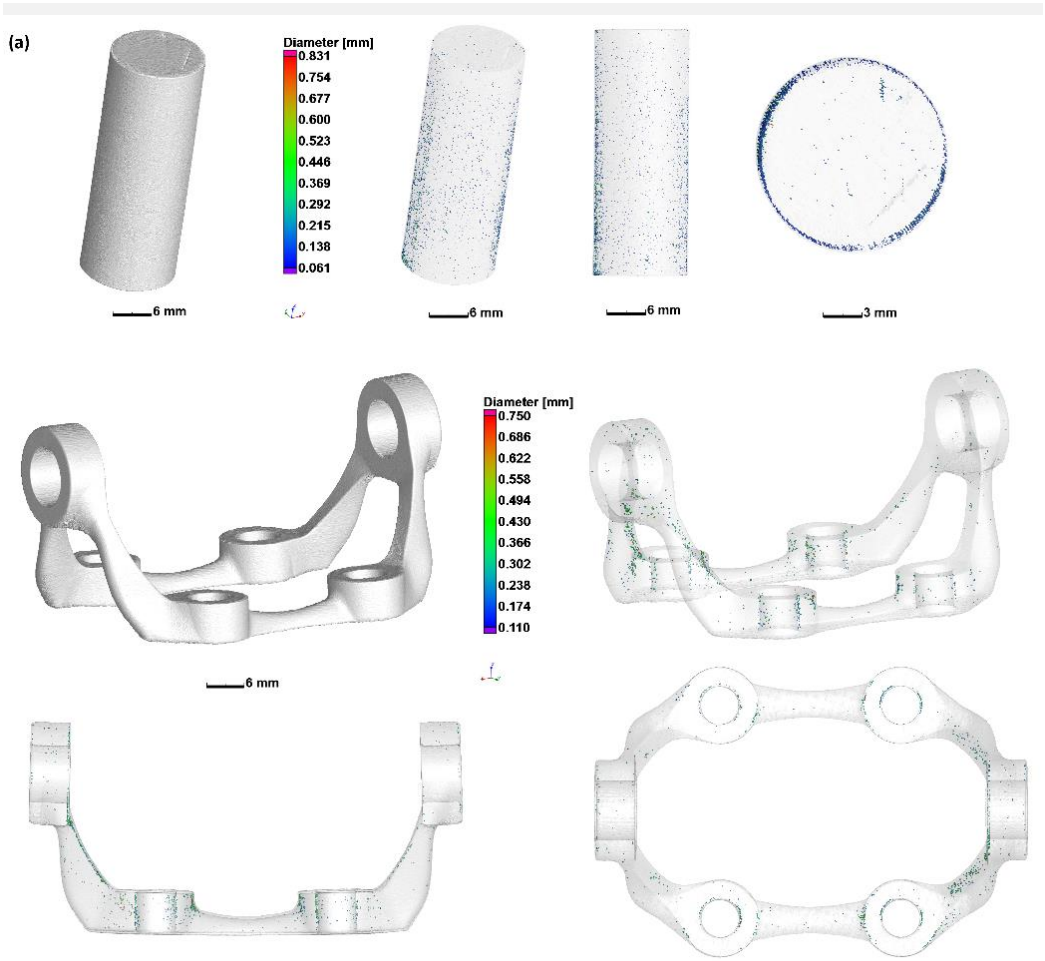
AM round robin test

Contour porosity

- Can be seen in witness
- And also present in complex part







AM round robin test

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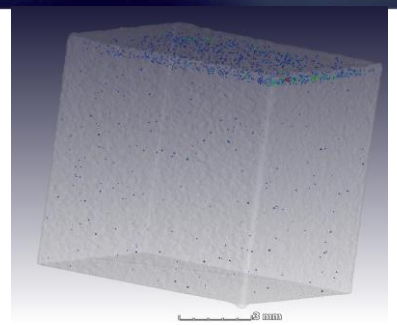
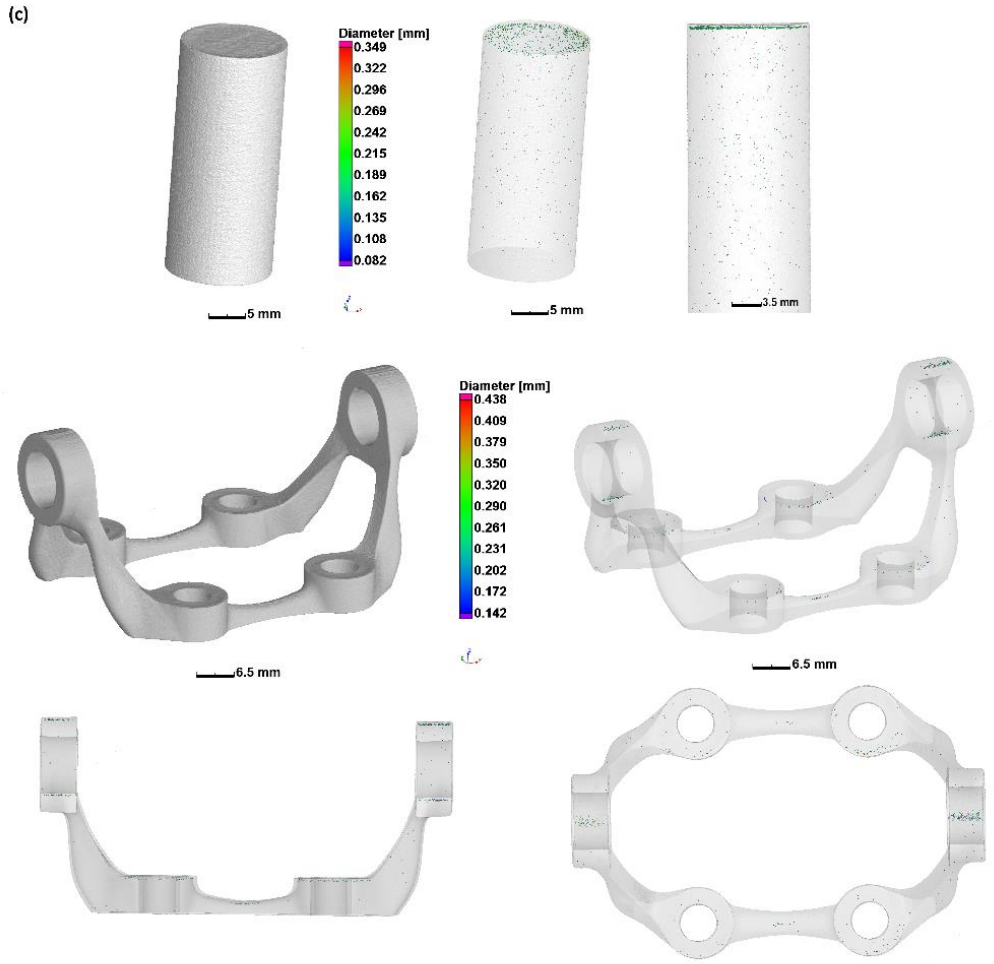
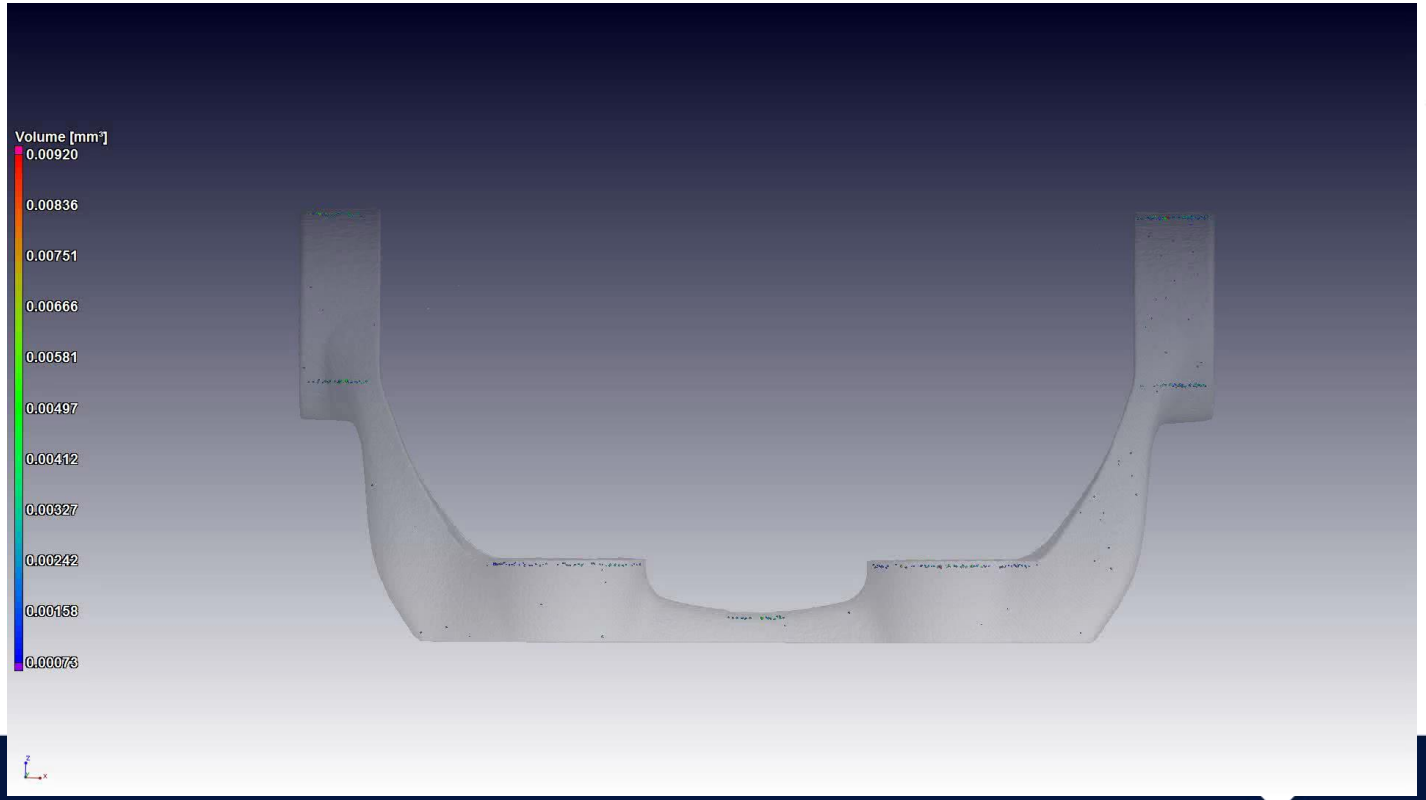
Upskin pores

- Can be seen in witness
- And also present in complex part



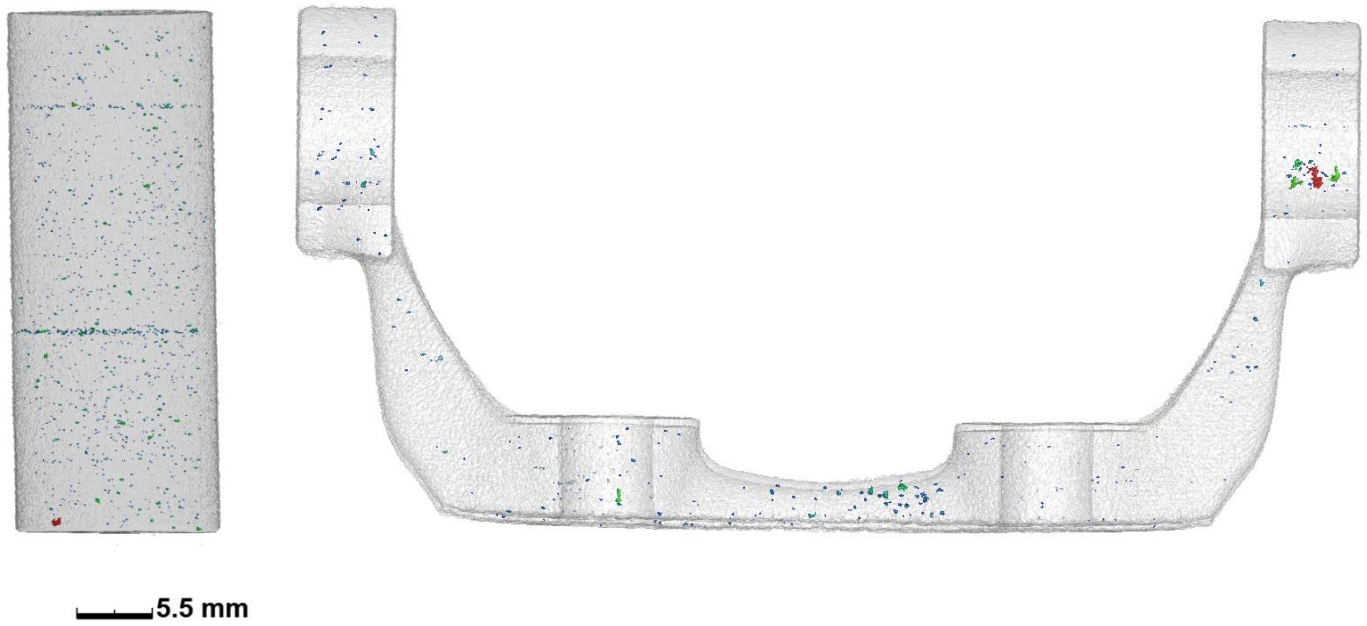


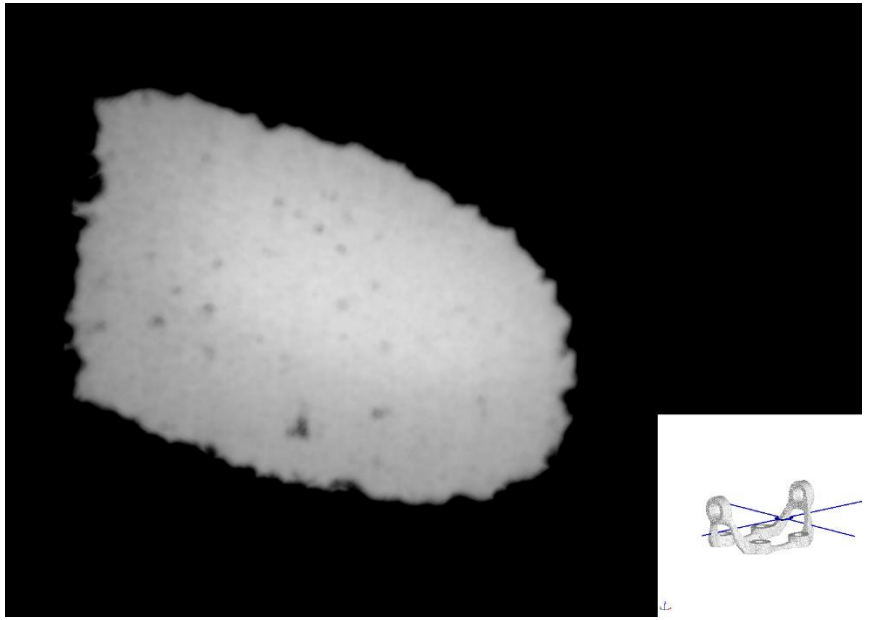


AM round robin test

Layered lack of fusion flaws

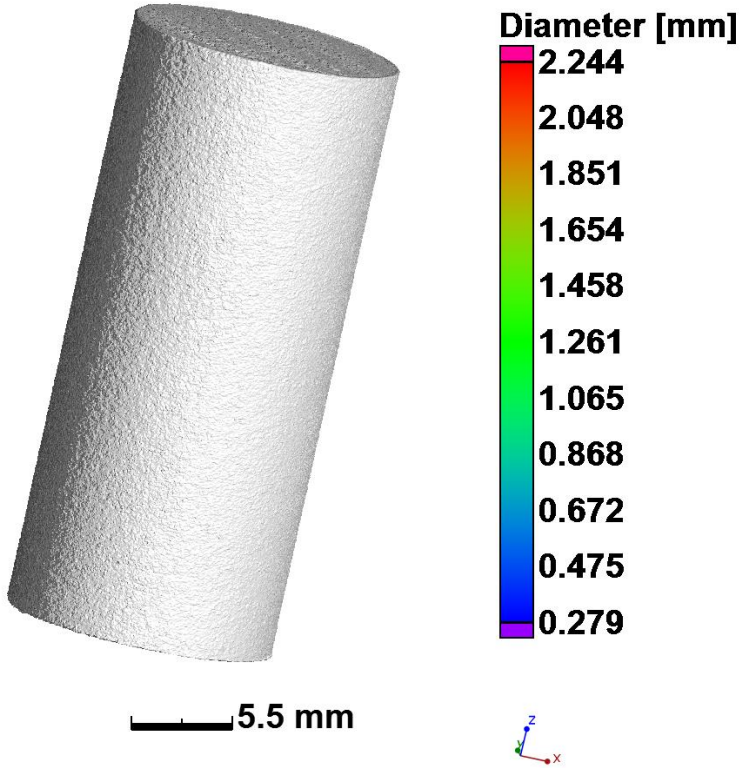
- Can be seen in witness
- Also present in bracket





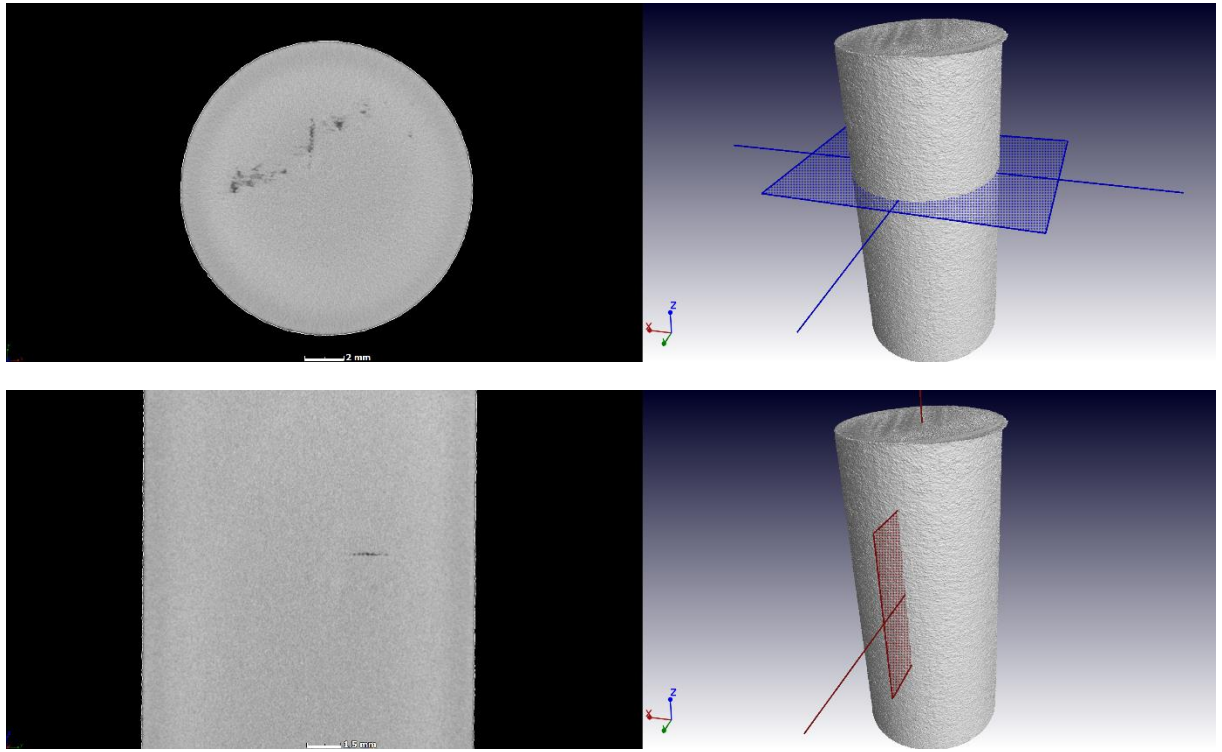
Stop-start flaw

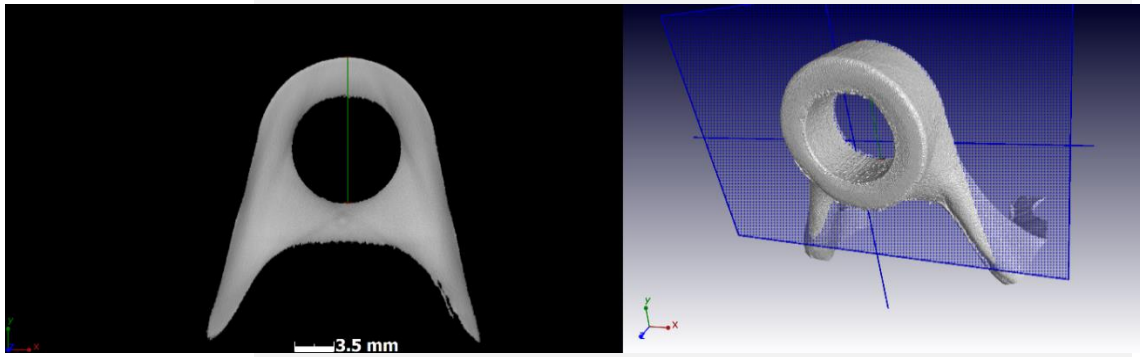
Intentional stop-start flaw



Stop-start flaw

Intentional stop-start flaw

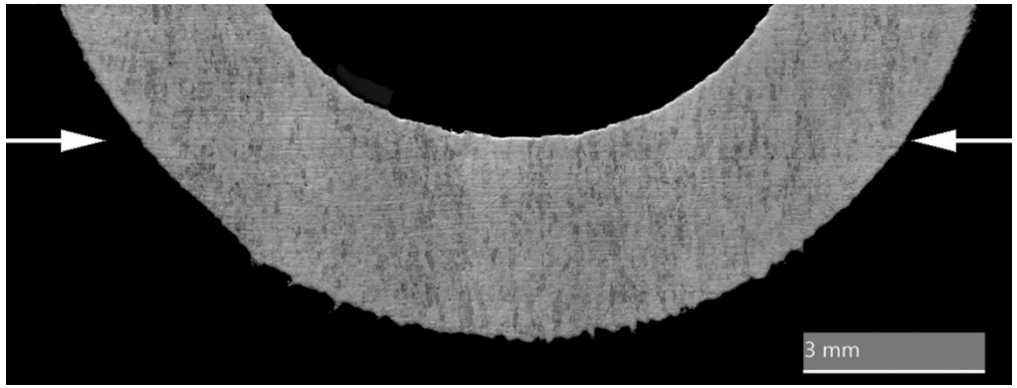




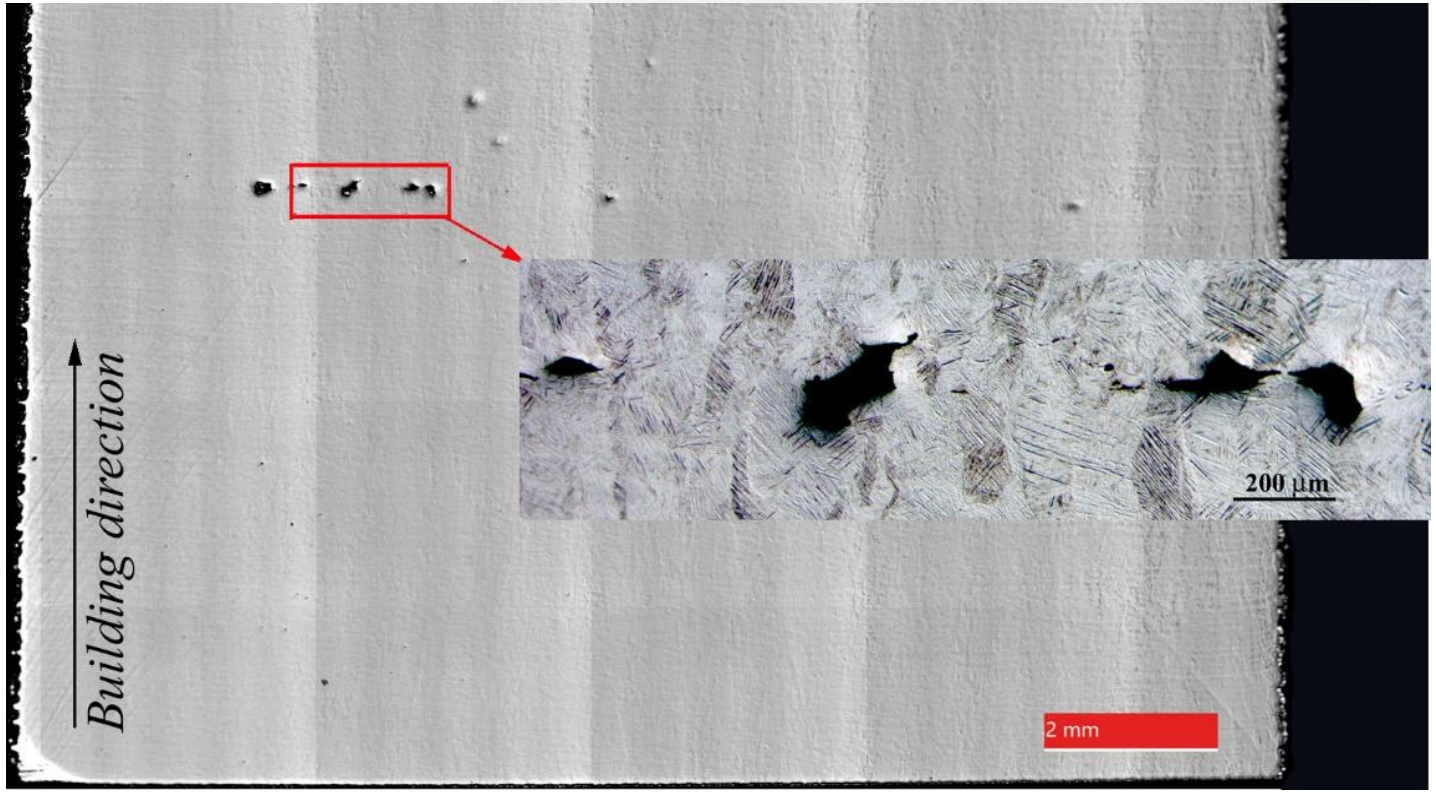
Stop-start flaw

Intentional stop-start flaw

- Can be seen in witness
- Not present in this case in bracket



- Scans of complex part still needed
- More work is needed to understand the formation of layered flaws and their extent across the build plane
- Can be seen in witness specimen by microCT



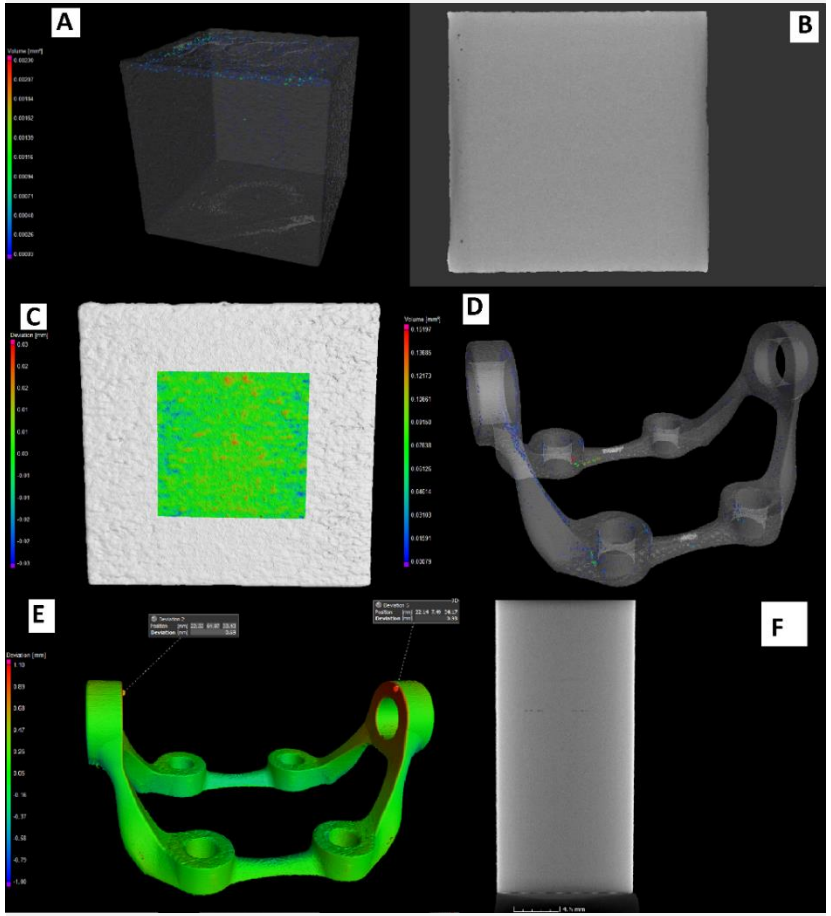
MicroCT robin test

Set of parts selected to send to 10 microCT labs

- 10 mm cube (upskin porosity)
- Witness cylinder (intentional stop-start flaw)
- Complex bracket (contour porosity)

- Result?
- **All labs could positively identify the porosity distributions**
- **Especially the stop-start flaw was no problem**

- To the right: one of the set of results as example – showing a series of completed analyses using pre-set X-ray CT scan parameters and image analysis steps (a recipe).

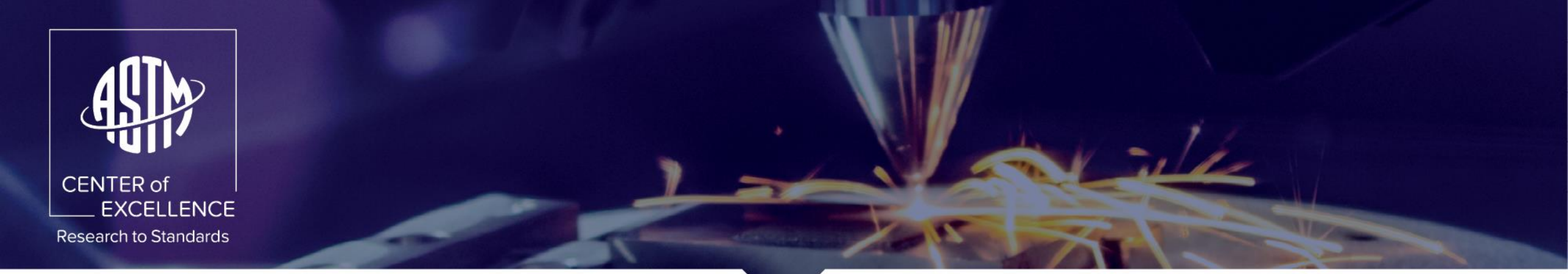


*** Laboratory X-ray tomography for metal additive manufacturing: Round robin test. Du Plessis et al**
https://doi.org/10.1016/j.addma.2019.100837

Conclusions

- Cube coupon samples can be used to improve AM processes
- Witness specimens contain information on process porosity as well as other flaws that can occur during build
- Fixed/prescribed CT scan and image analysis steps can be used to improve reproducibility of CT results – especially for fixed samples such as 10 mm coupon and 15 mm witness cylinder
- CT information cannot be used alone

CT image quality measurement method + video:
https://www.researchgate.net/publication/335842062_Not_all_scans_are_equal_X-ray_tomography_image_quality_measurement



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Thank you.

Prof Anton du Plessis

October 7-10, 2019
Gaylord National Resort and Convention Center

I am open for collaboration in the areas of AM structural integrity, biomimetic design for AM and X-ray CT in general. Please follow my work and keep in touch via:

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