3D METROLOGY CONFERENCE
Loughborough Uni, Sep 2024

The Future Metrology Hub

# Exploitation of Industrial X-ray Computed Tomography for Surface Metrology of Metal Additively Manufactured Parts

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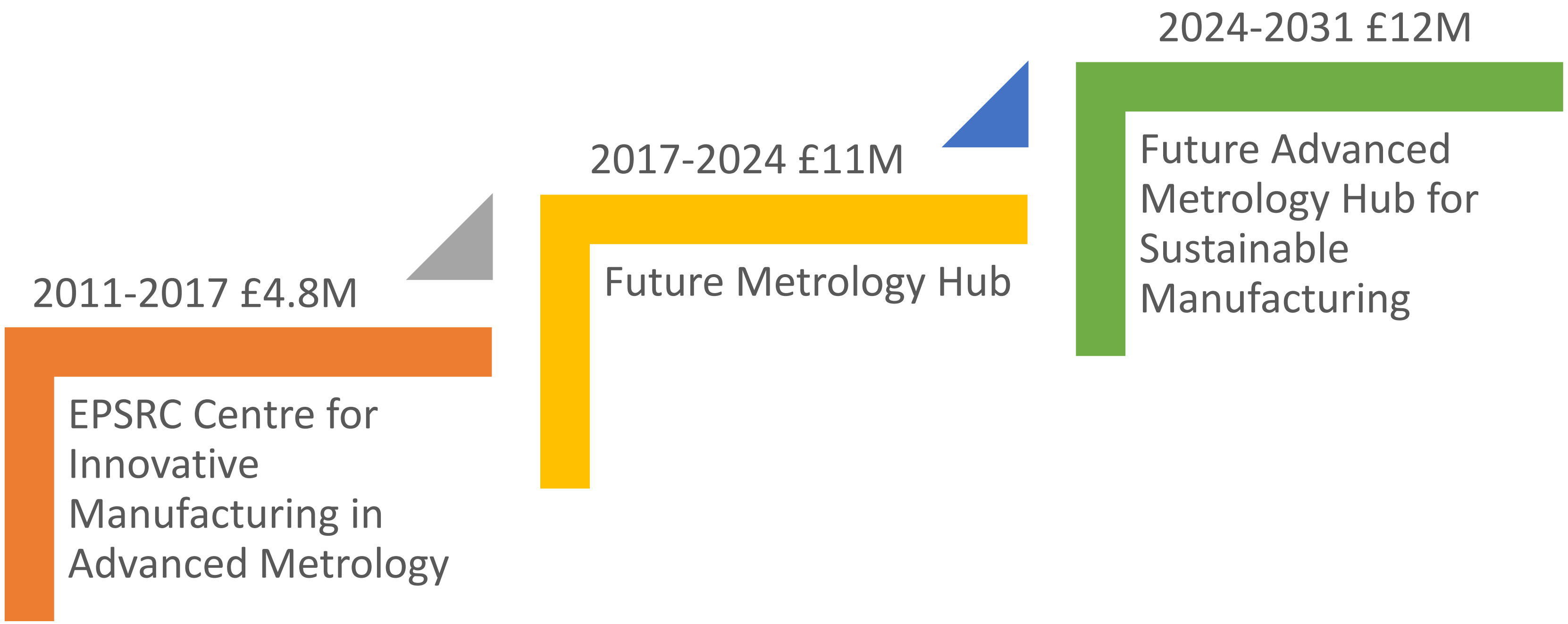
25 Sep 2024

# Centre for Precision Technologies (CPT)



- A world-leading institute for metrology research based at the University of Huddersfield
- Set up in 1997 by a metrology research group moving from the University of Birmingham (led by Prof Kenneth J. Stout, Prof Liam Blunt, and Prof Dame Jane Jiang)
- National Centre of Excellence in Advanced Metrology designated by EPSRC 2011
- Queen’s Anniversary Prize, for its innovative and ground-breaking research 2022



# Outline



1. Introduction
2. AM surface texture measurement using XCT
3. Improvement of XCT structural resolution
4. AM surface characterisation using XCT 3D data
5. Summary

# 1. Additive Manufacturing & XCT

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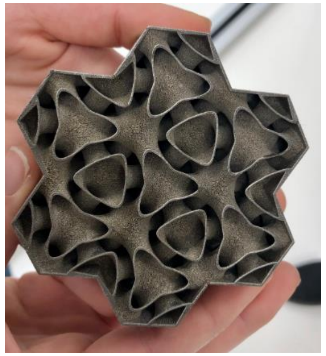
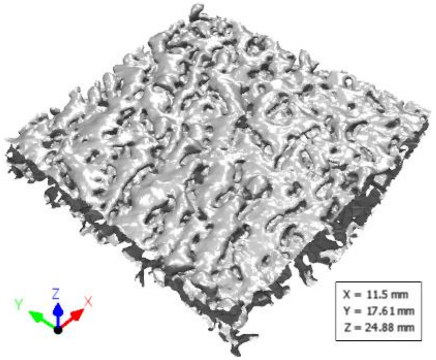
- Additive manufacturing

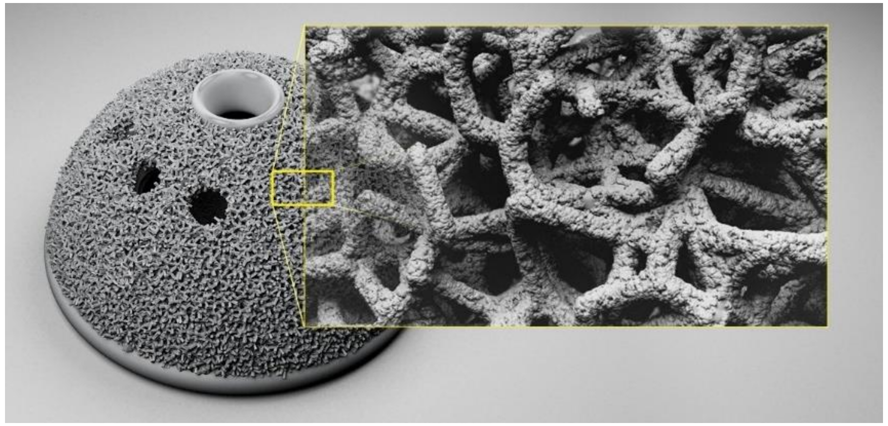
**GE Leap Engine Fuel Nozzle** (src: GE)



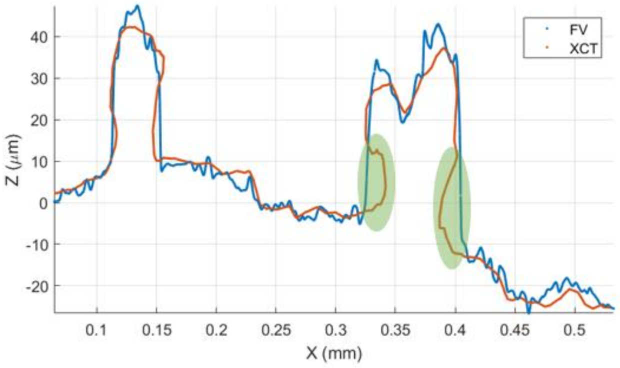
**Heat exchanger** (src: GE)




**Metal SLM surface with re-entrant features**

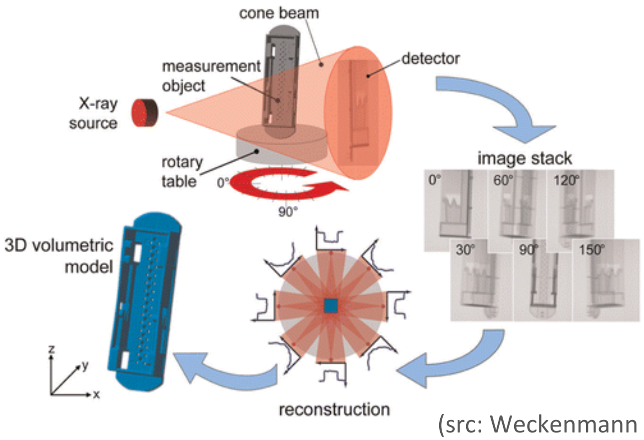


**Acetabular Cup** (src: Within)

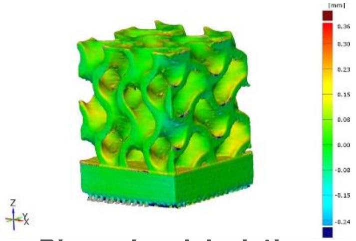



**Undercuts/re-entrance under particles (profile view)**

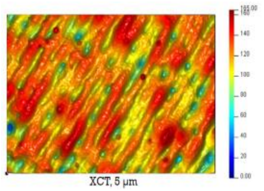
- X-ray computed tomography



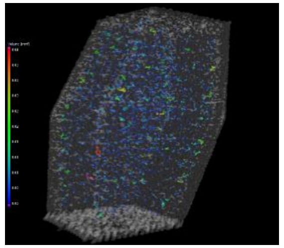

(src: Weckenmann A, 2013)



**Dimensional deviation**



**Surface texture**



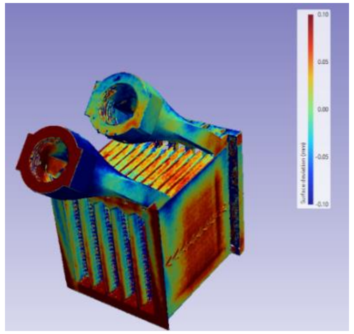
**Internal defects**

# 2. AM Surface Texture Measurement using XCT

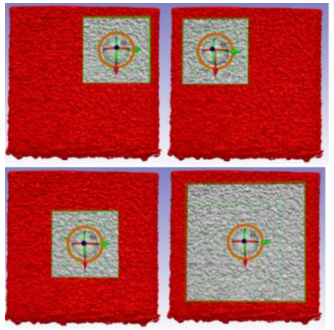
## Benchmark by focus variation microscope



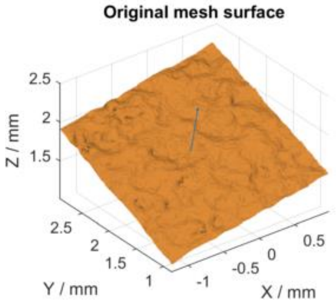
- IUK: 3-in-1 X-ray CT inspection (partners: Nikon Metrology, Synopsys, HiETA, MTC, UoH)

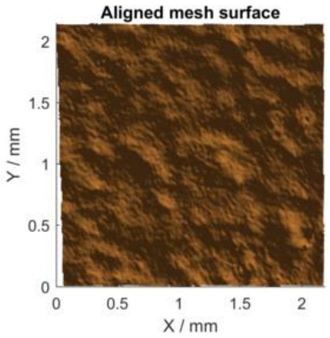


Select ROI

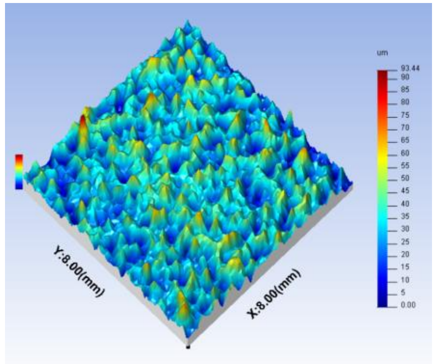


Rotation

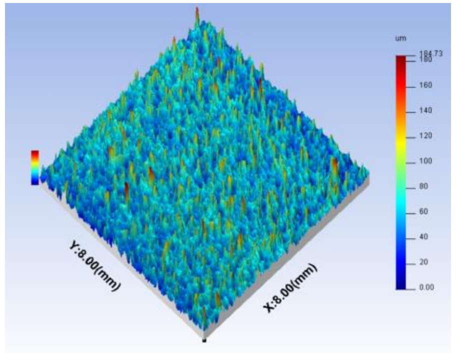


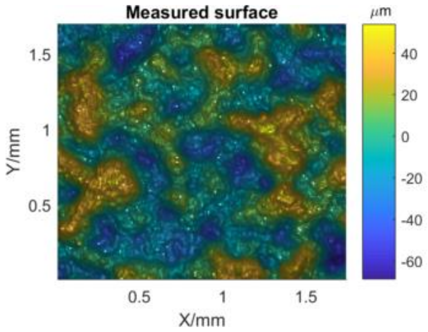

XCT

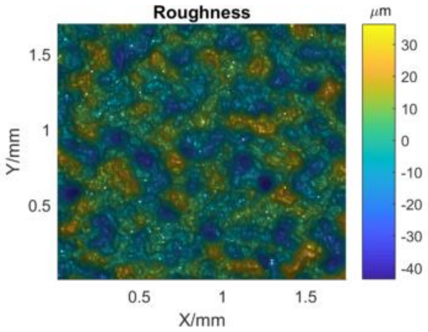


Focus Variation (FV)



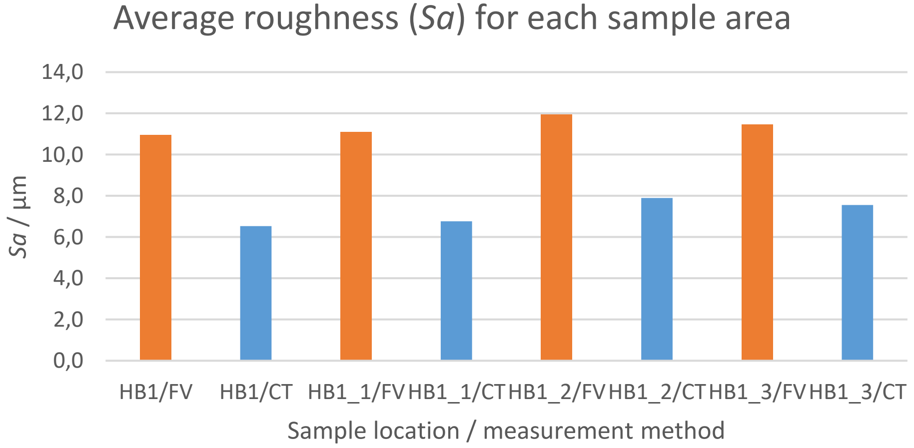
Generate the height map
(Truncate 20% to avoid blank data)




Surface texture parameters
(L-filter cut-off: 0.25 mm)

| Parameter | |
|---|---|
| Sa | 8.2 μm |
| Sq | 10.2 μm |
| Ssk | -0.273 |
| Sku | 3.047 |

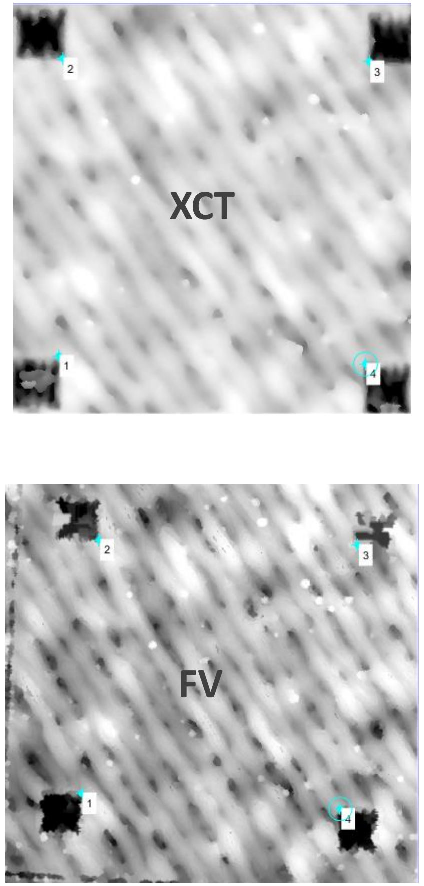


# 2. AM Surface Texture Measurement using XCT

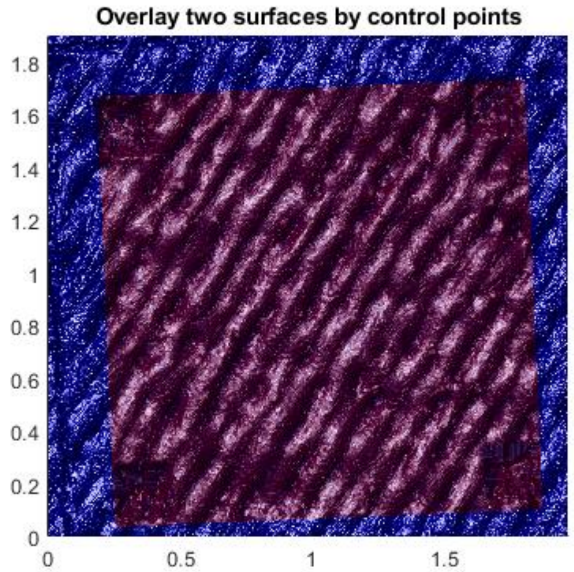
## Benchmark by focus variation microscope



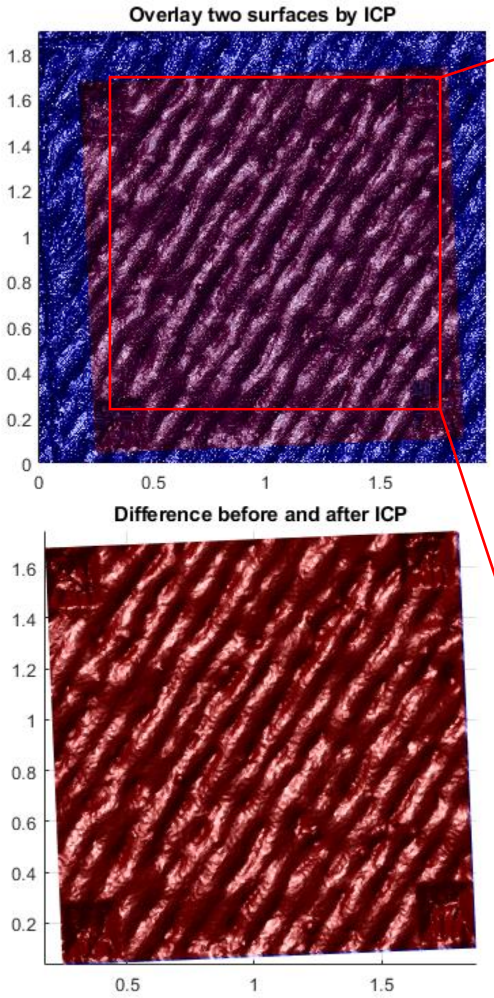
- XCT and FV comparison: two-stage surface registration

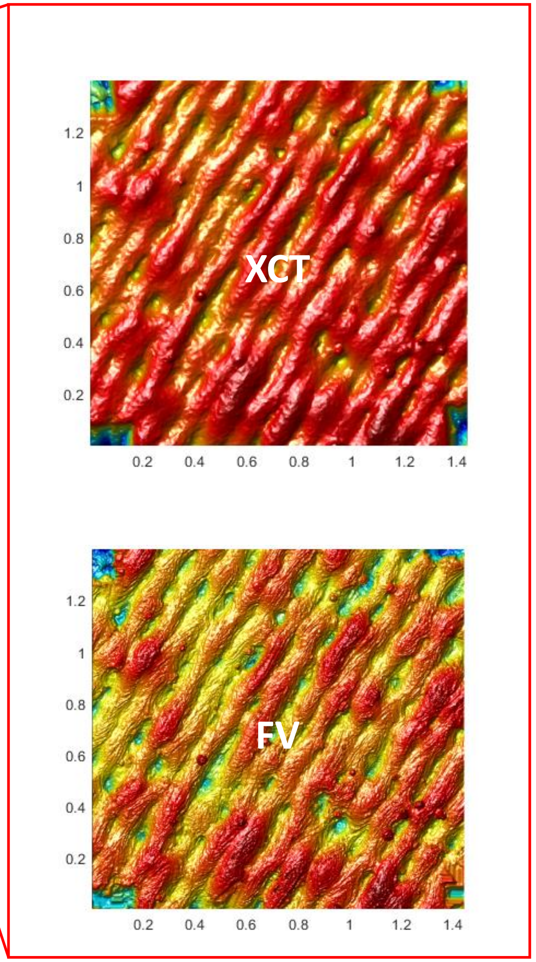



Manual selection of matching points




Coarse alignment by least squares fitting the best rigid transform




Fine alignment by ICP

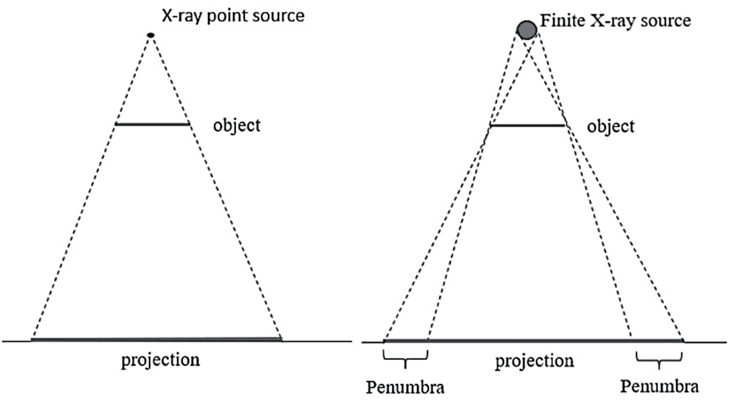
# 2. AM Surface Texture Measurement using XCT

## Blurring assessment

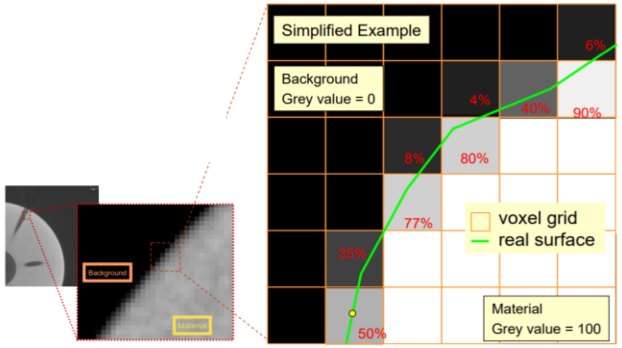


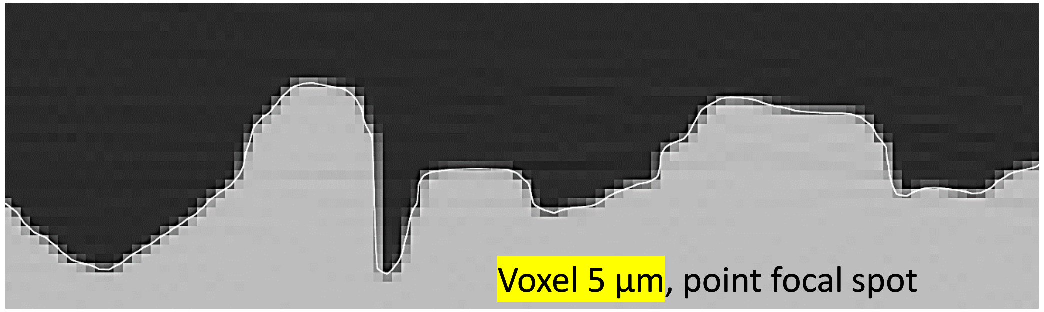
| Resolution | |
|---|---|
| AM surface measurement requirement | Below 10 µm |
| Optical surface measurement instruments | Around 1 µm |
| Industrial XCT(for metal AM sample) | high X-ray power (>20 watt),<br>large focal spot size;<br>Voxel size >10 µm; |

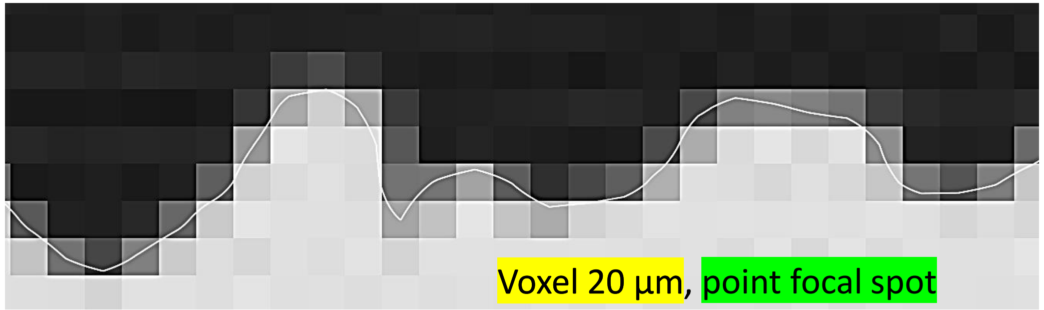
- Focal spot blur - penumbra effect

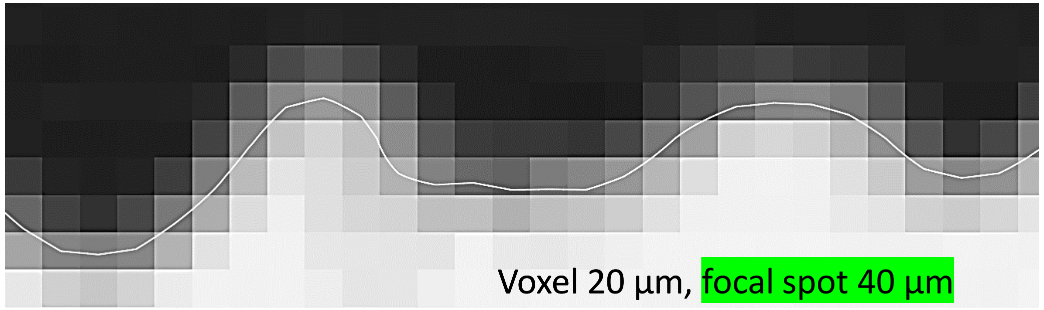



- Finite size of detector pixel - partial volume effect



# 2. AM Surface Texture Measurement using XCT

## Blurring assessment

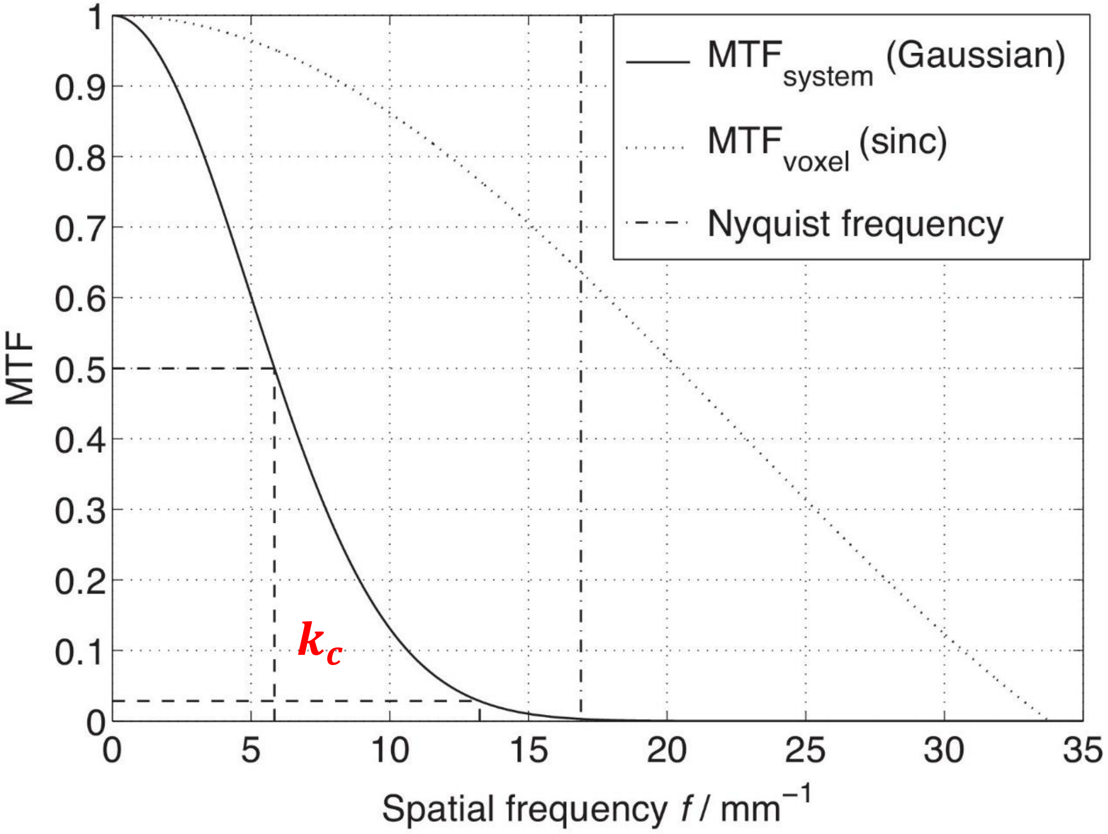
- Modulation transfer function (MTF) for the characterisation of the blurring effect

True surface → XCT system → Measured surface

$$\text{MTF} = \frac{A_{measured}}{A_{ture/reference}} = \frac{|\mathcal{F}\{\text{measured surface}\}|}{|\mathcal{F}\{\text{ture/reference surface}\}|}$$

$$\text{MTF} = \exp\left(-\ln(2) \cdot \left(\frac{\sqrt{(u^2+v^2)}}{k_c}\right)^n\right)$$

- $u, v$: surface wavelengths
- $n$: fitted order 1~2
- $k_c$: fitted frequency corresponding to the 0.5 MTF
- $\lambda_c = 1/k_c$




**Ref**: Hiller, J. and Hornberger, P., 2016. *Precision Engineering*, *45*, pp.18-32.

# 2. AM Surface Texture Measurement using XCT

## Blurring assessment

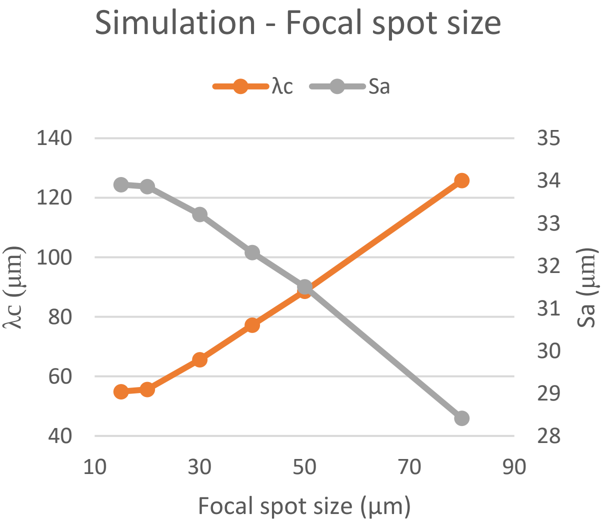


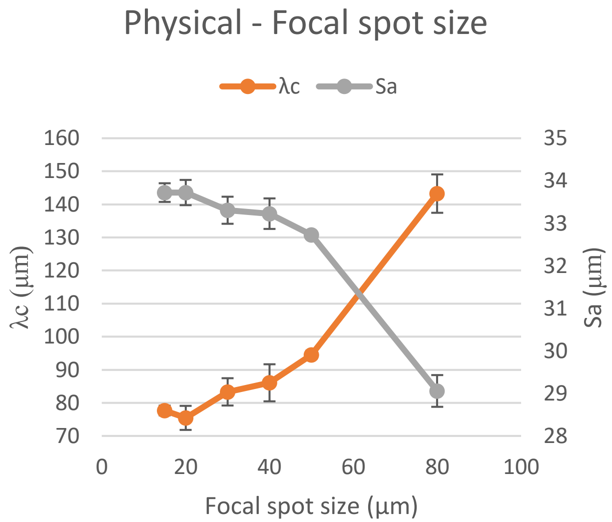
- **Focal spot size**

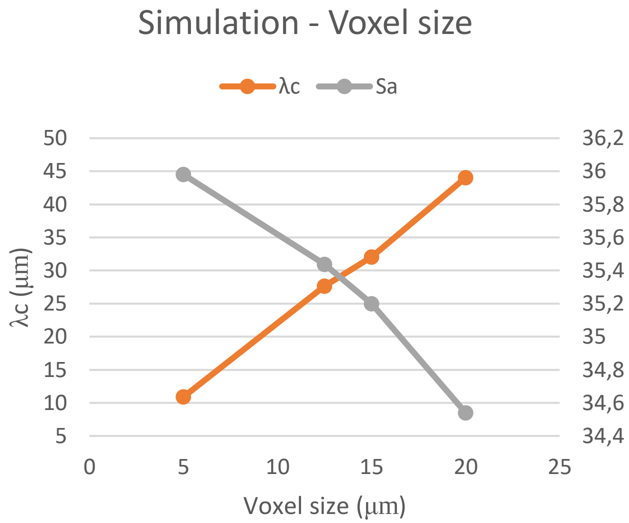
Focal spot size: 15 - 80 µm
Voxel size: 20 µm (fixed)

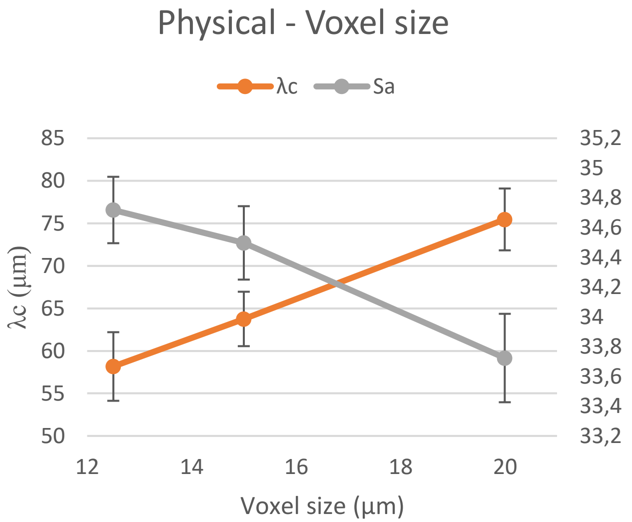
- **Voxel size**

Focal spot size: point
Voxel size: 5 - 20 µm




- A positive relationship between focal spot size & $\lambda_c$
- Simulation: linear relationship
- Physical: non-linear relationship

- A positive relationship between voxel size & $\lambda_c$
- Simulation: linear relationship
- Physical: linear relationship

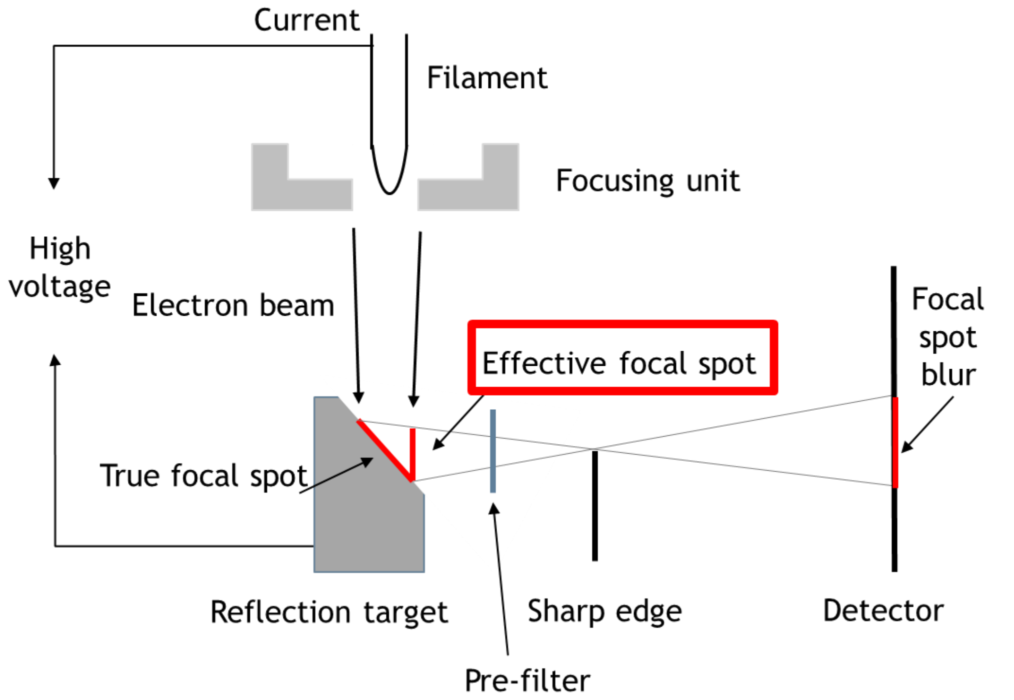
# 3. Improvement of XCT Structural Resolution

## Reconstruction of the focal spot



- **Controlling the focal spot size**

  current, voltage, beam focusing




- **Removing the focal spot blur by deconvolution**

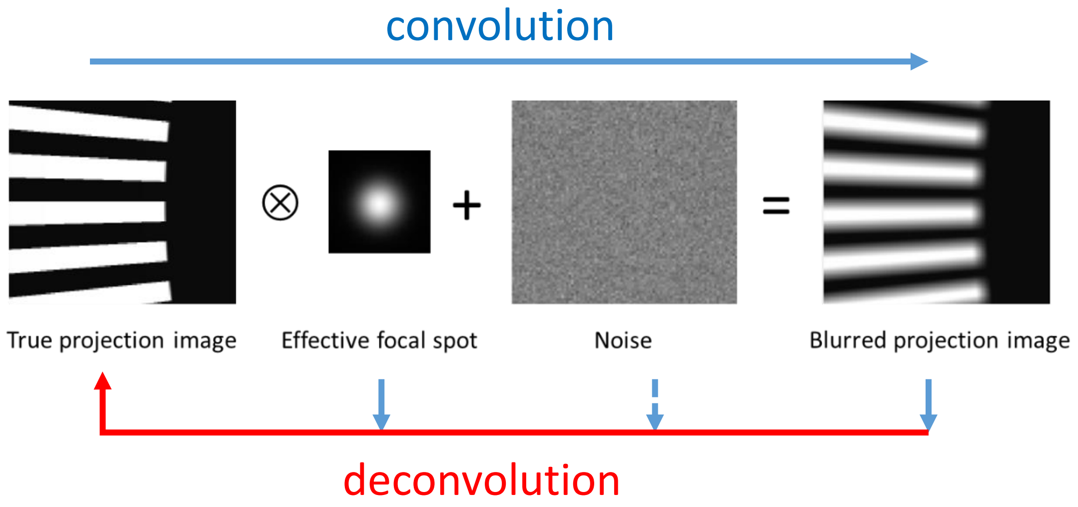



Image restoration performance is affected by:

- Convolution assumption
- Focal spot accuracy and stability
- Noise information

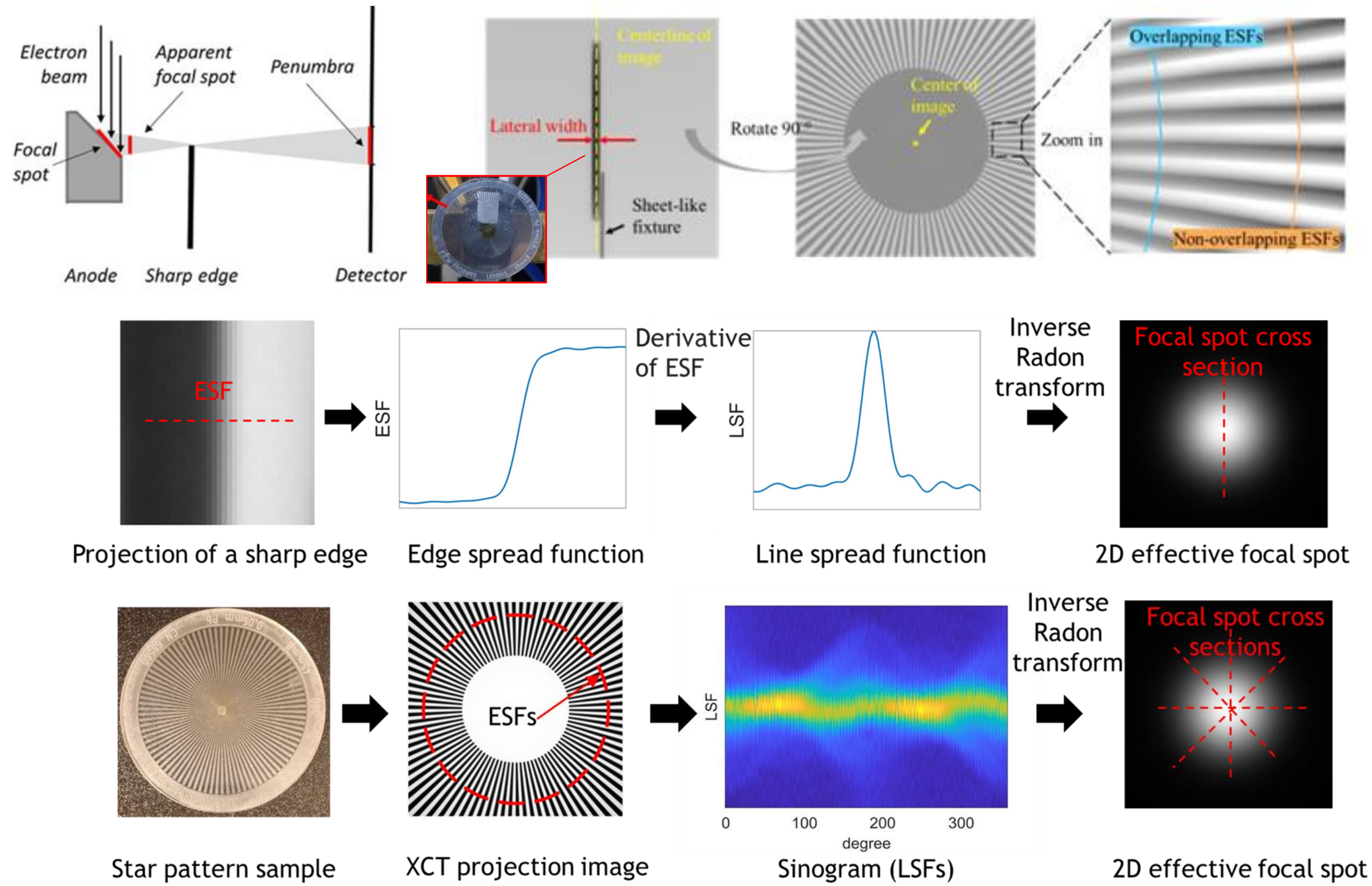
Collaboration work with NPL National Physical Laboratory

# 3. Improvement of XCT Structural Resolution

## Reconstruction of the focal spot



- Focal spot reconstruction




- The focal spot cross section can be reconstructed from the edge spread function (i.e., ESF) of a projected blurred edge with the same orientation.
- A **star pattern phantom** can provide multiple edges with different orientations to reconstruct the 2D (effective) focal spot.
- The **reconstructed focal spot is a blurred (low-resolution) version of the true focal spot**, which is affected by the number of edges and the measurement magnification.

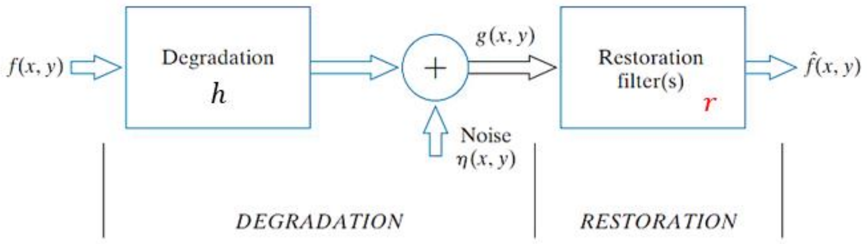
*Ref: Probst et al., Characterization and stability monitoring of X-ray focal spots, CIRP 2020*

**Collaboration work with** NPL National Physical Laboratory

# 3. Improvement of XCT Structural Resolution

## Resolution enhancement via deconvolution





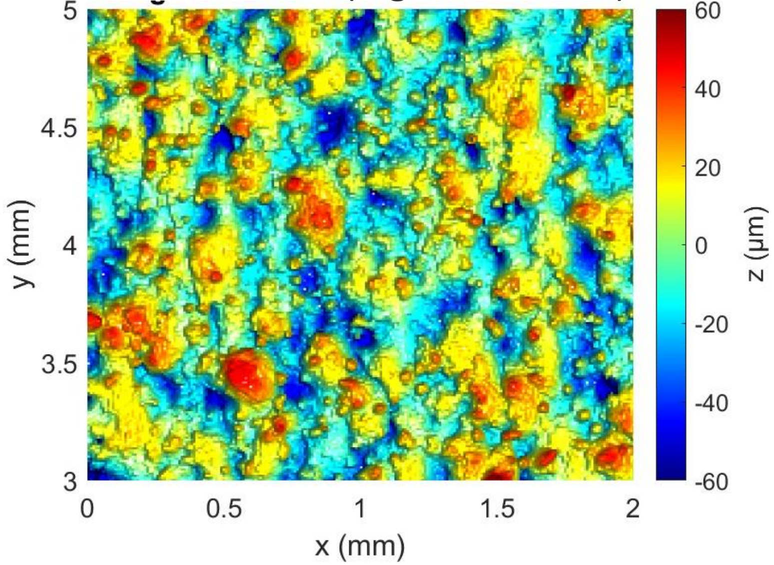

Spatial domain: $g = f * h + n$

Frequency domain: $G = F \cdot H + \mathrm{N}$

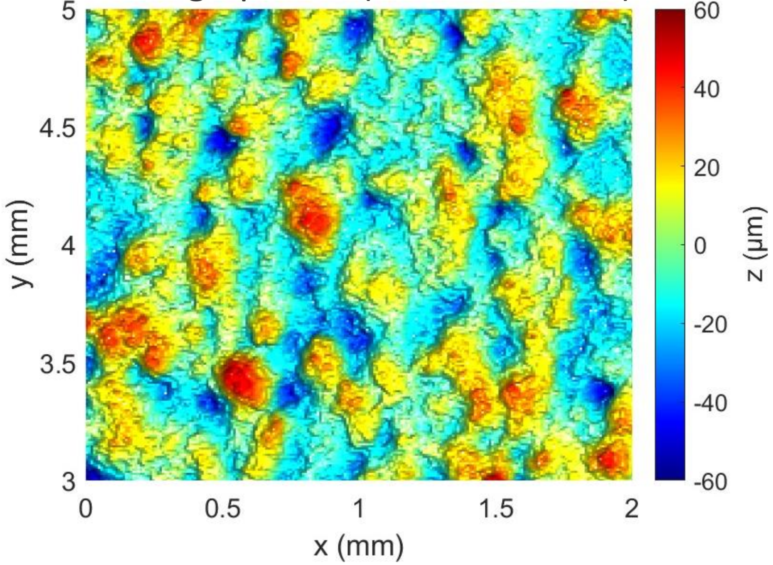
Solution: $\hat{F} = \frac{G}{H} = F + \frac{N}{H}$

| Measurement | Power | Deconvolution methods |
| --- | --- | --- |
| 0 (reference) | low | NA |
| 1 | middle | • Wiener filter<br>• Regularised Wiener filter<br>• Lucy-Richardson iterative deconvolution method |
| 2 | high | |

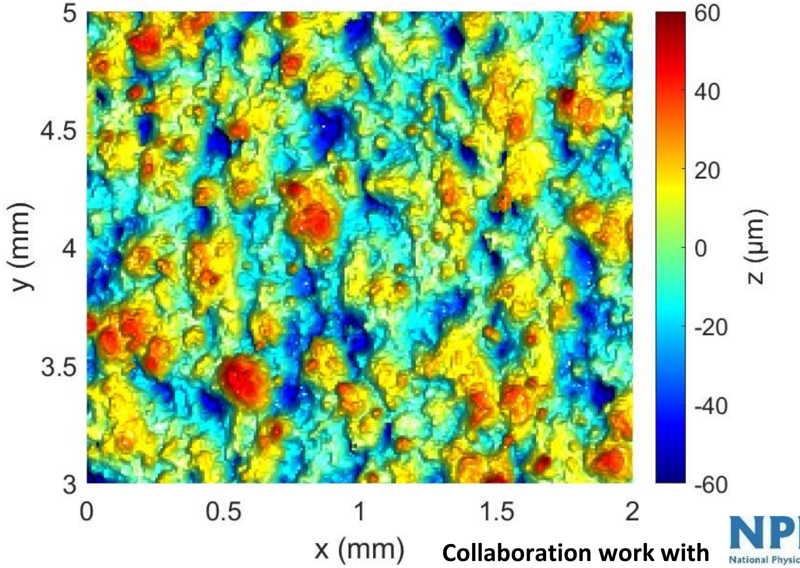
Reference (high resolution)




High power (low resolution)




Restored surface

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# 4. AM surface characterisation using XCT 3D data

## General framework

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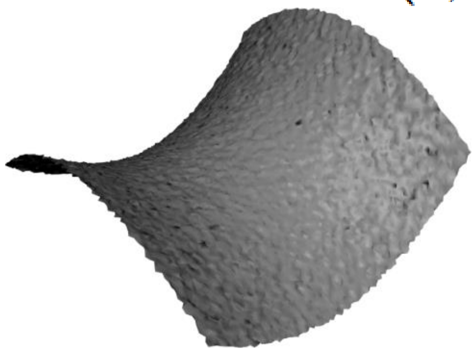
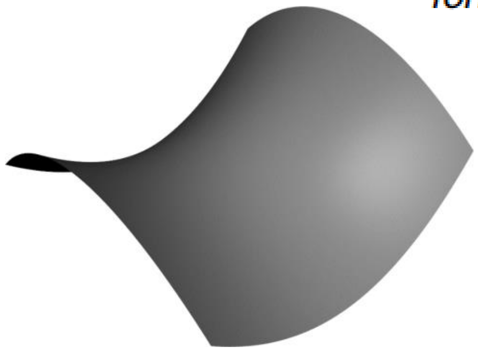
$r(u, v)$



$r_{form}(u, v)$



$r_{sl}(u, v)$

**Stage 1: Measured Surface(sampling and representation)** → **Stage 2: Surface Decomposition and Reconstruction** → **Stage 3: Surface analytics and parameterisation**

### Association

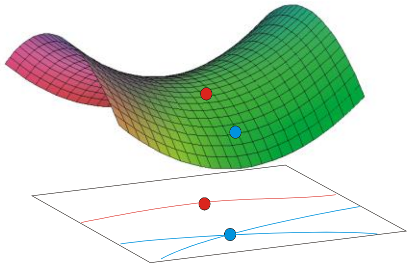
Nominal form is known

- Best fit surface based on the nominal form
- Orthogonal distance
- Usually one that works in two stages: a coarse approximation fit, followed by a more refined optimised fit

### Filtration

Nominal form is unknown

- filtration operator that does not require a reference surface can be used to determine the reference surface
- Morphological;
- Laplacian;
- MCF;
- etc..



A non-Euclidean geometry

- Association

$$\hat{\boldsymbol{\beta}} = arg\ min_{\boldsymbol{\beta}} \sum_{i=1}^{n} \left(\boldsymbol{x}_i - \boldsymbol{f}(\boldsymbol{\beta}, \boldsymbol{x}_i)\right)^2$$

Total Least square

$$\hat{\boldsymbol{\beta}} = arg\ min_{\boldsymbol{\beta}} \sum_{i=1}^{n} w_i \cdot \left(\boldsymbol{x}_i - \boldsymbol{f}(\boldsymbol{\beta}, \boldsymbol{x}_i)\right)^2$$

$$w_i = \frac{1}{k} \sum_{j \in N_i} A_j$$

Weighted Total least square

$$\hat{\boldsymbol{\beta}} = arg\ min_{\boldsymbol{\beta}} \sum_{i=1}^{n} \rho_i \left(w_i \cdot \left(\boldsymbol{x}_i - \boldsymbol{f}(\boldsymbol{\beta}, \boldsymbol{x}_i)\right)^2\right)$$

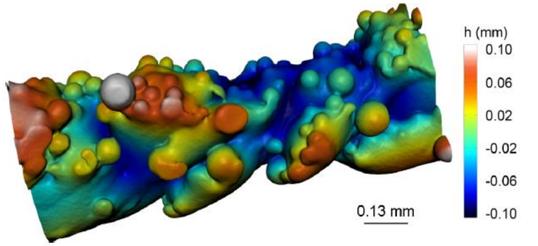
Robust Total least square

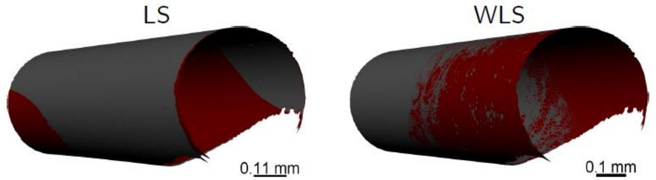
cylinder

$$\min_{r, \boldsymbol{x}_0, \boldsymbol{a}} \sum_{i=1}^{n} w_i \cdot \left[r - \left\|\boldsymbol{x}_i - \boldsymbol{x}_0 + (\boldsymbol{x}_i - \boldsymbol{x}_0) \cdot \boldsymbol{a}\right\|\right]^2.$$

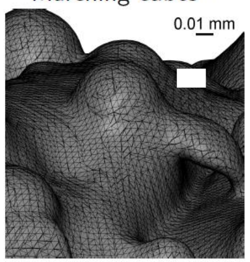
sphere

$$\min_{r, \boldsymbol{x}_0} \sum_{i=1}^{n} w_i \cdot \left(r - \|\boldsymbol{x} - \boldsymbol{x}_0\|\right)^2.$$

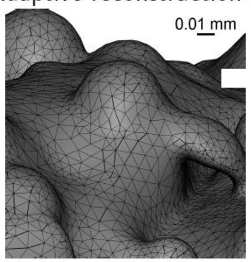



Marching cubes[11]




Adaptive reconstruction[12]




| Fitting method | LS | | WLS | |
|---|---|---|---|---|
| Reconstruction method | MC | AR | MC | AR |
| Radius (μm) | 209.35 | 205.08 | 209.24 | 209.28 |
| Diff (%) | - | 2.08 | - | 0.02 |

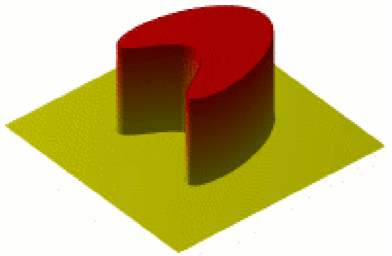
# 4. AM surface characterisation using XCT 3D data

## Surface decomposition - filtration

- Laplacian filtration

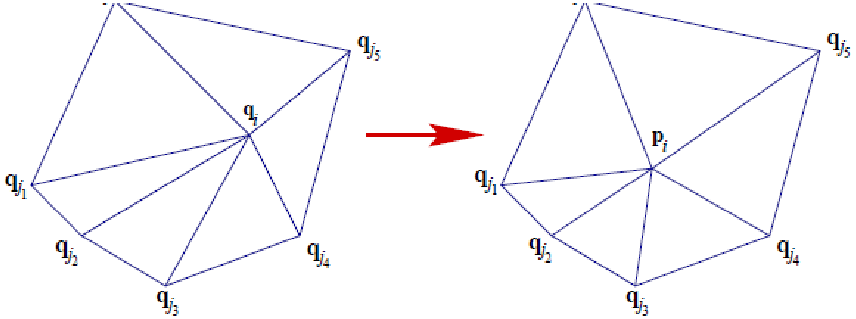
$$\frac{\partial f(p,t)}{\partial t} - \Delta f(p,t) = 0$$

$$t \approx 0.0176\lambda_c^2$$

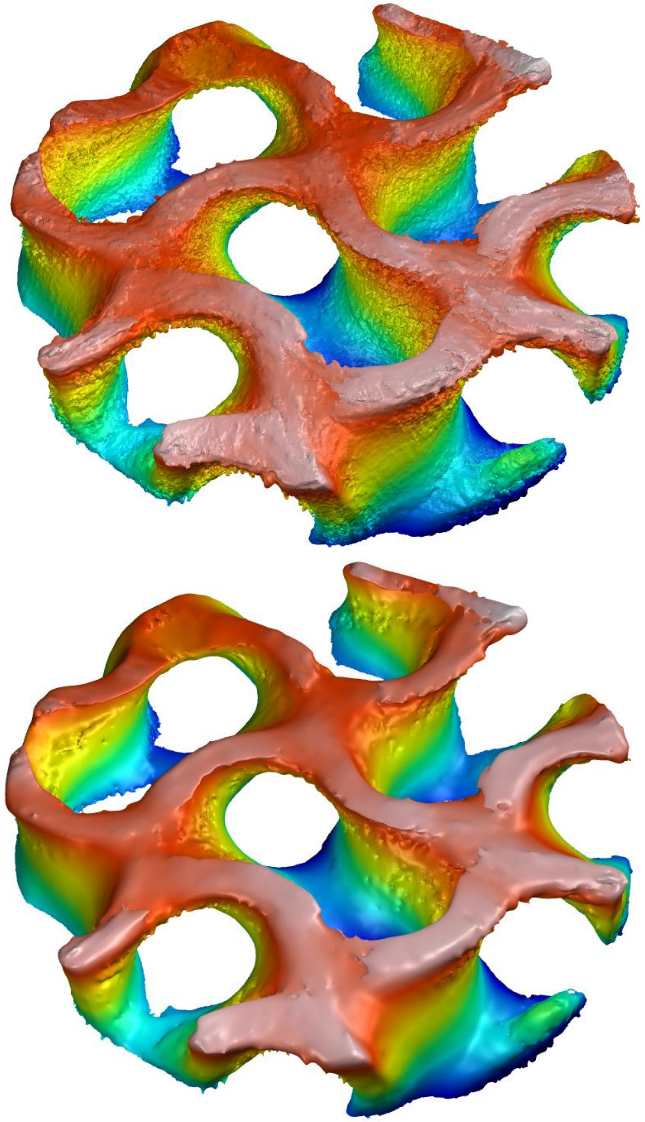


Diffusion time: 0.1126s
Gaussian cutoff wavelength: 0.8 mm

$$\mathbf{p}_i := \begin{cases} \frac{1}{|adj(i)|}\sum_{j\in adj(i)} \mathbf{q}_j, & i \in V_{var}, \\ \mathbf{q}_i, & i \in V_{fix}. \end{cases}$$




Improved LBO using weighted average of the neighborhood vertex, such as Gaussian weighting depends on the triangle area or the edge length.



Advantages:

- Easy to implement;
- Fast;
- Direct link between the LBO and the Gaussian filter

Disadvantages:

- Shrinkage problems;
- Boundary problem;

**Improved LBO diffusion**

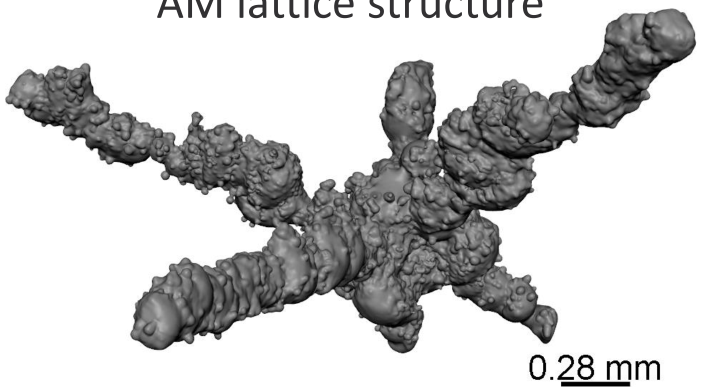
- No shrinkage;
- No boundary problem;
- Meet the requirement for metrology

# 4. AM surface characterisation using XCT 3D data

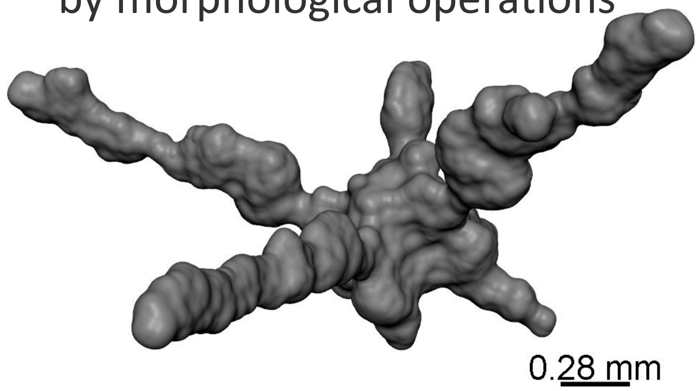
## Surface decomposition – 3D watershed segmentation



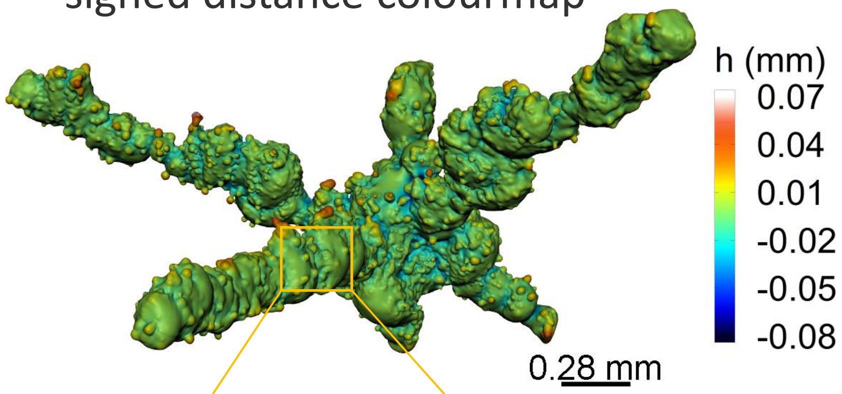
A portion of the measured AM lattice structure

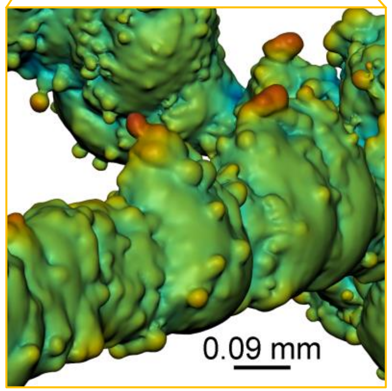



Reference form computed by morphological operations

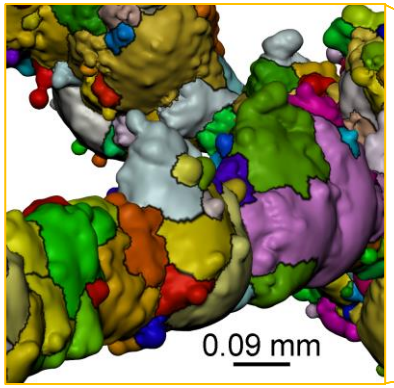


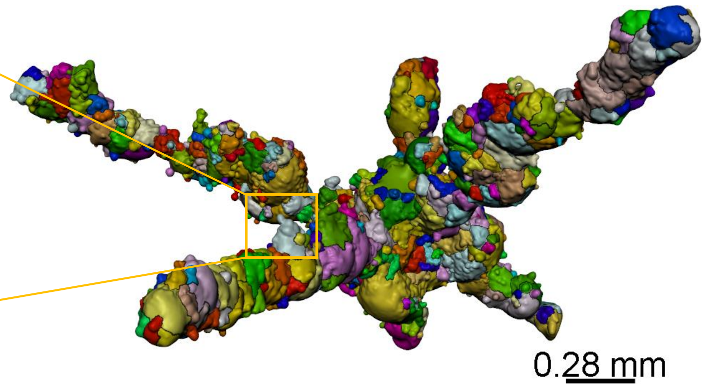

Residuals displayed as the signed distance colourmap




Pit-based watershed



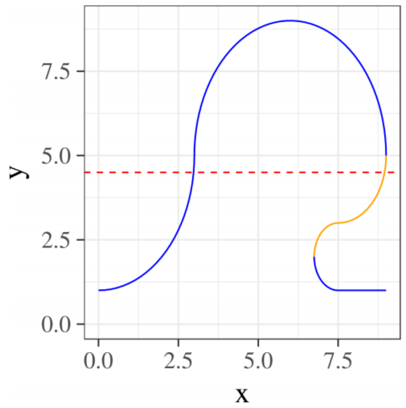

L. Pagani, W. Zeng, S, Lou, F. Blateyron, X. Jiang, P. J. Scott 2019 A characterization framework for freeform surfaces, *22nd Met&Props*, Lyon, France.
S. Lou, L. Pagani, W. Zeng, X. Jiang, P. J. Scott 2020 Watershed segmentation of topographical features on 3D freeform surfaces and its application to additively manufactured surfaces, *Precision Engineering*, 63 177-186.

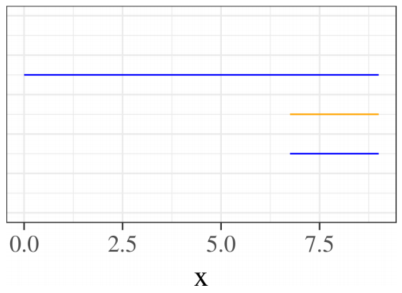
# 4. AM surface characterisation using XCT 3D data

## 3D Surface texture parameters to address AM re-entrance

- 3D height parameters

| | ISO 25178-2[2] | | Proposed[3] |
|---|---|---|---|
| A | $(x_1 - x_0) \cdot (y_1 - y_0)$ | $\rightarrow$ | $\iint_{\Sigma_{form}} d\sigma_{form}$ |
| Sa | $\frac{1}{A} \int_{x_0}^{x_1} \int_{y_0}^{y_1} \lvert z(x,y)\rvert \, dx\, dy$ | $\rightarrow$ | $\frac{1}{A} \iint_{\Sigma_{form}} \lvert \mathbf{r}_{sl}(u,v) \cdot \mathbf{n}_{form}(u,v)\rvert \, d\sigma_{form}$ |
| Sq | $\sqrt{\frac{1}{A} \int_{x_0}^{x_1} \int_{y_0}^{y_1} z^2(x,y)\, dx\, dy}$ | $\rightarrow$ | $\sqrt{\frac{1}{A} \iint_{\Sigma_{form}} (\mathbf{r}_{sl}(u,v) \cdot \mathbf{n}_{form}(u,v))^2 \, d\sigma_{form}}$ |
| Ssk | $\frac{1}{A\, Sq^3} \int_{x_0}^{x_1} \int_{y_0}^{y_1} z^3(x,y)\, dx\, dy$ | $\rightarrow$ | $\frac{1}{A\, Sq^3} \iint_{\Sigma_{form}} (\mathbf{r}_{sl}(u,v) \cdot \mathbf{n}_{form}(u,v))^3 \, d\sigma_{form}$ |
| Sku | $\frac{1}{A\, Sq^4} \int_{x_0}^{x_1} \int_{y_0}^{y_1} z^4(x,y)\, dx\, dy$ | $\rightarrow$ | $\frac{1}{A\, Sq^4} \iint_{\Sigma_{form}} (\mathbf{r}_{sl}(u,v) \cdot \mathbf{n}_{form}(u,v))^4 \, d\sigma_{form}$ |
| Sp | $\lvert \max_{x,y} z(x,y)\rvert$ | $\rightarrow$ | $\lvert \max_{u,v} \mathbf{r}_{sl}(u,v) \cdot \mathbf{n}_{form}(u,v)\rvert$ |
| Sv | $\lvert \min_{x,y} z(x,y)\rvert$ | $\rightarrow$ | $\lvert \min_{u,v} \mathbf{r}_{sl}(u,v) \cdot \mathbf{n}_{form}(u,v)\rvert$ |
| Sz | $\max_{x,y} z(x,y) - \min_{x,y} z(x,y)$ | $\rightarrow$ | $\max_{u,v} \mathbf{r}_{sl}(u,v) \cdot \mathbf{n}_{form}(u,v) - \min_{u,v} \mathbf{r}_{sl}(u,v) \cdot \mathbf{n}_{form}(u,v)$ |




- 3D hybrid parameters

$$Sdq = \sqrt{\frac{1}{A_{form}} \iint_{\Sigma_{form}} \left\| \boldsymbol{J}_{form} \left( \boldsymbol{G}_{form}^{-1} \right)^{-1} \nabla_U r_{sl}(u,v) \right\| \, d\sigma_{form}}$$

$$Sdr = \frac{A - A_{form}}{A_{form}}$$

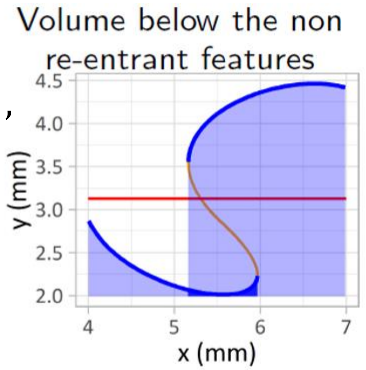
$$Srf = \frac{A_{form} - A_{shadow}}{2 \cdot A_{shadow}}$$

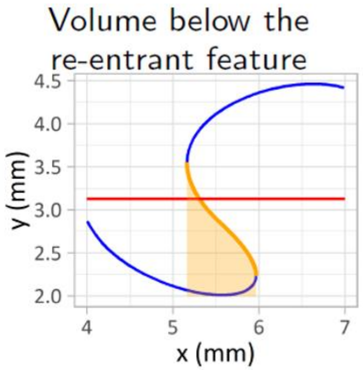
- 3D volume parameters

$$Vm(p) = \frac{h_{max} - h_{min}}{A_{max}} \int_p^1 f_V(h^\star)\, dh^\star ,$$

$$Vv(p) = \frac{h_{max} - h_{min}}{A_{max}} \int_0^p f_{V,max} - f_V(h^\star)\, dh^\star ,$$

$$Vmp = Vm(p) - Vm(1)$$
$$Vmc = Vm(q) - Vm(p),$$
$$Vvc = Vv(q) - Vv(p)$$
$$Vvv = Vv(p) - Vv(0)$$

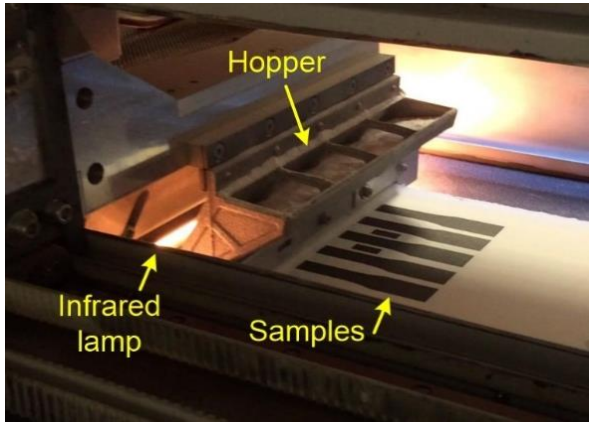


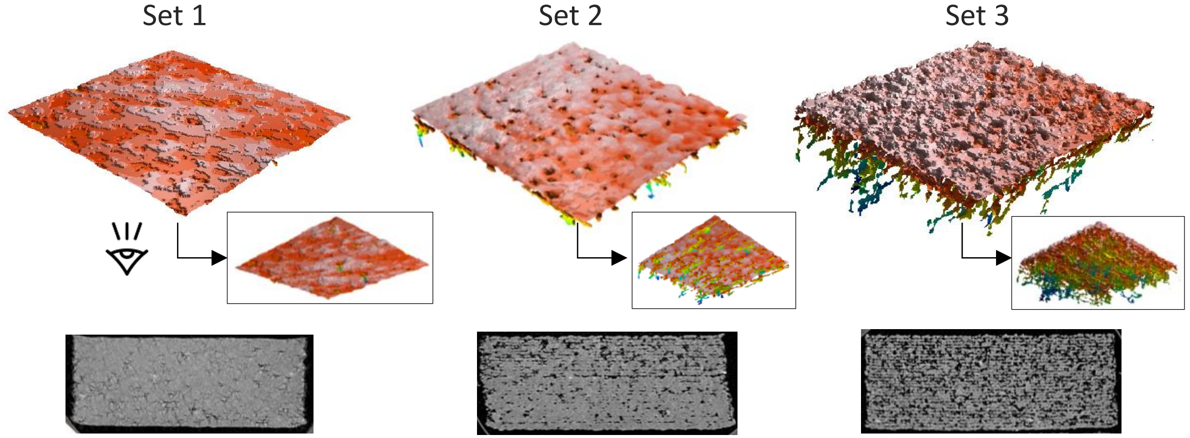




L. Pagani, et al. Towards a new definition of areal surface texture parameters on freeform surface, *Measurement*, 109, 2017, 281-291.
L. Pagani, A. Townsend, W. Zeng, S. Lou, L. Blunt, X. Jiang, P. J. Scott 2019 Towards a new definition of areal surface texture parameters on freeform surface: Re-entrant features and functional parameters, *Measurement* , 141: 442-459.

# Case Study 1: Characterisation of High Speed Sintering Surface Topography with Re-entrant Open Surface Pores

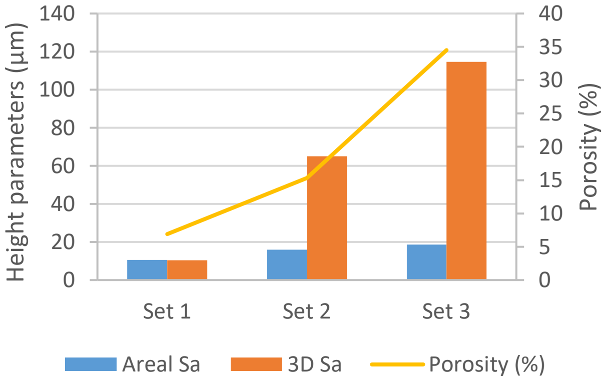
The Future Metrology Hub



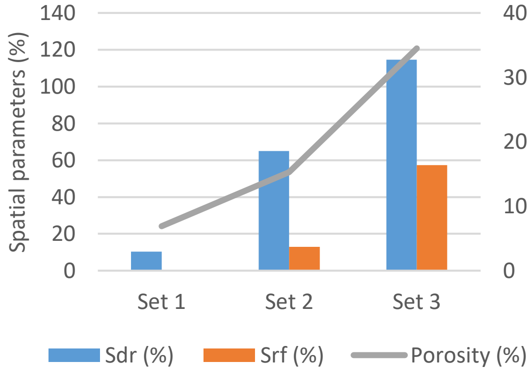

## 3D height parameters

| Set No. | Set 1 | Set 2 | Set 3 |
|---|---|---|---|
| Areal Sa (μm) | 10.5 | 16.0 | 18.6 |
| 3D Sa (μm) | 10.4 | 65.0 | 114.6 |
| Porosity (%) | 6.9 | 15.3 | 34.5 |

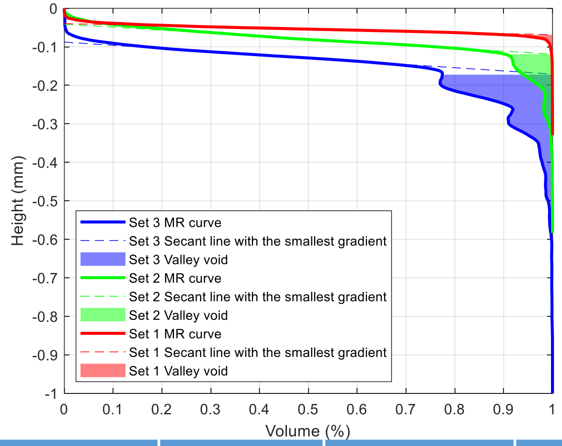



## 3D spatial parameters

| Set No. | Set 1 | Set 2 | Set 3 |
|---|---|---|---|
| Sdq | 2.4 | 4.5 | 4.9 |
| Sdr (%) | 8.9 | 61.3 | 130.9 |
| Srf (%) | 0.5 | 12.9 | 57.4 |




## 3D volume parameters – re-entrant open surface pores

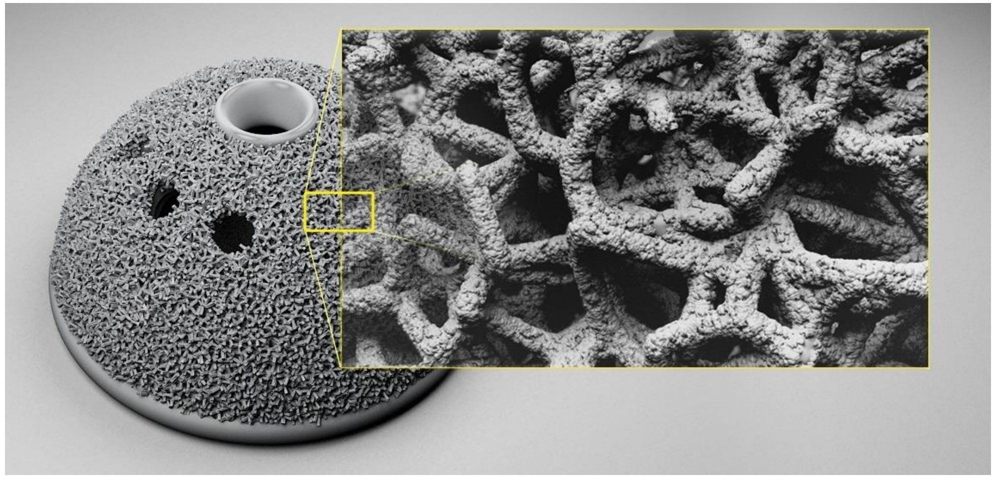



| Set No. | Set 1 | Set 2 | Set 3 |
|---|---|---|---|
| $Mr2$ (%) | 90.1% | 90.2% | 77.4% |
| $Vvv$ (mm³/mm) | 2.2x10$^{-7}$ | 3.8 x10$^{-6}$ | 7.5x10$^{-5}$ |

S. Lou, Z. Zhu, W. Zeng, C. Majewski, P. J. Scott, X. Jiang 2021 Material ratio curve of 3D surface topography of additively manufactured parts: an attempt to characterise open surface pores, *Surface Topography: Metrology and Properties*, 9: 015029

# Case Study 2: Surface Measurement and Characterisation of Metallic Acetabular Cup



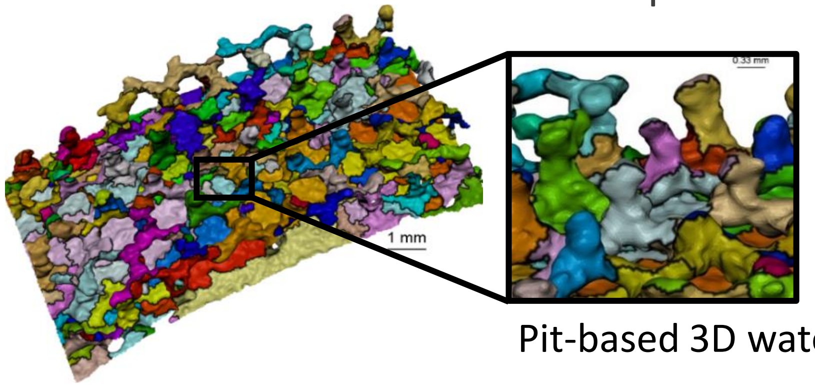


- **Fatal challenge**: impossible to define the surface roughness of the porous structures accurately because of their 3D character
- **Controversy**: post-processing VS as-built
- *Ra* < 24.9 μm positive effect, *Ra* > 56.9 μm negative
- Too much high surface peaks: inhibit cell-cell interactions & hinder cell proliferation; dense pits can favour cell proliferation: cells prefer lying the concave pits (minimise energy expenditure)

3D height parameters

| Patch No. | 1 | 2 | 3 | 4 | Mean | STD |
|---|---|---|---|---|---|---|
| Sa (μm) | 5.94 | 5.71 | 5.61 | 5.73 | 5.75 | 0.14 |
| Sq (μm) | 10.77 | 10.33 | 9.94 | 11.62 | 10.67 | 0.72 |
| Ssk | 4.29 | 4.22 | 3.84 | 6.99 | 4.84 | 1.45 |
| Sku | 32.26 | 31.89 | 24.92 | 94.83 | 45.98 | 32.74 |

3D feature parameters




Pit-based 3D watershed segmentation

$$Spd = \frac{\#\, peaks}{A}$$

$$Svd = \frac{\#\, valleys}{A}$$

| Patch No. | 1 | 2 | 3 | 4 | Mean | STD |
|---|---|---|---|---|---|---|
| Spd (1/mm²) | 0.22 | 0.24 | 0.23 | 0.23 | 0.23 | 0.01 |
| Svd (1/mm²) | 0.97 | 1.18 | 1.08 | 1.10 | 1.08 | 0.09 |

S. Lou, L. Pagani, W. Zeng, M. Ghori, X. Jiang, P. J. Scott 2019 Surface Texture Evaluation of Additively Manufactured Metallic Cellular Scaffolds for Acetabular Implants Using X-ray Computed Tomography, *Bio Design and Manufacturing*, 2(2): 55-64.

# 5. Summary

The Future Metrology Hub

- The metrological structural resolution of XCT limits its effectiveness for surface texture measurement.
- For metal AM surface texture measurement, XCT focal spot size is a significant source of blurring; MTF can characterise this blurring.
- Applying deconvolution with the reconstructed focal spot can enhance XCT structural resolution.
- 3D surface texture parameters can maximise the advantage of 3D data from XCT scan, particularly useful to address the unique characteristics of AM surfaces.
- Overall, XCT proves to be a capable non-destructive metrology tool for measuring and analysing the multi-scale geometries of AM functional components, especially those with intricate shapes.

# Thank you

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University of HUDDERSFIELD