Seeing inside powder bed fusion with X-ray imaging and image-based modelling

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Prof. P.D. Lee and Dr. C.L.A. Leung co-direct the Materials, Structure, and Manufacturing group at Harwell (MSM@H) with 16 Staff + 15 PhD students.

AM team

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Collaborators

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Elodie Boller, Alexander Rack (ESRF)

Margie P. Olbinado (PSI)

Samuel J. Clark, Kamel Fezzza (Advanced Photon Source)

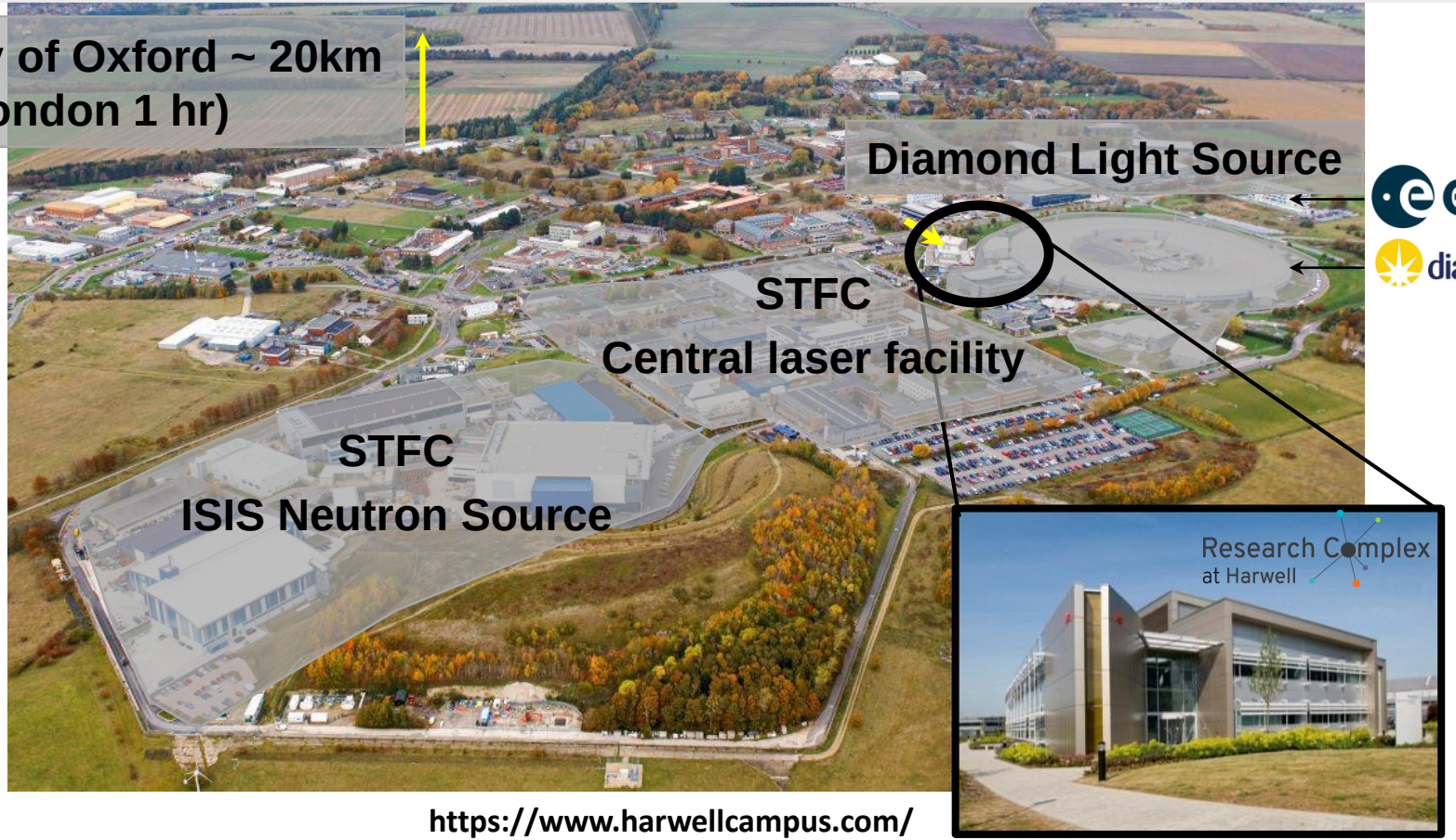
Iain Todd, Leigh Stanger, Jon Wilmott (Uni. Of Sheffield)

Mark Issacs / Shaoliang Guan (Harwell XPS)

Eduardo Saiz, Iuliia Elizarova (Imperial College London)

and many others…

The Harwell campus



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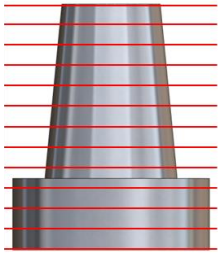
Content

- Introduction
- Scientific challenges in AM
- Application of 3D and 4D imaging in AM
- *In situ* and *operando* process replicator (ISOPR)
- Multi-modal imaging and image-based modelling
- Results and discussion
- Summary

Credit to Bathsheba Sculpture

Metal 3D printing, *i.e.* Additive Manufacturing (AM)

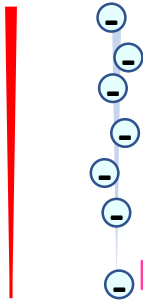
Create a CAD model



Divide the CAD into slices

Digital file

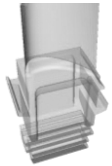
Feedstock materials



Infra-red

Photochemical

Heat source(s) and other curing methods

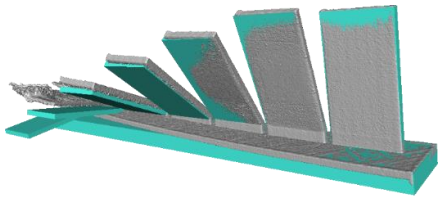


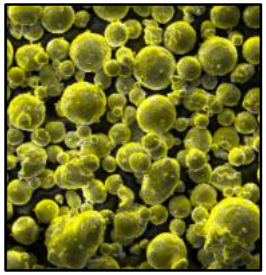
Turbine blade
(Courtesy Siemen)

Near-net shaped part

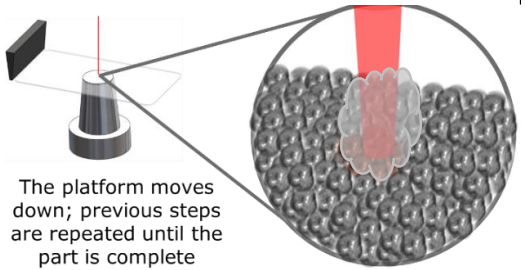
Scientific challenges

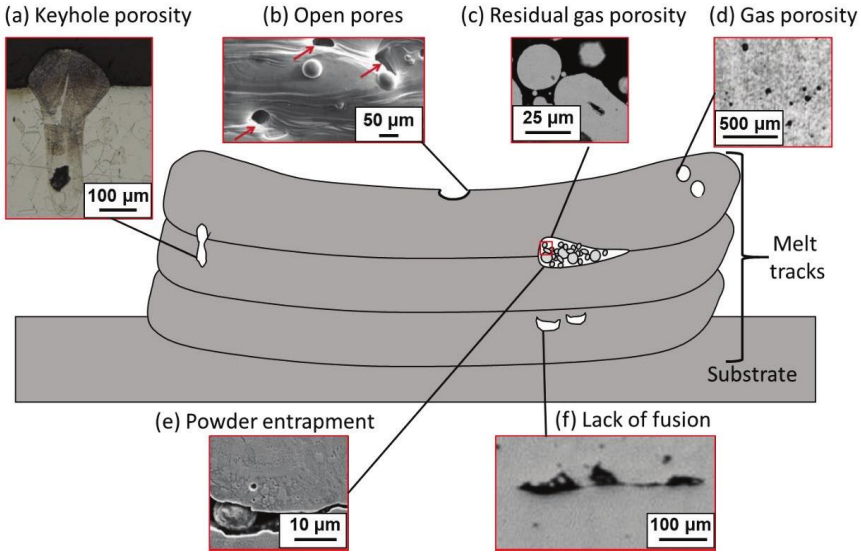
Design → Powder management → Production → Post processing → Inspection & validation → End-use





Process-structure-



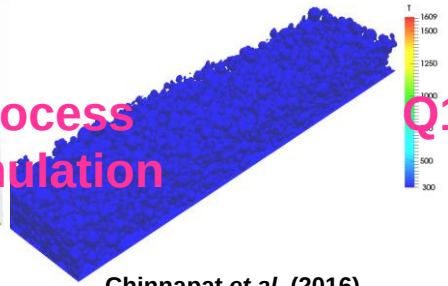


Leung *et al.* 2018 http://bit.ly/PhD_AL_thesis

Key research tools to tackle these challenges

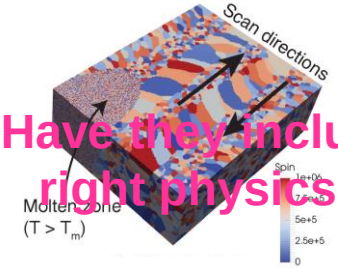
Courtesy to EDEM

Process Simulation

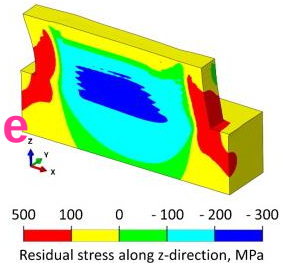


Chinnapat *et al.* (2016)
Acta Materialia

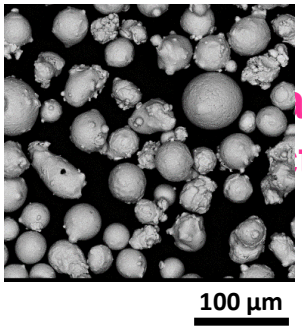
Q1. Have they include the right physics?



Rodgers *et al.* (2017)
Computational material science



Mukherjee *et al.* (2017)
Computational material science



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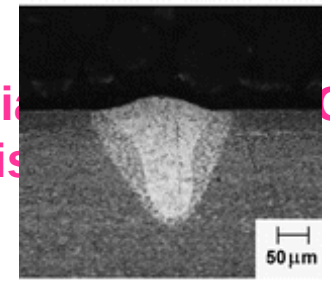
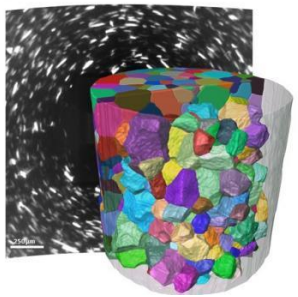


Q2



SA McDonald *et al.* *(2015)*
Scientific report

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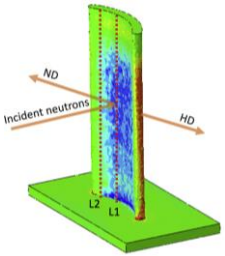
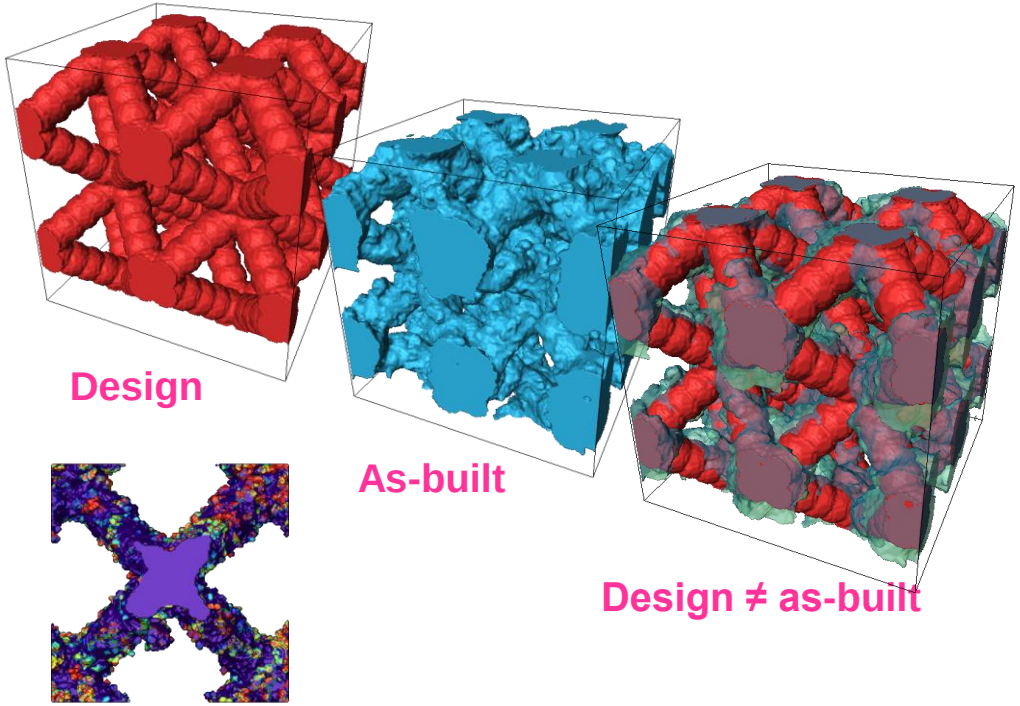
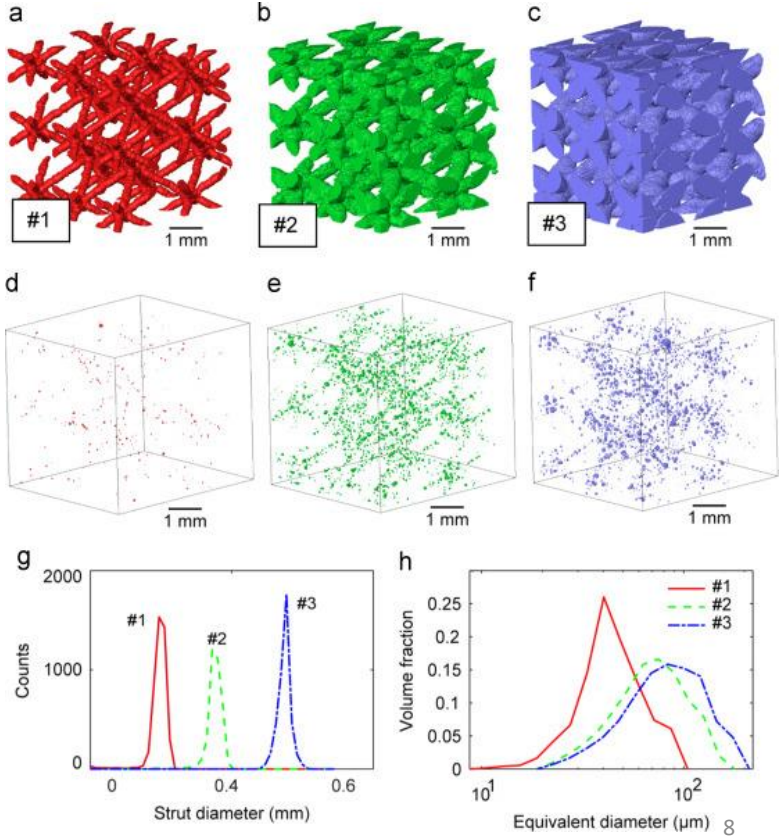


An *et al.* (2017)
Materials & design

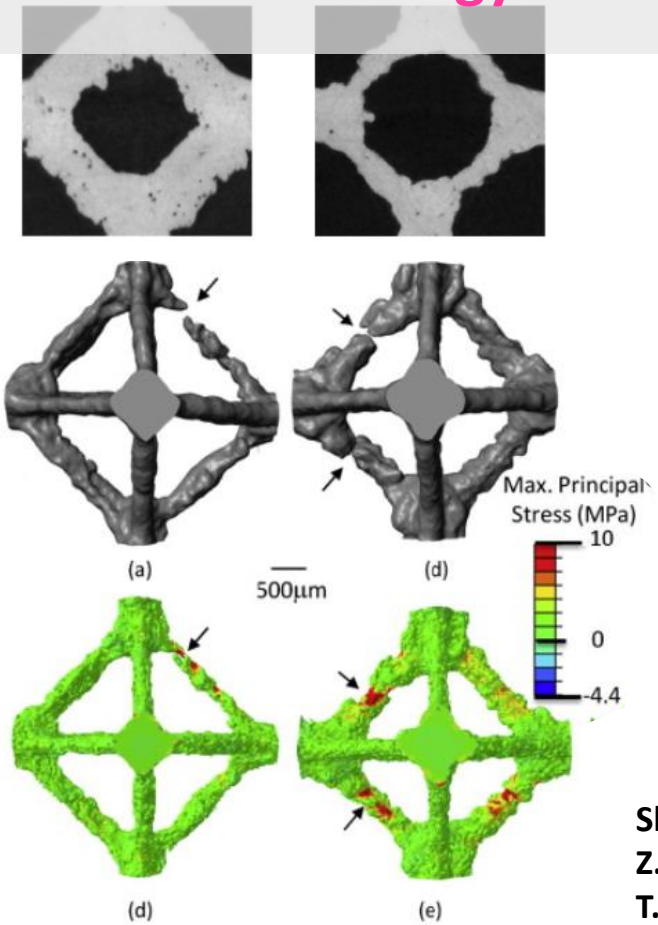
XCT - 3D characterisation / metrology of AM parts

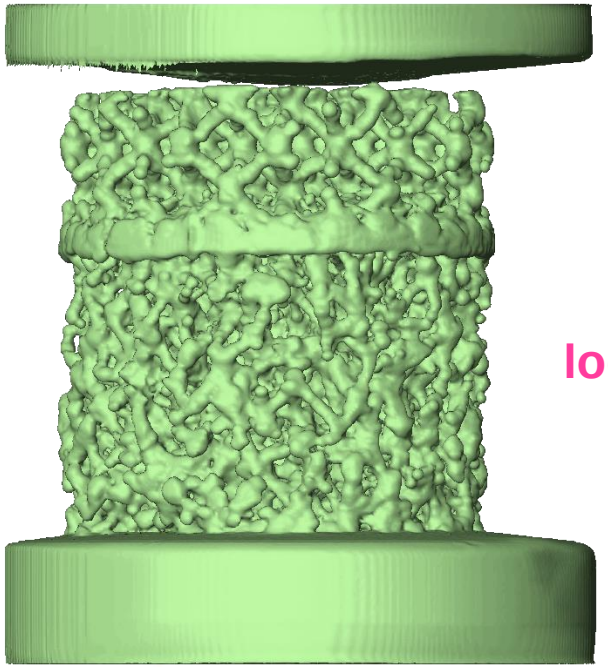




S. Yue *et al.* J. Mat. Sci.: Mat. in Med, 2010
TB. Kim *et al.*, J. Mat. Proc. Tech. 2014
C. Qiu *et al.*, Mat. Sci. Eng. A, 2015

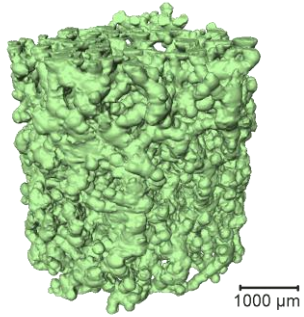
XCT - 3D metrology + evaluate in service performance of AM parts



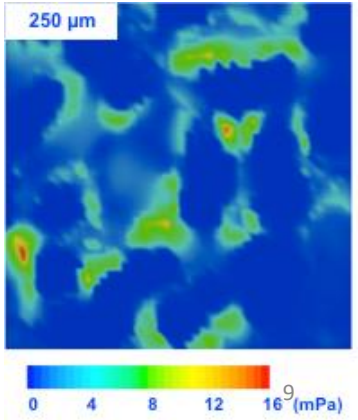


Sheng Yue et al. 2010
Z. Zhang *et al.*, Mat. Sci. Eng. C, 2013
T. Sercombe *et al.*, Materials and Design, 2015

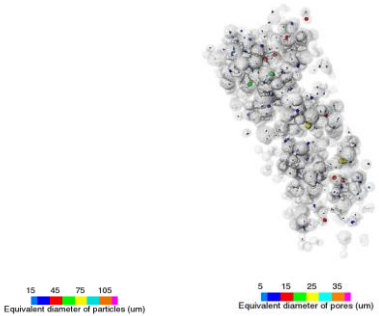
Random structure



local shear distribution

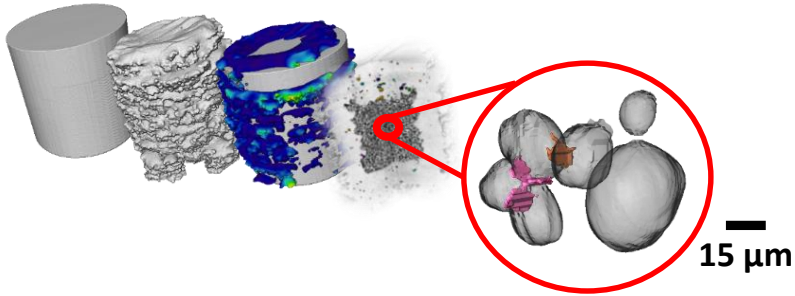


Imaging of AM processes



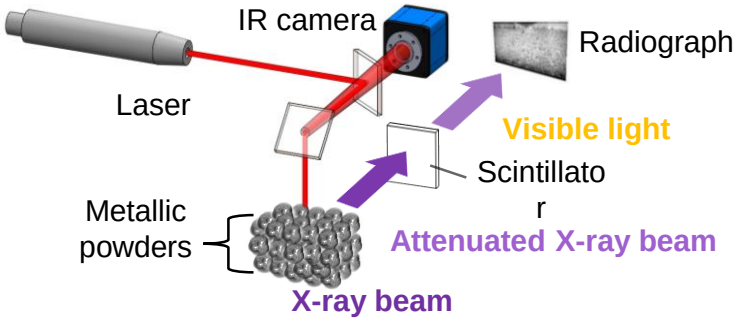
Powders for additive manufacturing

Leung *et al.* Mat & Des (2019)



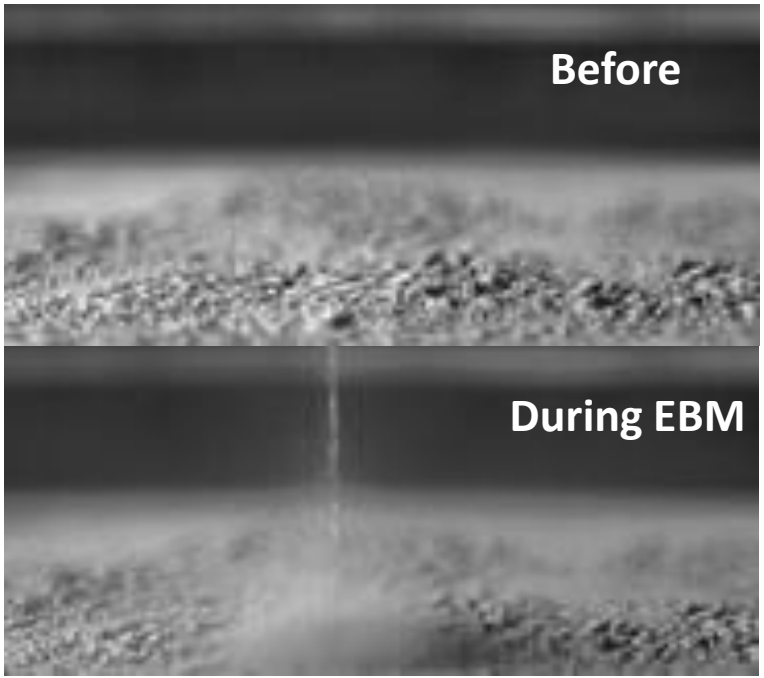
Preheating effects on powder bed

Leung *et al.* Nat. Comms. (2018)

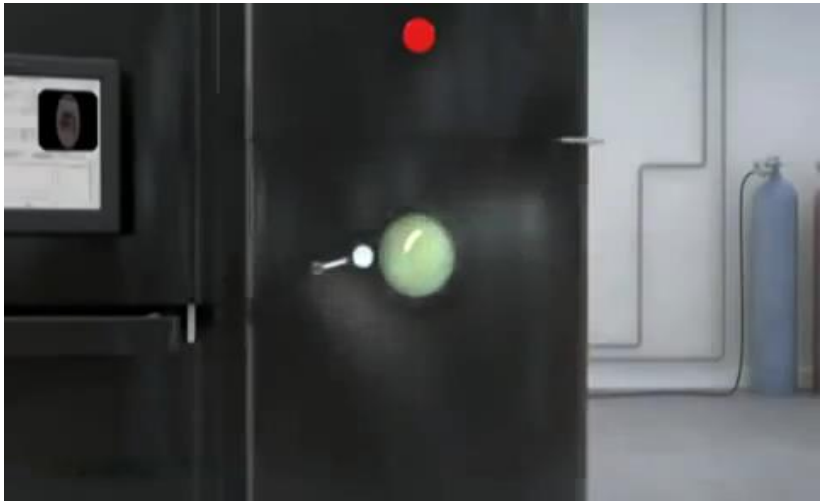


Observe the laser-matter interactions

Preheating effects on EBM

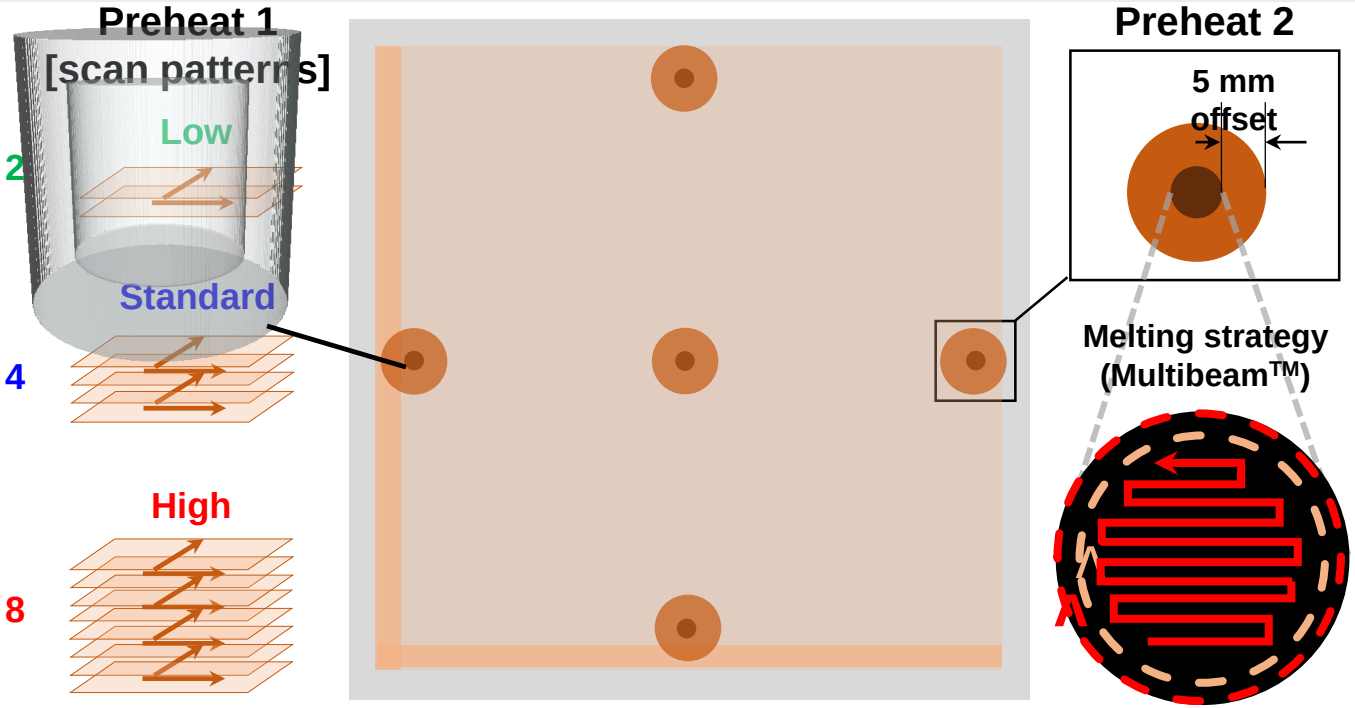


Powder spreading effect during EBM (after *M. Kahnert et al. 2007*)



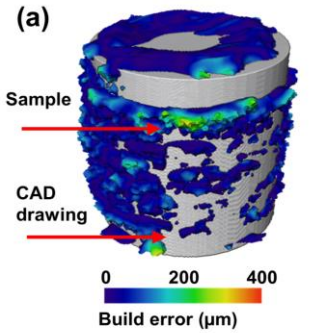
- Prevents powder spreading
- ↑ mechanical strength between particles
- ↑ Effective thermal conductivity of the powder bed ($\lambda_{eff,\ bed}$)
- ↓ energy required to melt materials
- ↓ residual stress

Preheating and melting in EBM AM



Case study 1: sintered characteristics in electron beam melting

Image based metrology



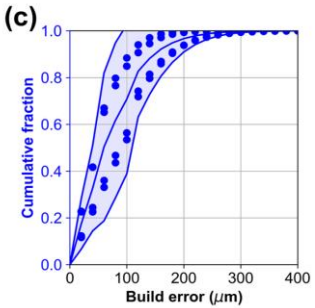
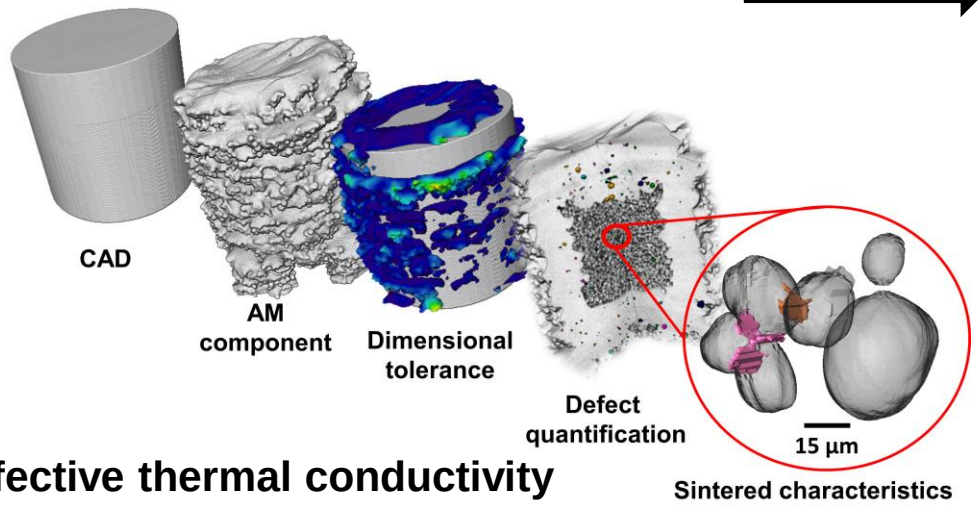
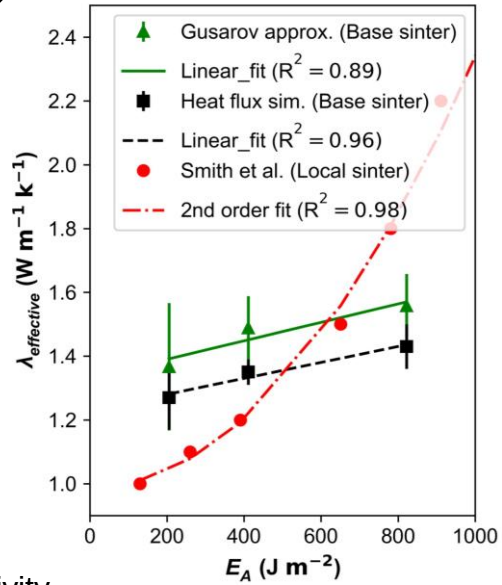


Image based model





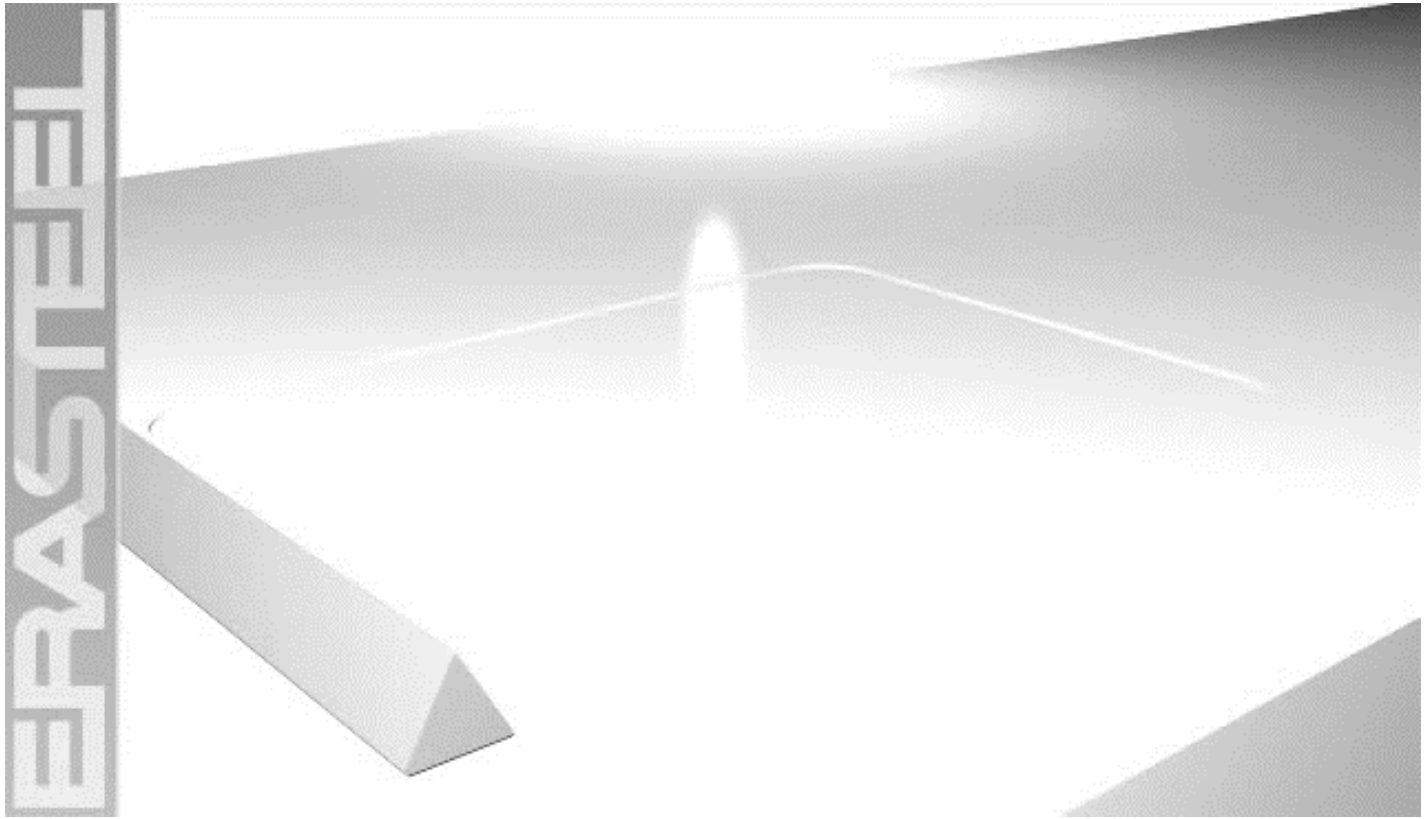
Effective thermal conductivity ($\lambda_{eff,\ bed}$) for random structure:

$$\lambda_{eff} = \lambda_{bulk} \frac{(Pf * Cn * Nr)}{\pi}$$

where:
λ_{bulk} = bulk thermal conductivity
Pf = packing fraction
Cn = coordination number
Nr = neck ratio

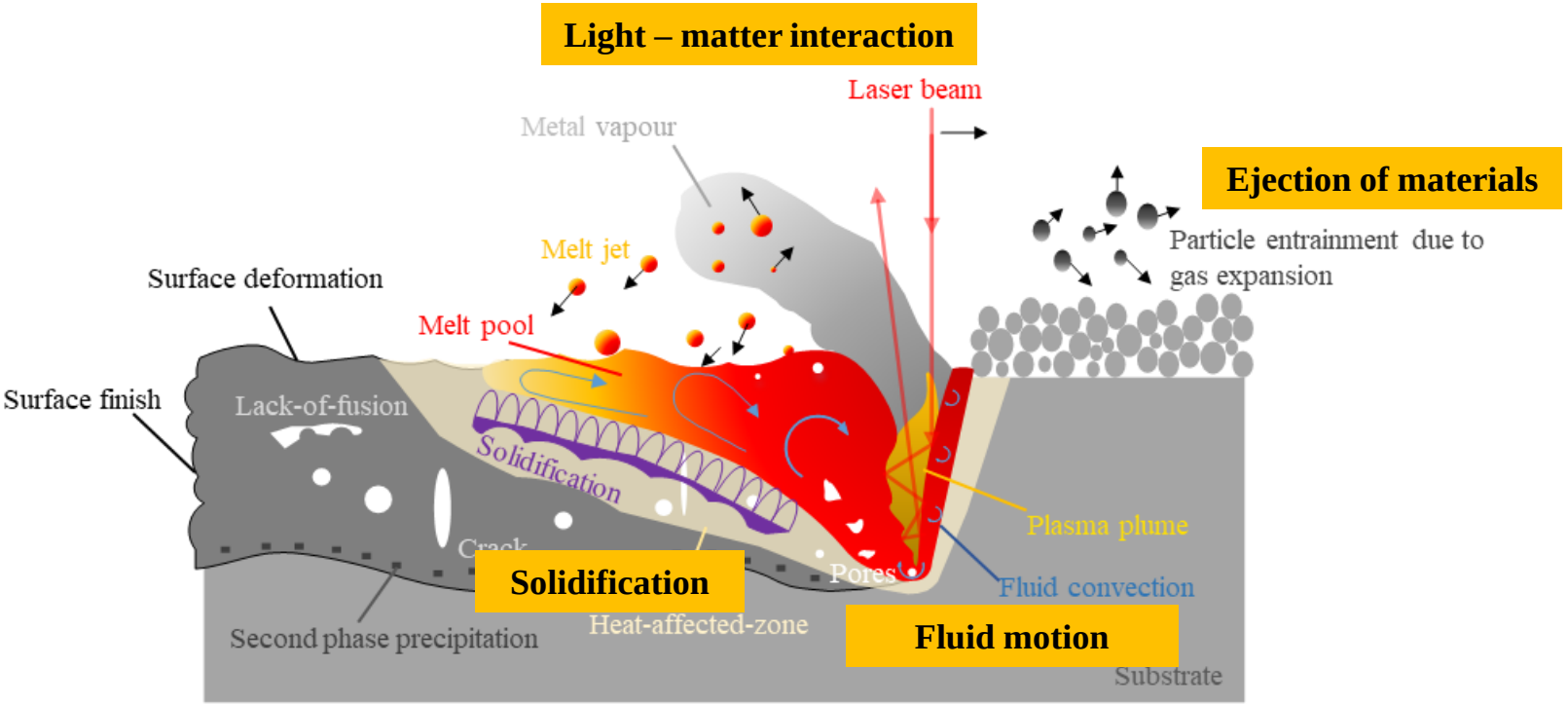
Leung *et al.* Material and Design, 174, 107792 (2019)

Laser powder bed fusion (LPBF)



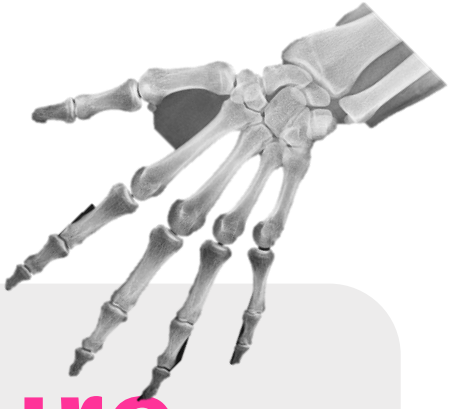
[1] Erasteel (2012, July 12), Additive manufacturing of Near Net Shape or Net Shape components [Video file]. Retrieved from https://www.youtube.com/watch?v=GjbkxVku39Y

What physical phenomena does LPBF involve?

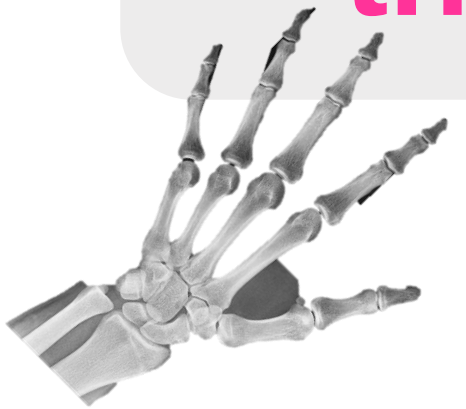


Schematic illustration of major phenomena in LPBF with metallic powder.

Reproduced from Panwisawas *et al.* Nat Commun 11, 2327 (2020).

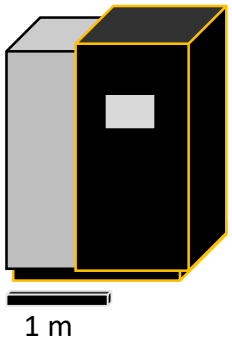


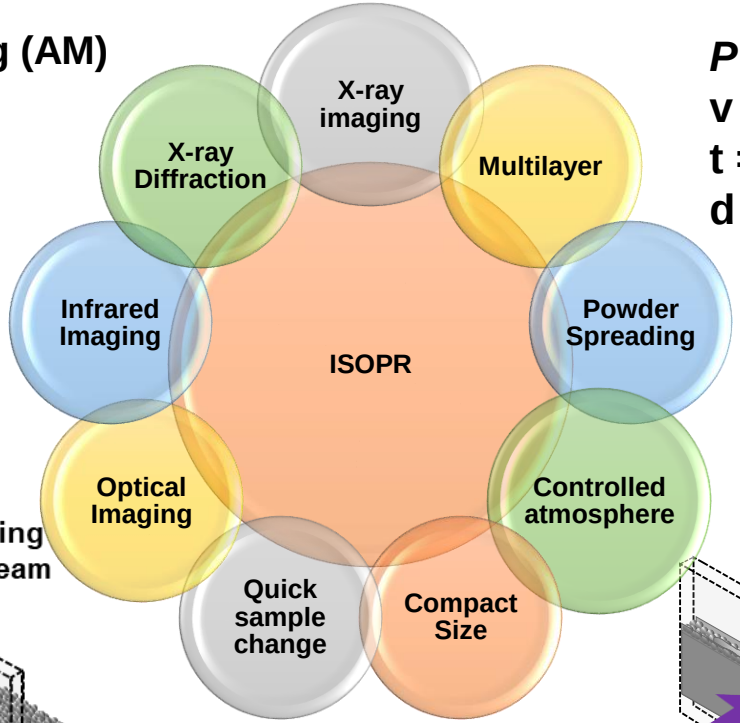
How do we capture these phenomena?



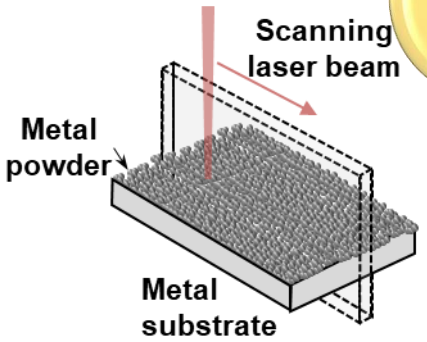
In situ and *Operando* Process Replicator (ISOPR)

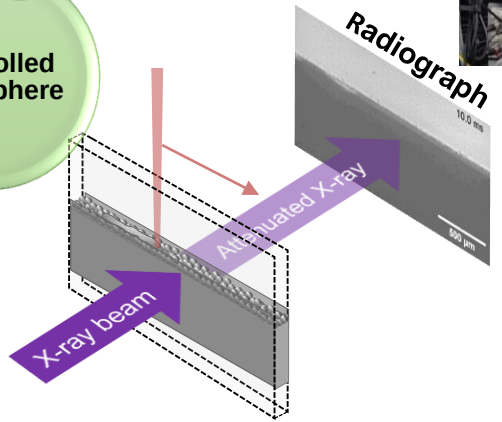
Additive manufacturing (AM) machine





P = 200 W
v = 4 m s^{-1}
t = 20 - 100 µm
d = 50 µm ($4\sigma_{x,y}$)

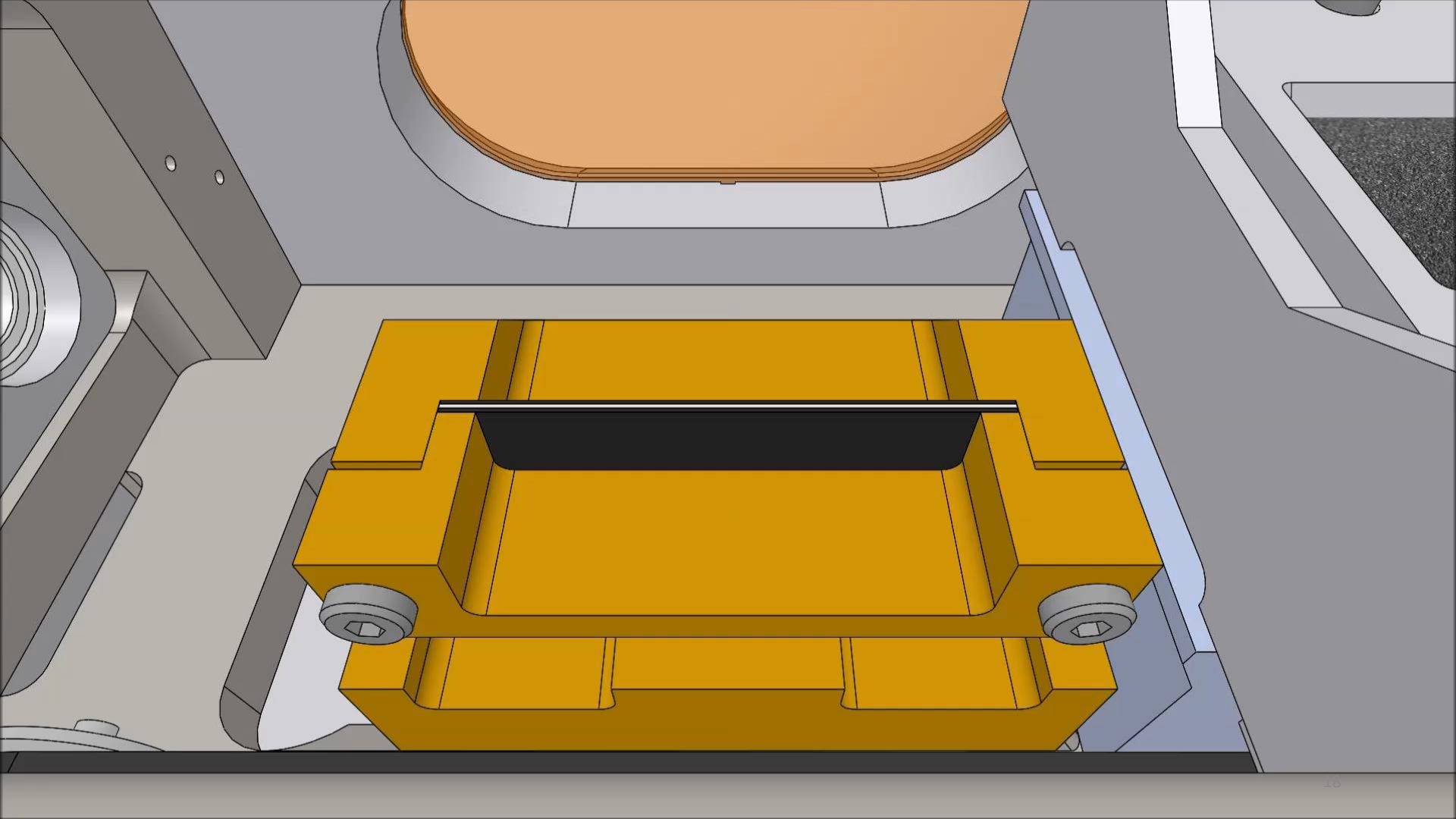




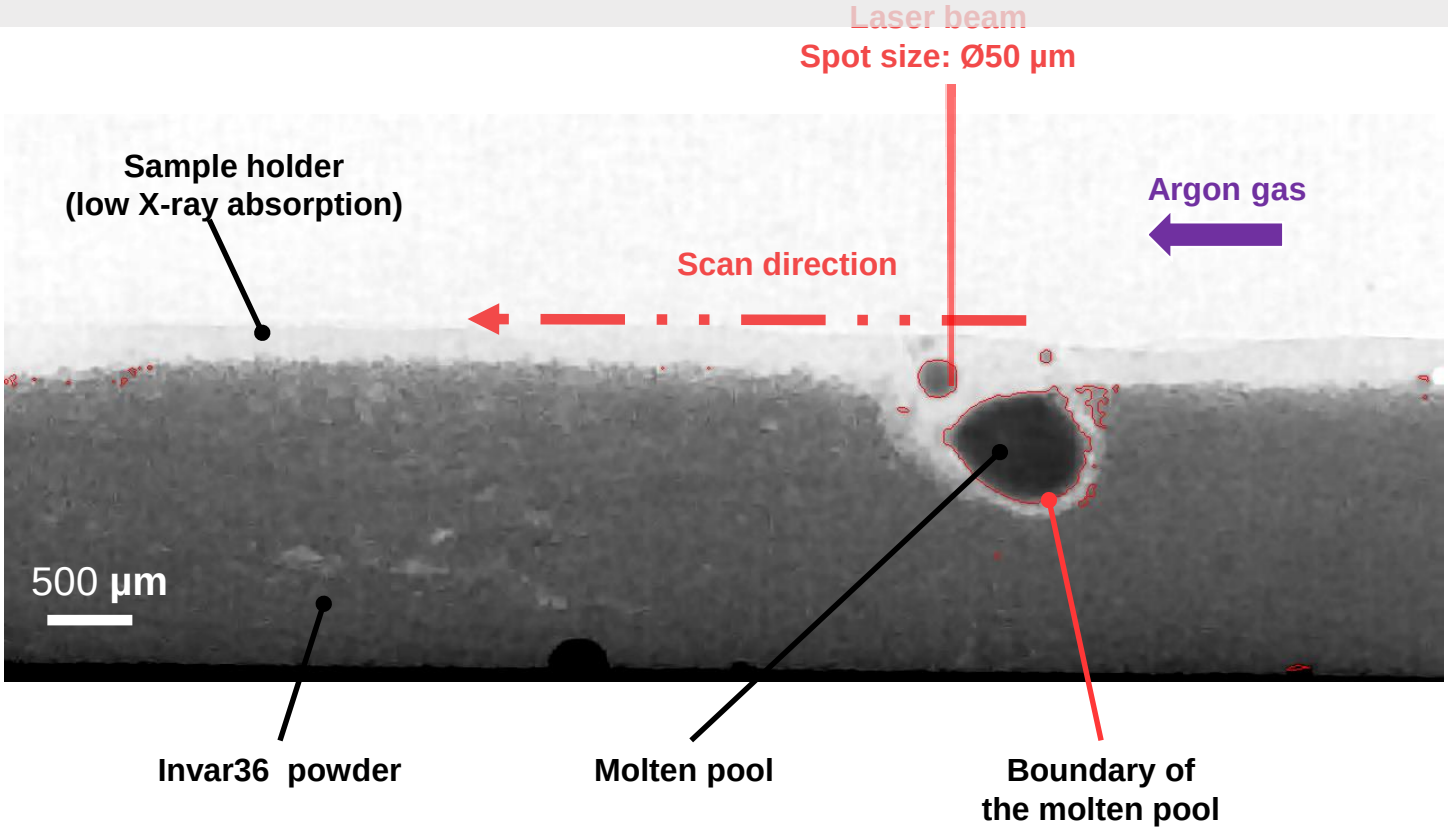
UCL

OXFORD LASERS IMAGING DIVISION

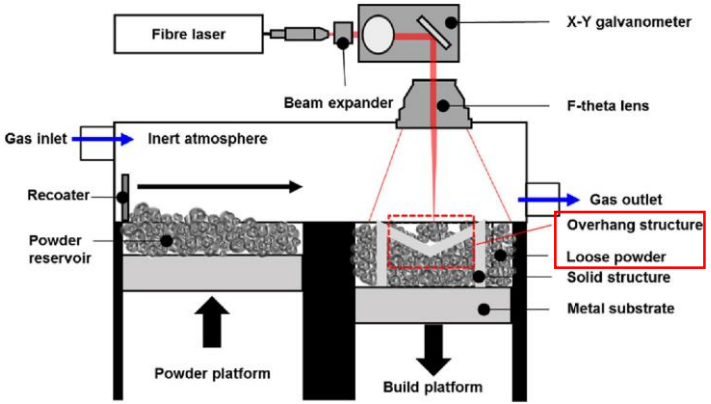
MAPP
Manufacture using Advanced Powder Processes
EPSRC Future Manufacturing Hub



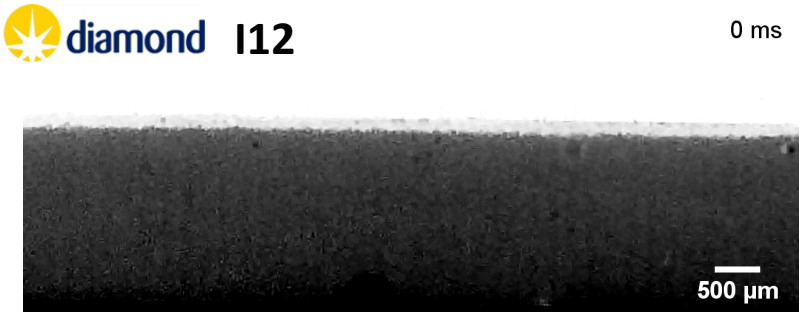
A typical radiograph



Typical results from different beamlines

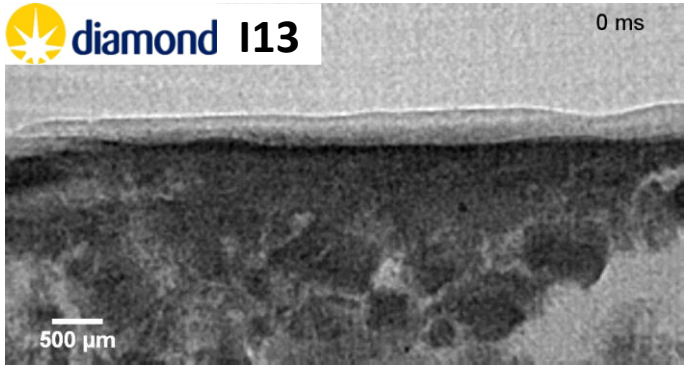


Invar 36 (Fe-Ni alloy)



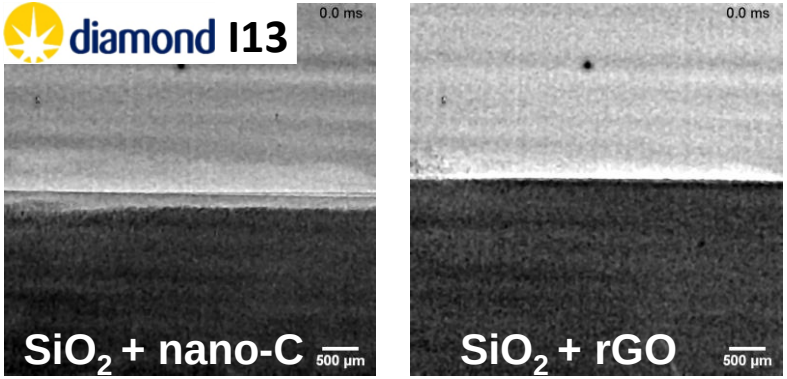
Leung et al. 2018 *Nat. comms vol 9, 1355*

Bioactive glass 13-93



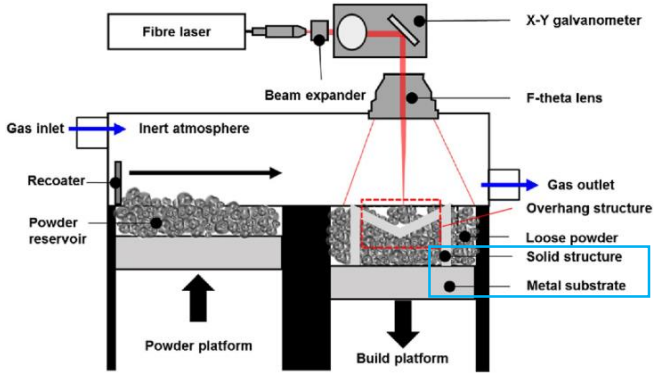
Leung et al. 2018 *Add. Man.* vol. 24, pg 647-657

SiO_2 fused silica

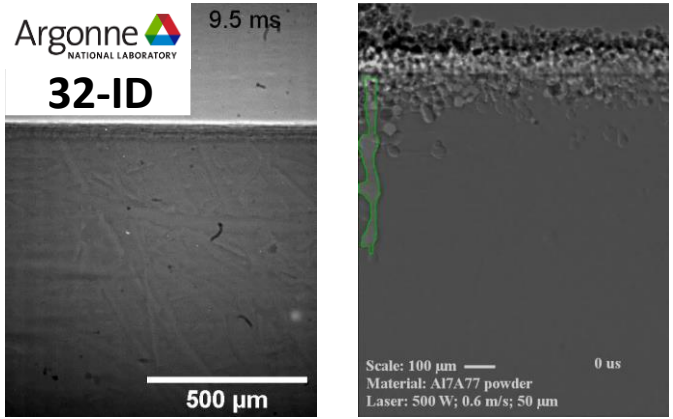


Leung and Elizarova et al. 2021, *Applied Materials Today,* vol. 3

Typical results from different beamlines

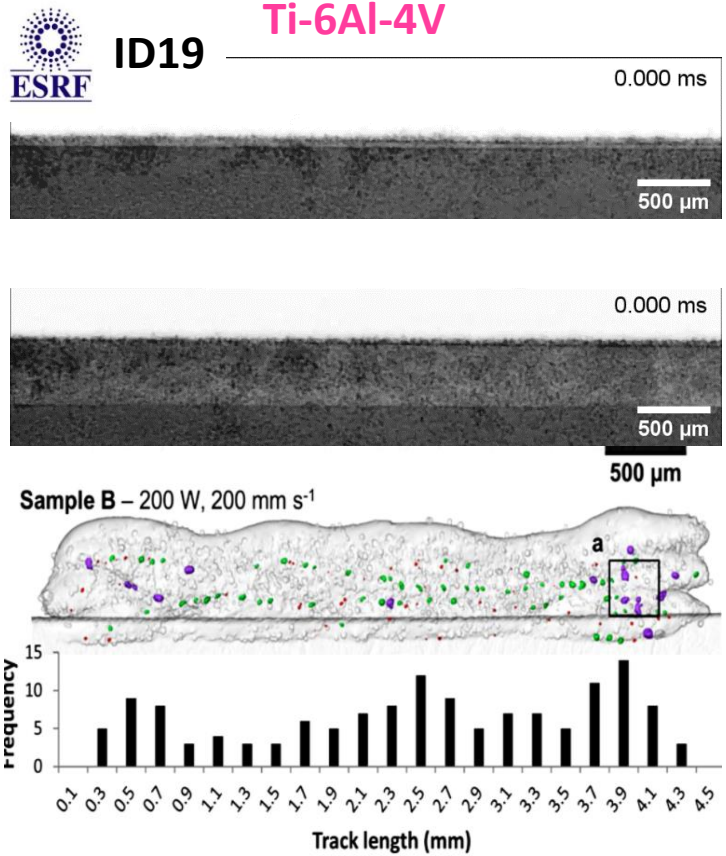


Al / Al alloy



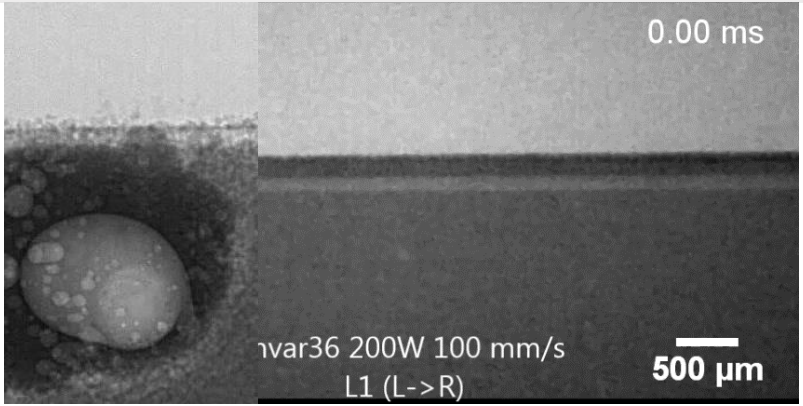
Huang *et al.* Nat. Comms (under review)

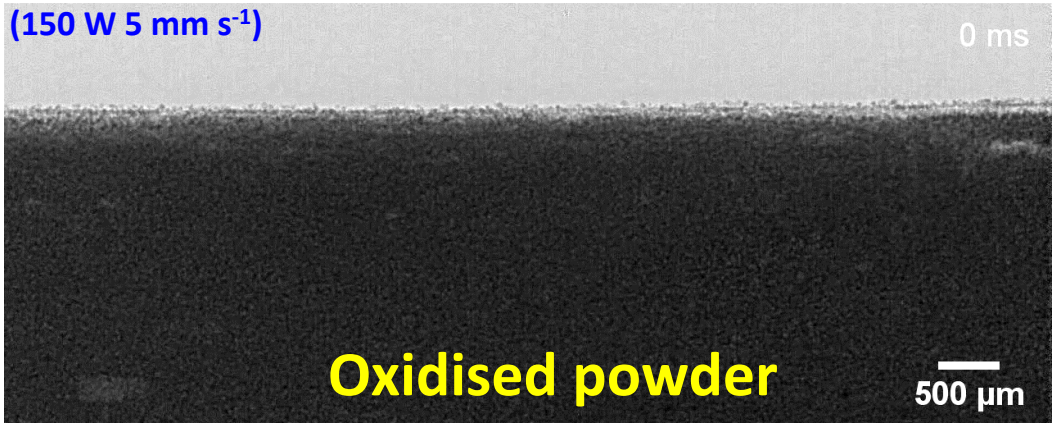
Ti-6Al-4V

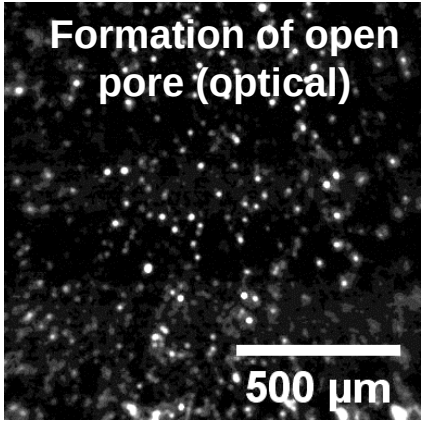


Sinclair *et al. 2020* Additive Manufacturing *V*ol 36, 101512

Study the impact of powder oxidation on AM







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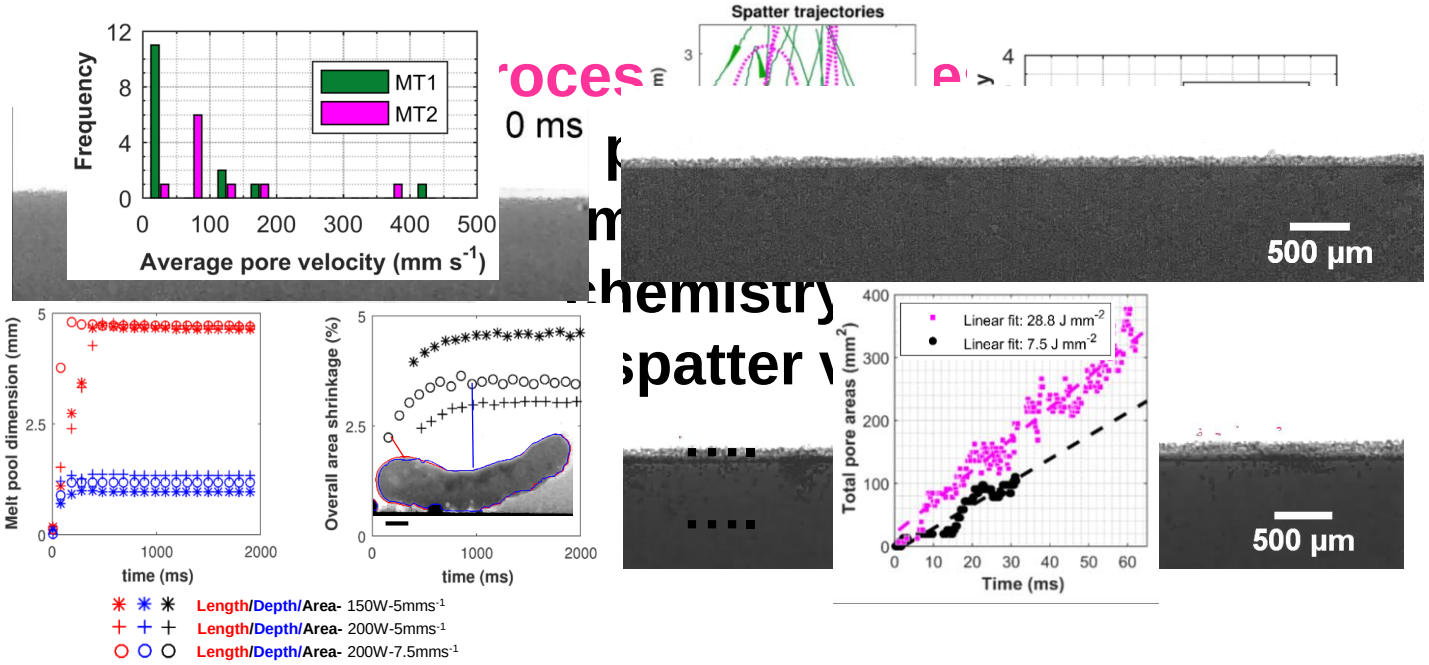
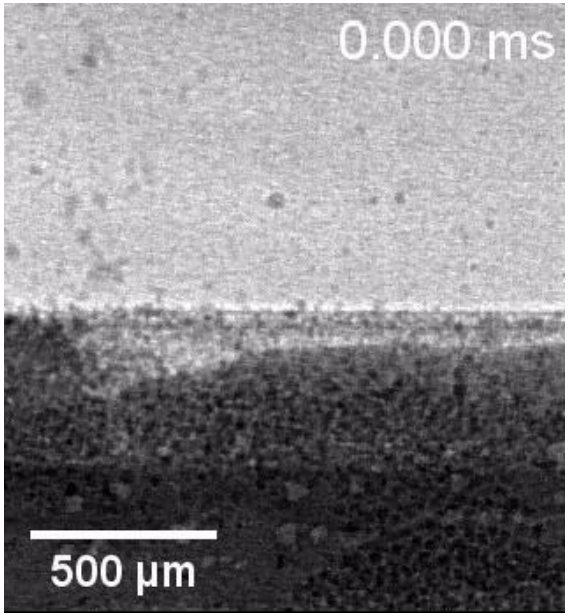
Leung *et al.*, Acta Materialia, 2018

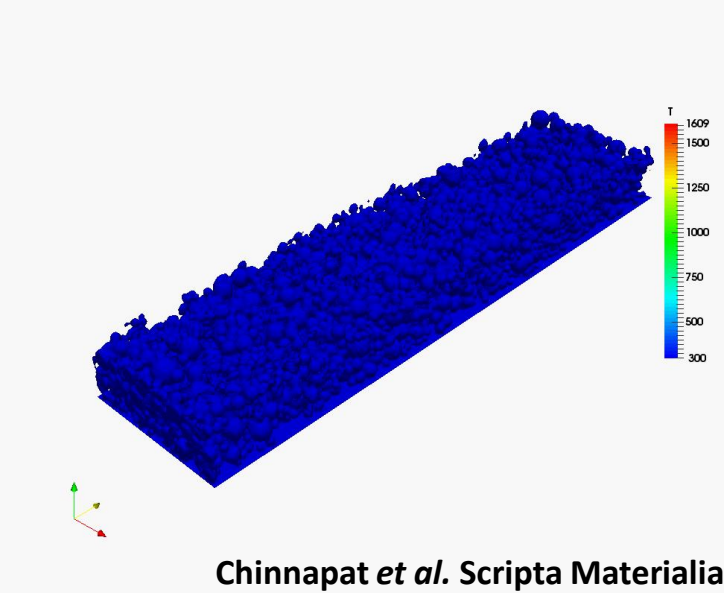
Advanced image quantification applied in AM



Leung *et al. Nature communications (2018), Additive Manufacturing (2018) & Acta Materialia (2019)*

How well do these models match with experiments?





Chinnapat *et al.* Scripta Materialia

Model limitations:

- No laser-induced plasma
- Does not predict multi-phase flow
- Powder denudation
- Metal vaporisation
- Porosity motion/dissolution
- Wetting, *etc.*

Summary

- Application of 2D, 3D, and 4D imaging in probing the heart of AM processes and *in* service performance of AM parts.

- To provide ground truth data for:
  1. Revealing complex melt pool and defect dynamics across a wide range of materials, not limited to alloys.

  2. Calibration low-cost sensing technologies.

  3. Development of image-based process simulation or ‘Digital Twins’ that enable predictions of AM process.

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Questions

Credit to Bathsheba Sculpture