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Quantitative surface texture data extraction from X-ray CT scans of additively manufactured parts

Andrew Townsend and Jefferson Cuadra

September 12, 2018

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An EPSRC Future Manufacturing Research Hub

UNIVERSITY OF BATH

Loughborough University

NPL National Physical Laboratory

The University Of Sheffield.

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The Future Metrology Hub

Nationally funded centre of excellence in advanced metrology. One of eight UK EPSRC Future Manufacturing Research Hubs. Based at the University of Huddersfield's Centre for Precision Technologies, with an international reputation in precision engineering, metrology research and standards development.

Key areas of research are:

- Additive Manufacturing
- Software Development
- Hardware Applications
- Surface Measurement & Applications
- Ultra Precision Manufacturing
- Industrial Metrology

Outline

- Application industries
- Importance of areal AM surface texture measurement: Function!
- Scale-of-interest: Function and filtering!
- Areal surface texture data extraction from X-ray CT
- CT-STARR Stage 1 - an interlaboratory comparison
- Automation of the measurement and characterisation process
- Factors affecting the accuracy of CT surface measurements
- CT measurement of re-entrant surfaces
- Surface-specific AM artefacts
- Conclusions and future work

“Previous life”: Aerospace quality

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Aerospace – and medical

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GE buys AM machine manufacturers Arcam and Concept Laser, 2016

Manufacturing: leadership in additive

CONCEPTLASER

- **Location:** Germany
- **Revenue 2016:** ~$100M
- **Products:** Metal Additive machines (Laser technology)
- **Industries:** Aerospace, Medical, Auto, Jewelry

CAD TO METAL arcam Arcam AB

- **Location:** Sweden
- **Revenue 2016:** ~$70MM[-a)]
- **Products:** Metal Additive machines (Electron Beam technology)
- **Industries:** Aerospace, Medical, Auto, Tooling

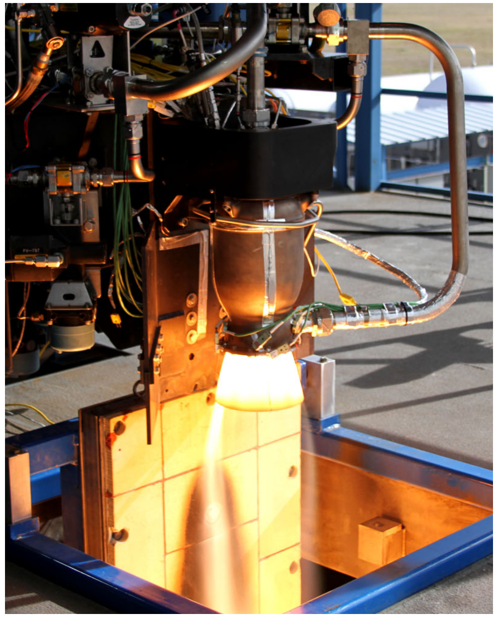
Leverage GE investments

Productivity
- Machine technology
- Additive repairs
- Analytics & Control

Materials
- Process modelling
- Powder recovery/reuse
- Material science

Digital
- Brilliant factory

Harnessing the GE Store
- ✓ Global Research Centers
- ✓ GE Digital
- ✓ Additive Development Centers
- ✓ Additive Production Facilities
- ✓ GE Advanced Manufacturing Works



SPACEX

SuperDraco Engine Chamber, 2014

Printing the chamber resulted in an order of magnitude reduction in lead-time compared with traditional machining – the path from the initial concept to the first hotfire was just over three months.

Pratt & Whitney
A United Technologies Company

Pratt and Whitney and University of Connecticut Additive Manufacturing Innovation Centre, 2013

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Importance of areal surface texture measurement for additive manufacturing

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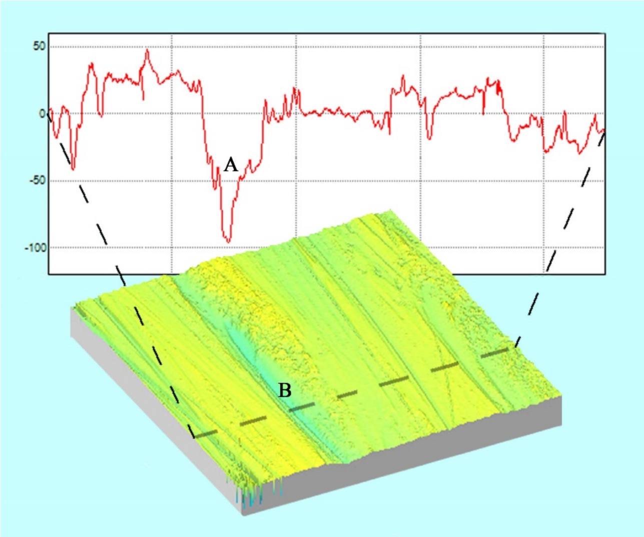
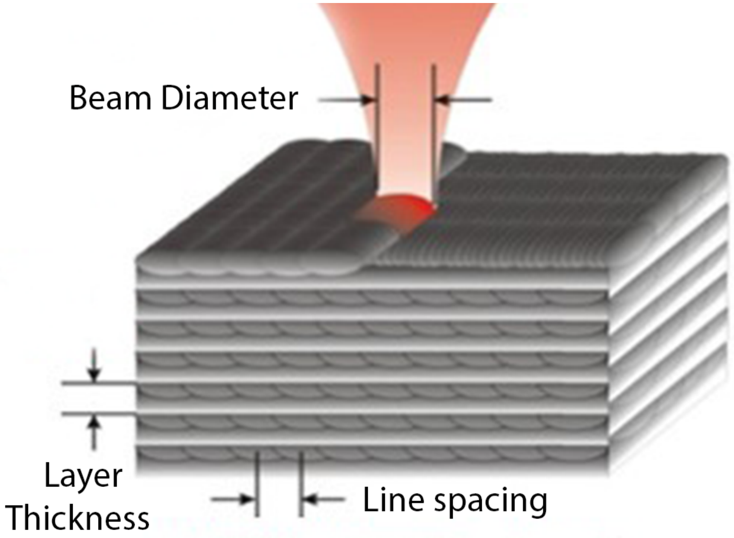


Profile vs areal: pit or valley?



- Cube 10 mm per side
- 100 µm build layer thickness
- 100 µm line spacing

Approximate percentage of total surface area produced *during* the manufacturing process remaining as outside surface on completion: 3%

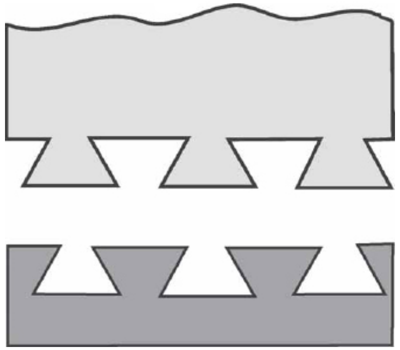
Defects embedded?
Surface irregularities magnified?
Process changing?

Function:

- Coating adhesion
- Electrical conduction
- Heat transfer
- Bio-integration
- Fatigue resistance

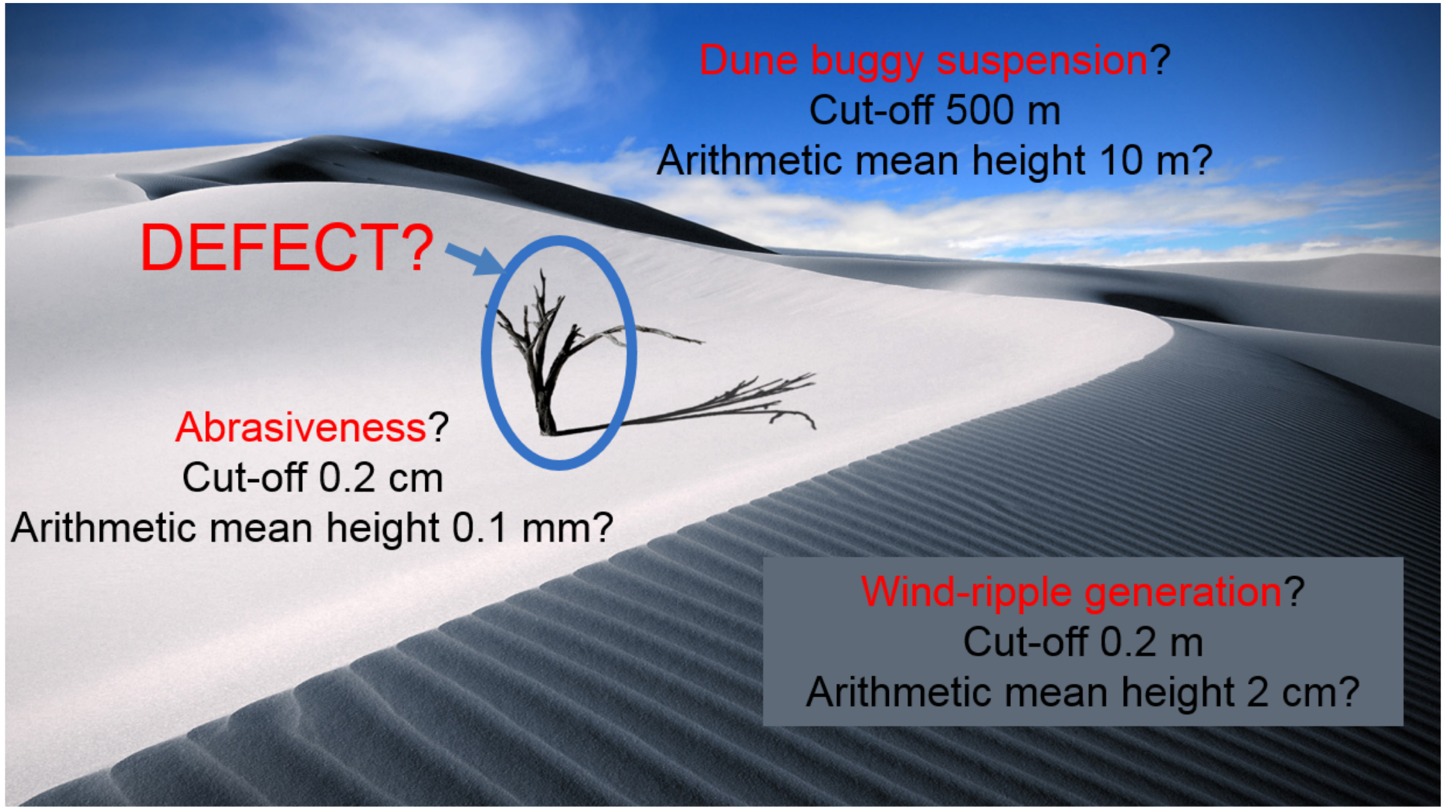
Re-entrant features:

- Locking function
- Larger specific surface area



Furniture tool marks and altered joints confuse age. Fred Taylor. https://www.realorrepro.com/article/Furniture-made-to-fool

Scale-of-interest: function and filtering

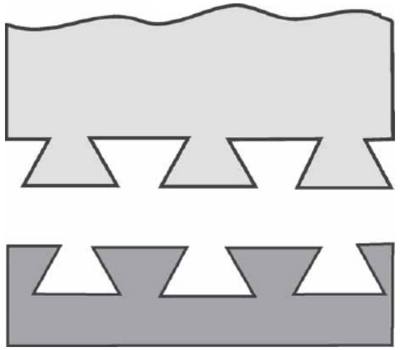


Function:

- Coating adhesion
- Electrical conduction
- Heat transfer
- Bio-integration

Re-entrant features:

- Locking function
- Larger specific surface area



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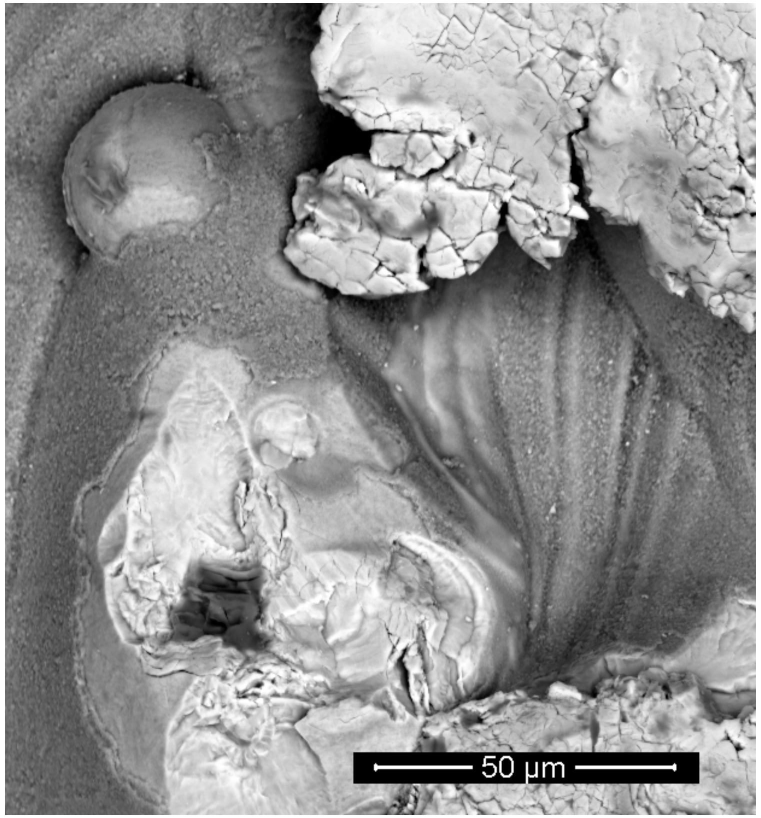
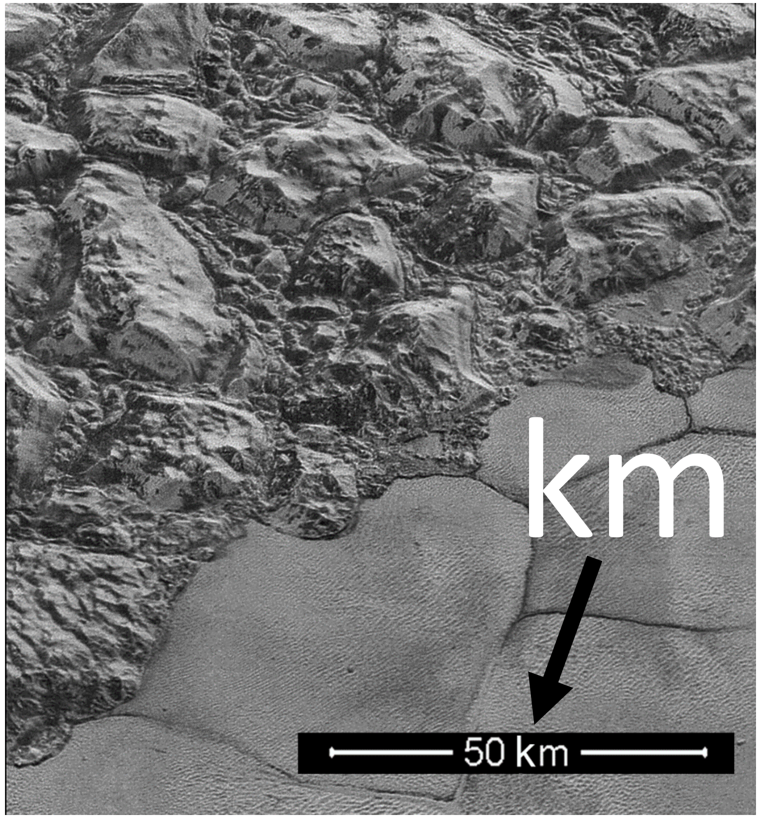
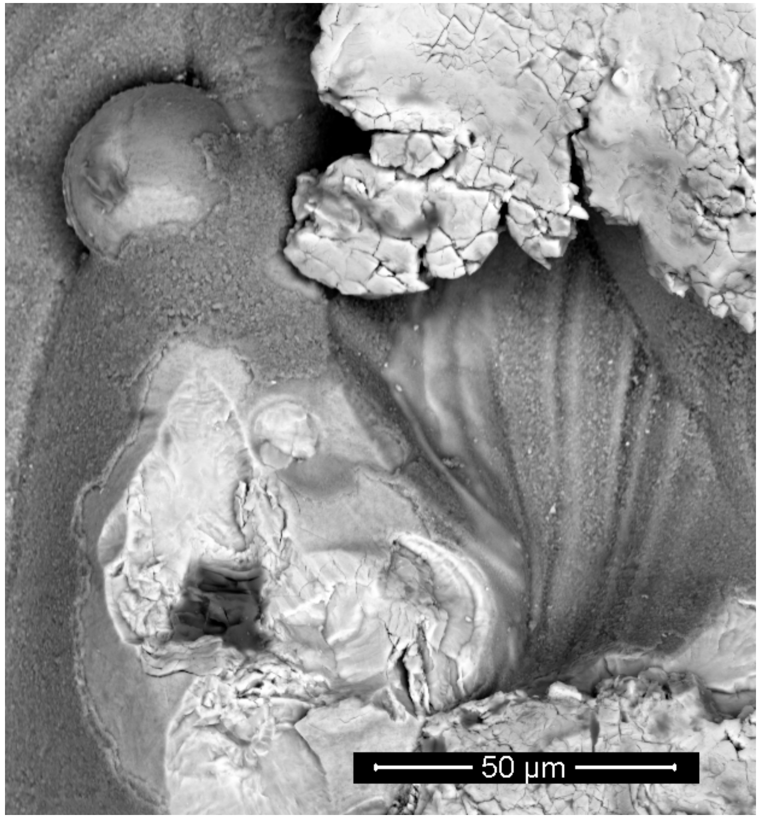
Scale-of-interest: function and filtering



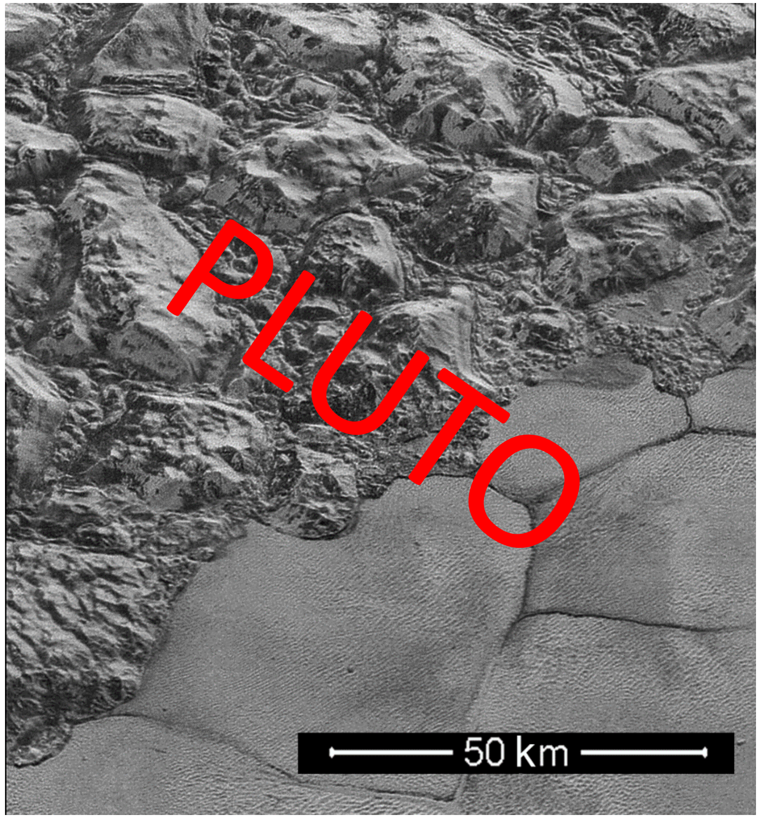


Scale-of-interest: function and filtering

1 : 1,000,000,000

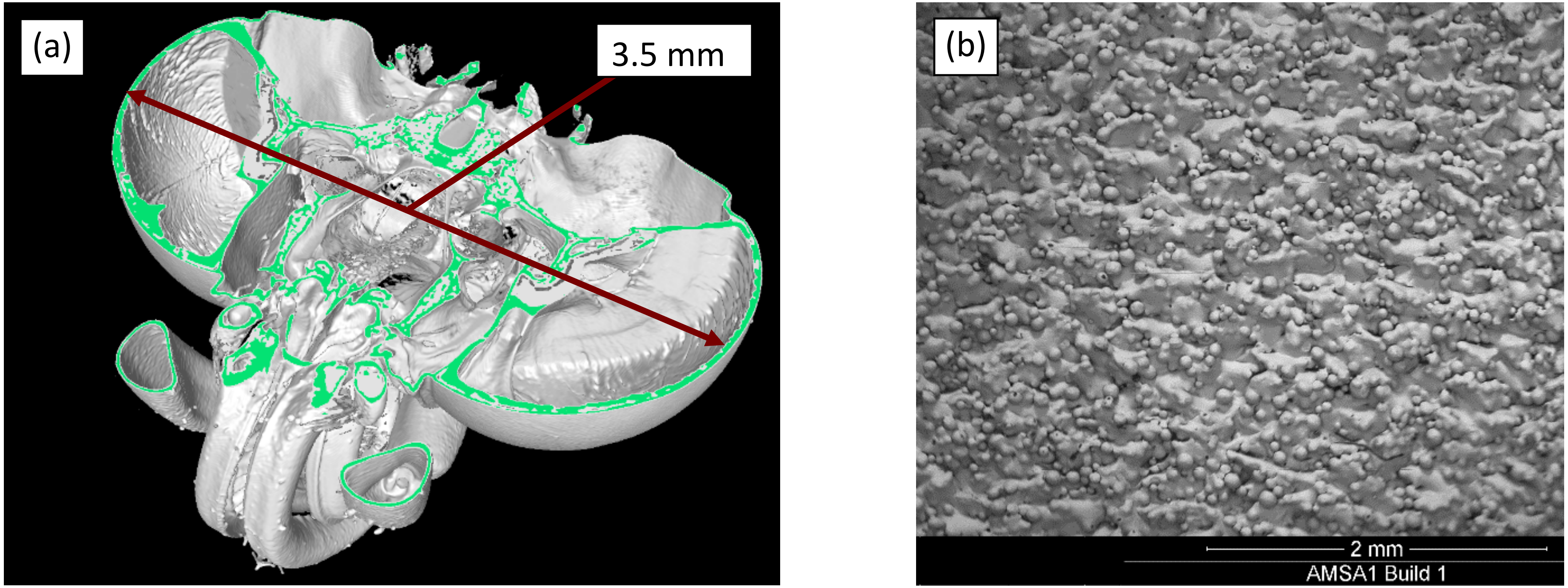


SEM image Ti6Al4V



New Horizons mission
NASA/JHUAPL/SwRI

X-ray CT for powder bed fusion AM surfaces? Internal surfaces?



Moth eye and AM surface (both imaged using a Nikon XT H 225 commercial CT system)

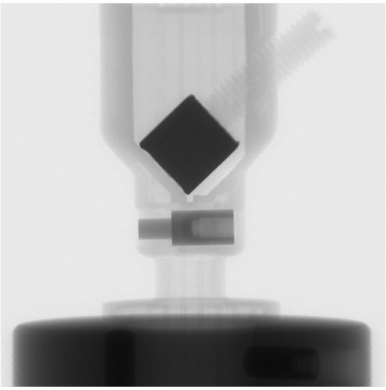
(a) Head of Hofmannophila pseudospretella, sectioned in VGStudio MAX 3.0. Voxel size 7.5 µm

(b) SEM image of an EBM AM as-built side surface (similar scale)

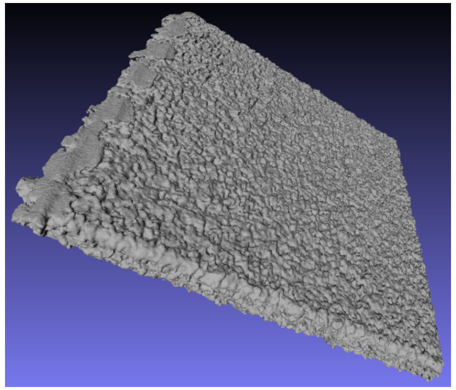
Quantitative surface texture from CT

FILENAME:	NPL MCT225 Ti6Al4V ELI 1
CUTOFF LENGTH:	X=(0.025---8)mm, Y=(0.025---8)mm
AMPLITUDE PARAMETERS	
Sq(um)	32.615
Ssk	0.213
Sku	3.632
Sp(um)	197.418
Sv(um)	138.296
Sz(um)	335.713
SPACING PARAMETERS	
Sds(1/mm^2)	85.922
Str	0.779
Sal(mm)	0.117
HYBRID PARAMETERS	
Sdq	1.027
Ssc(1/um)	0.05
Sdr(%)	43.681
CURVES PARAMETERS	
Vmp(um^3/mm^2)	1.90E+06
Vmc(um^3/mm^2)	2.86E+07
Vvc(um^3/mm^2)	3.85E+07
Vvv(um^3/mm^2)	3.52E+06
SK FAMILY	
Spk(um)	39.453
Sk(um)	82.578
Svk(um)	30.271
Smr1(%)	9.6
Smr2(%)	90.3
OTHER PARAMETERS	
Std(deg)	0
S5z(um)	299.609
Sa(um)	25.588

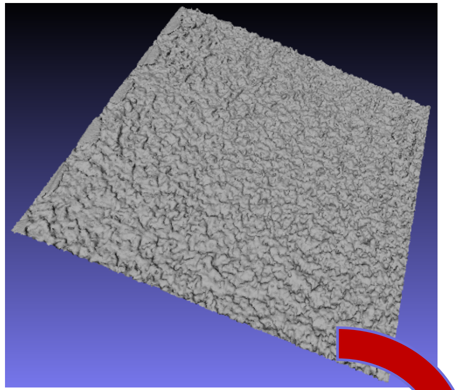
CT acquisition



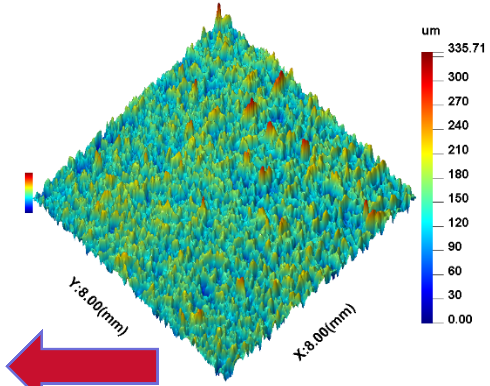
Generate volume data



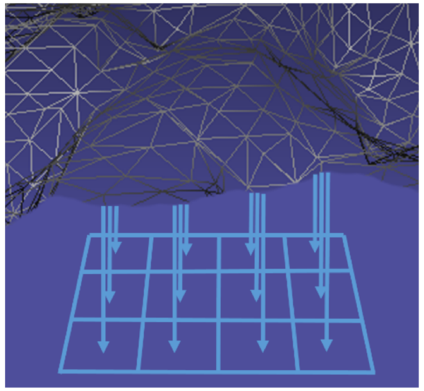
Extract surface section



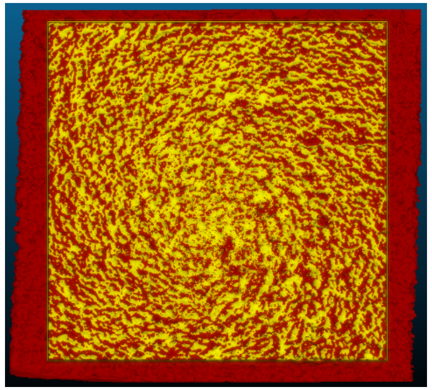
Crop and clean mesh



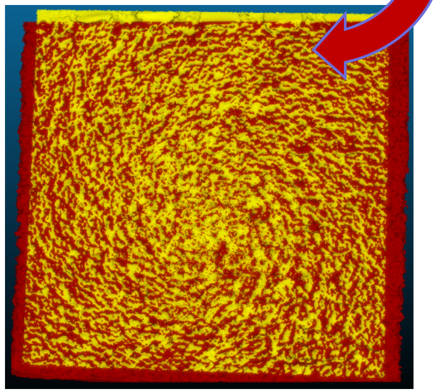
Filter per ISO 25178-3. Generate parameters per ISO 25178-2



Remove non-visible surfaces, convert mesh to height map and crop to final size



Crop mesh



Align with master (e.g. Alicona G4)

Innovate UK funded surface-from-CT project

mtc Manufacturing Technology Centre

SYNOPSYS® Silicon to Software™

Nikon
NIKON METROLOGY
VISION BEYOND PRECISION

HiETA technologies

Innovate UK
Knowledge Transfer Network

University of HUDDERSFIELD

CT-STARR Stage 1 Surface-from-CT interlaboratory comparison

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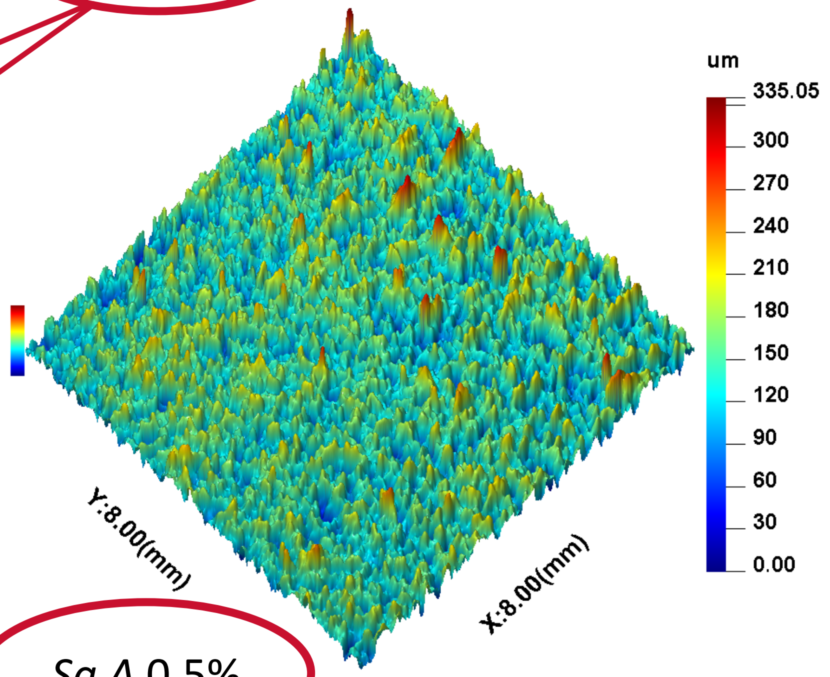
Laboratory	CT machine
University of Huddersfield	Nikon XT H 225
University of Nottingham	Nikon MCT225
National Physical Laboratory	Nikon MCT225
Nikon Metrology	Nikon MCT225

FILENAME:	Alicona G4 Ti6Al4V ELI 1	NPL MCT225 Ti6Al4V ELI 1
CUTOFF LENGTH:	X=(0.025---8)mm, Y=(0.025---8)mm	X=(0.025---8)mm, Y=(0.025---8)mm
AMPLITUDE PARAMETERS		
Sq(um)	32.565	32.615
Ssk	0.256	0.213
Sku	3.749	3.632
Sp(um)	196.482	197.418
Sv(um)	138.57	138.296
Sz(um)	335.053	335.713
SPACING PARAMETERS		
Sds(1/mm^2)	37.469	85.922
Str	0.791	0.779
Sal(mm)	0.121	0.117
HYBRID PARAMETERS		
Sdq	1.001	1.027
Ssc(1/um)	0.021	0.05
Sdr(%)	40.207	43.681
CURVES PARAMETERS		
Vmp(um^3/mm^2)	1.94E+06	1.90E+06
Vmc(um^3/mm^2)	2.83E+07	2.86E+07
Vvc(um^3/mm^2)	3.86E+07	3.85E+07
Vvv(um^3/mm^2)	3.49E+06	3.52E+06
SK FAMILY		
Spk(um)	40.165	39.453
Sk(um)	81.649	82.578
Svk(um)	30.213	30.271
Smr1(%)	10	9.6
Smr2(%)	90.5	90.3
OTHER PARAMETERS		
Std(deg)	0	0
S5z(um)	296.09	299.603
Sa(um)	25.455	25.588

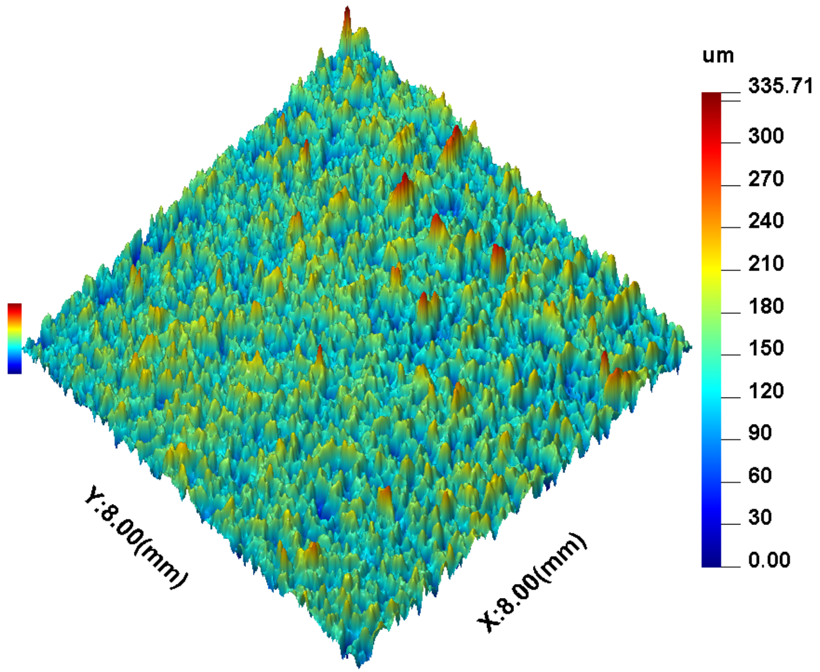
Sz Δ 0.2%

Sa Δ 0.5%

After filtering per ISO 25178-3
L-filter nesting index (hi-pass) 8 mm
S-filter nesting index (low-pass) 0.025 mm



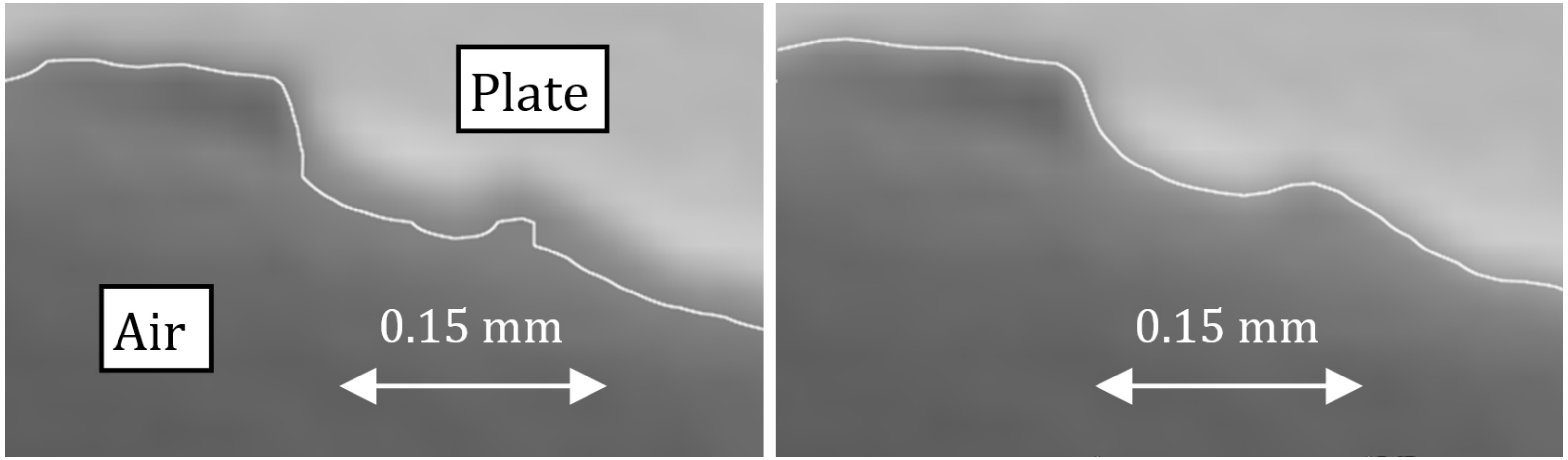
Alicona G4 focus variation
False color height map
Ti6Al4V ELI EBM side surface



Nikon MCT225
Voxel size 8.7 µm
False color height map
Ti6Al4V ELI EBM side surface

Where is the surface?

- Surface determination defines boundary between background (usually air) and surface
- Based on the volume grey-scale values



ISO 50 surface determination | Local iterative surface determination

Rubert Microsurf 334 casting plate, 50 µm nominal *Ra* (VGStudioMAX 2.2)

Factors affecting the accuracy of Surface-from-CT
Surface determination (thresholding)

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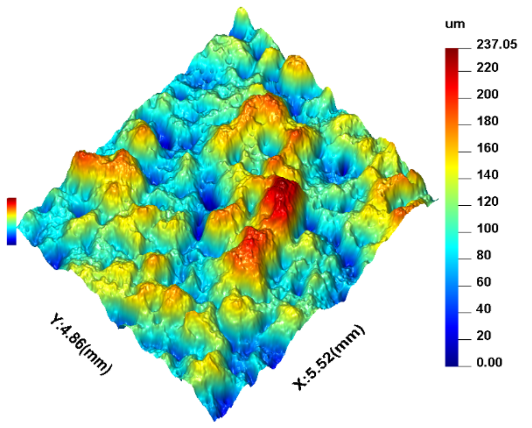
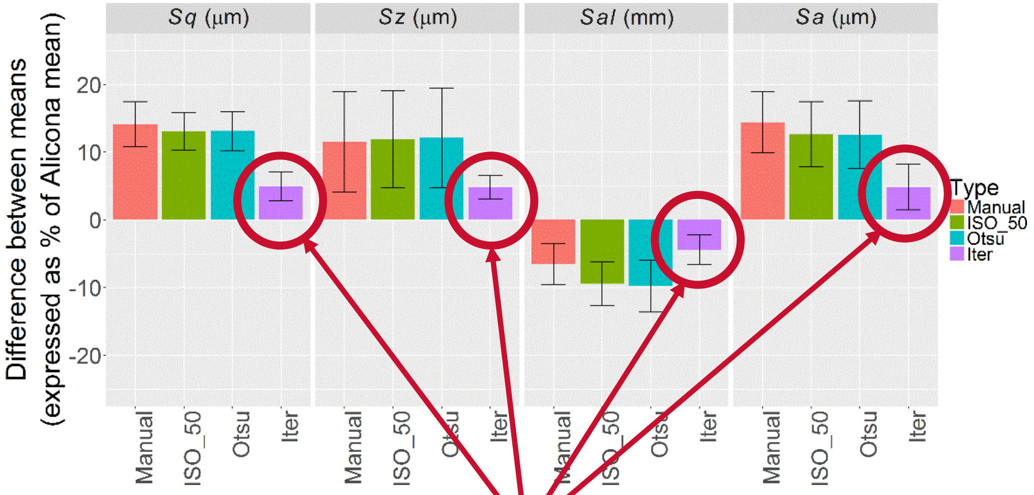
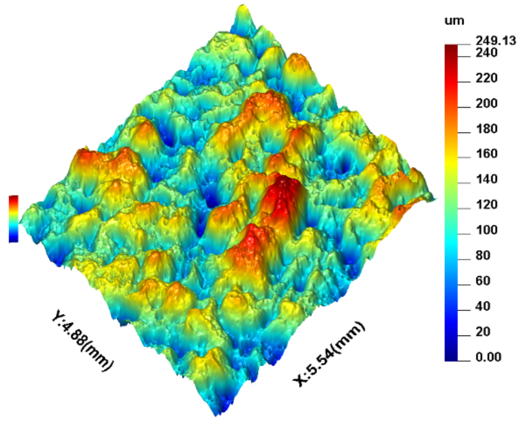
25 µm nominal *Ra* Rubert plate



Alicona G4



Local iterative (VGStudio MAX 2.2)

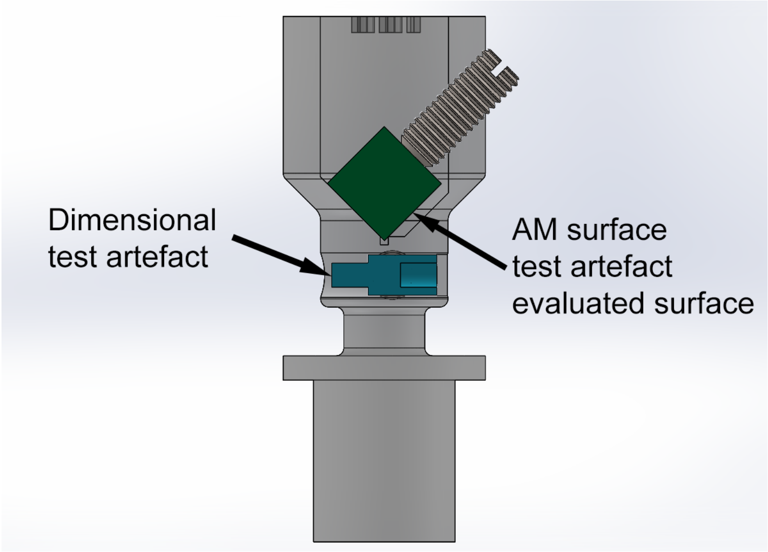


Nikon XT H 225 CT
Voxel size 12.9 µm
(iterative surface determination)

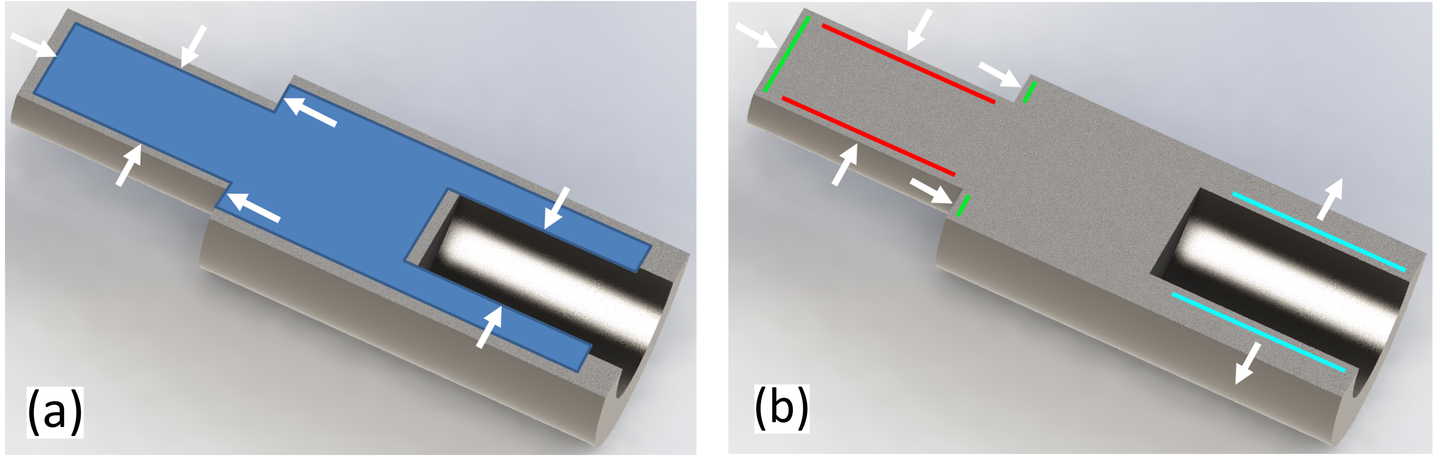
Parameter (ISO 25178-2)	Alicona mean value
Sq	34.5 µm
Sz	239 µm
Sal	0.37 mm
Sa	27.3 µm

Filtering per ISO 25178-3
L-filter nesting index (hi-pass) 5 mm
S-filter nesting index (low-pass) 0.020 mm

Dimensional artefact



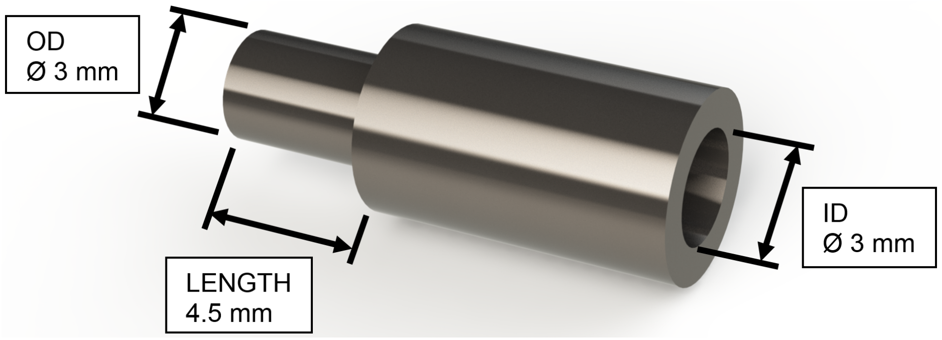
Rendering of artefacts within the ABS fixture



(a) Correction for the CT voxels being oversize
(b) Correction for surface determination computing the surface with excess material

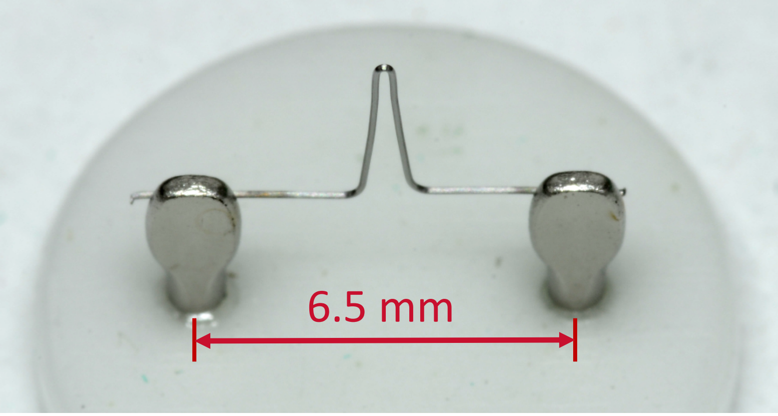
Feature	CMM mean (mm)	As measured XT H 225 (mm) [% dif. wrt CMM]	After correcting for the 0.54% global scaling error (mm) [% dif. wrt CMM]	After global scaling and surface determination correction (mm) [% dif. wrt CMM]
Length	4.6240	4.5992 **[-0.54%]**	4.6240 **[0.00%]**	4.6240 **[0.00%]**
OD	2.9735	2.9655 **[-0.27%]**	2.9815 **[+0.27%]**	2.9730 **[-0.02%]**
ID	2.9846	2.9597 **[-0.83%]**	2.9757 **[-0.30%]**	2.9841 **[-0.02%]**

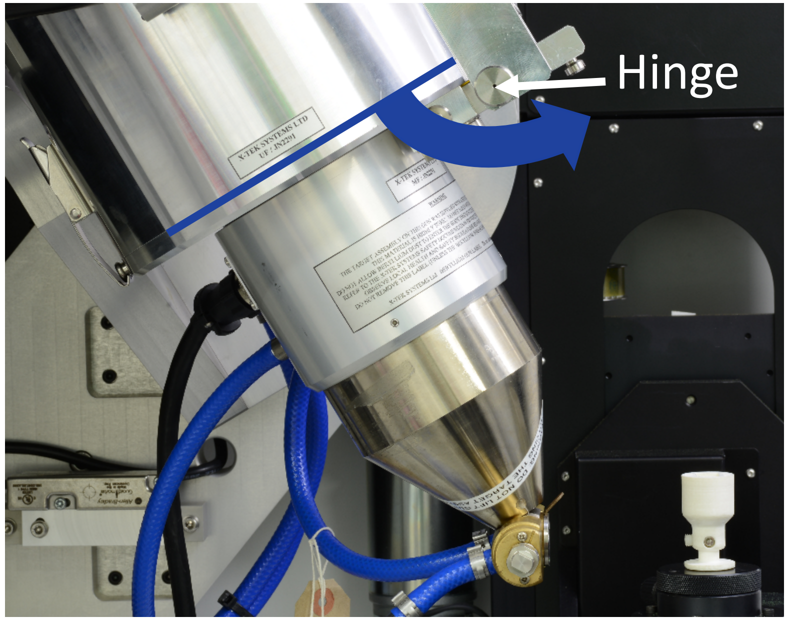
Accuracy improvement from two-stage correction



Rendering of the dimensional artefact

Factors affecting the accuracy of Surface-from-CT
CT electron generation filament replacement





- Typical filament life 20 – 100+ hours
- 10 mm x 10 mm AlSi10Mg Selective Laser Melting (SLM) cube
- Ten Alicona G4 measurements
- Five CT measurements pre filament change
- Five CT measurements post filament change
- Five CT measurements moving the stage between measurements
- All CT parameter settings the same for each measurement set
- Voxel size 17.3 µm
- Areal surface texture data per ISO 25178-2 extracted

Factors affecting the accuracy of Surface-from-CT
CT electron generation filament replacement

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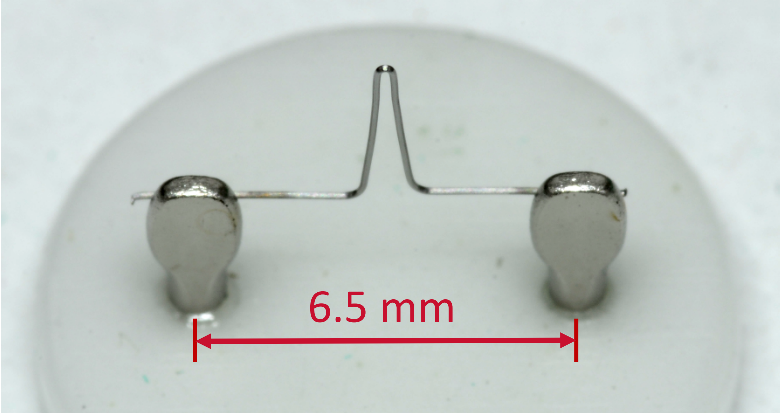
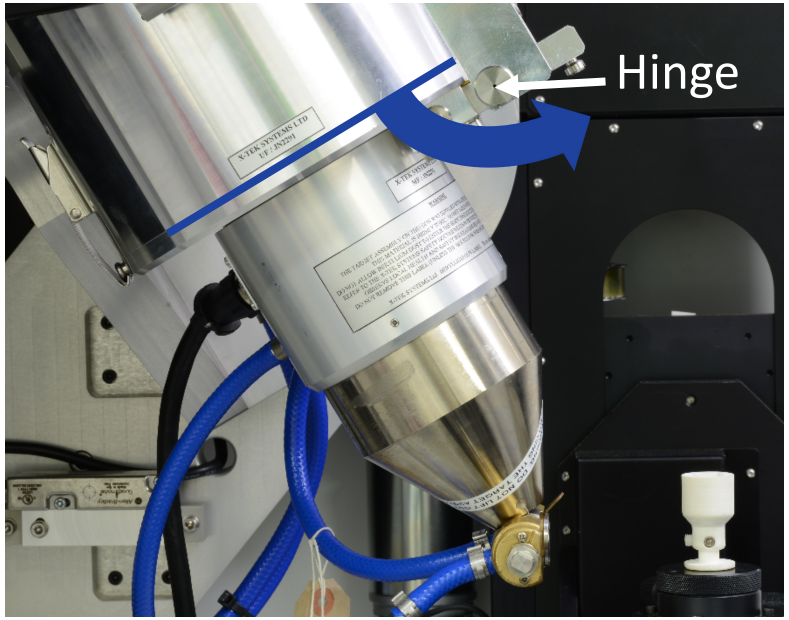
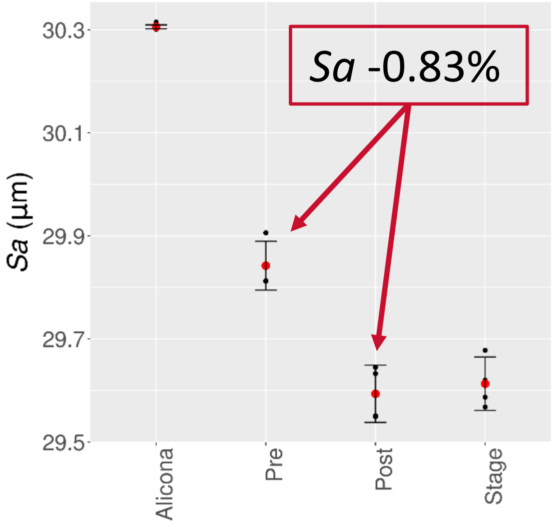
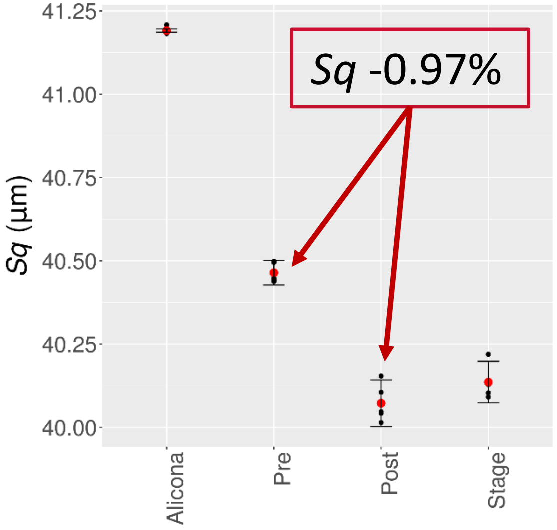








Filtering per ISO 25178-3
L-filter nesting index (hi-pass) 8 mm
S-filter nesting index (low-pass) 0.025 mm

Parameters per ISO 25178-2
95% confidence interval shown

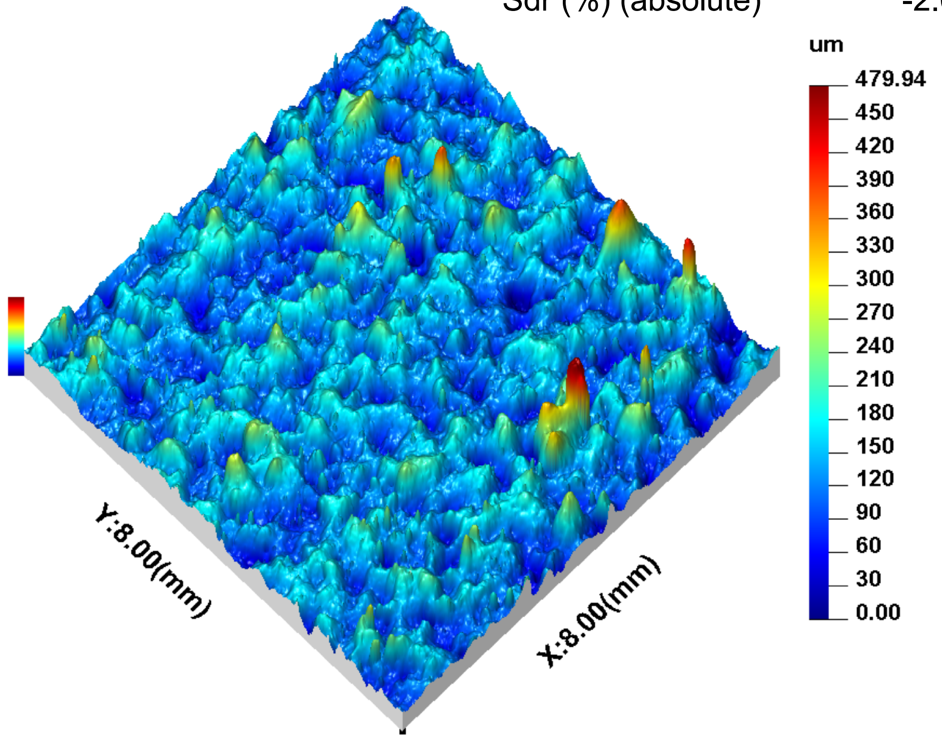
Zeiss Xradia 510 Versa
Working towards RR Stage 2

AlSi10Mg top surface
Renishaw AM250 SLM system

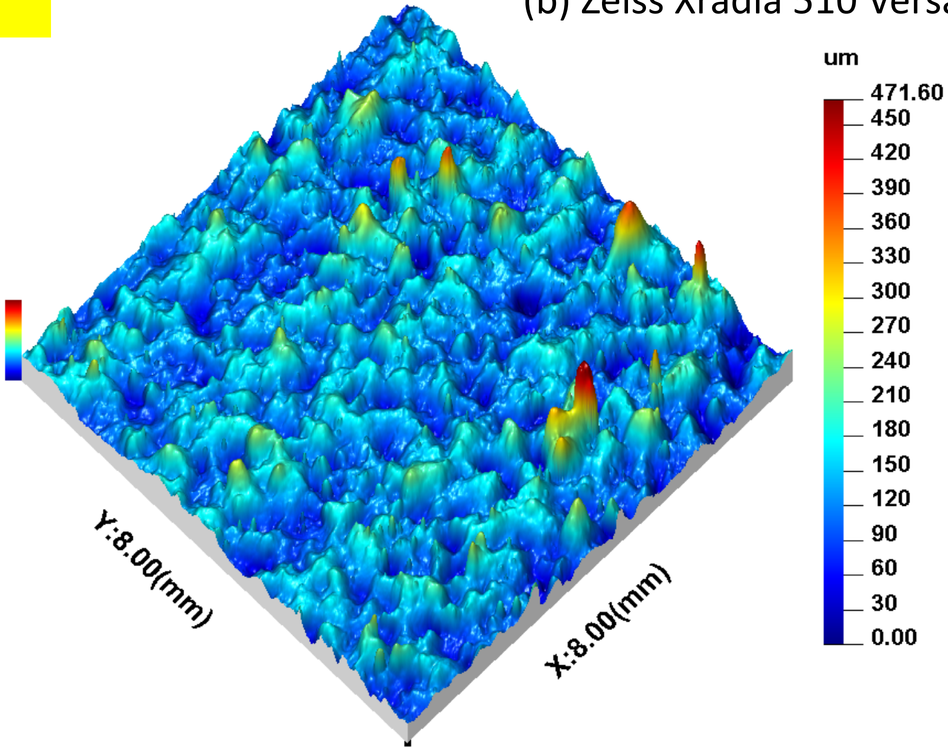
Filtering per ISO 25178-3
L-filter nesting index 8 mm
S-filter nesting index 0.025 mm

Parameter	% Difference between mean CT value and mean FV value			
	XT H 225			Xradia 510
	Pre	Post	Stage	
Sa / µm	-1.5	-2.3	-2.4	-1.3
Sq / µm	-1.8	-2.7	-2.7	-1.6
Sz / µm	-0.1	-1.0	-1.5	-1.7
Ssk (absolute)	-0.1	-0.1	-0.1	0.0
Sku	-2.7	-3.4	-3.3	-2.7
Sdr (%) (absolute)	-2.6	-2.8	-3.1	-3.4

(a) Alicona G4



(b) Zeiss Xradia 510 Versa



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Factors affecting the accuracy of Surface-from-CT
Scan voxel size. Nikon XT H 225 CT.

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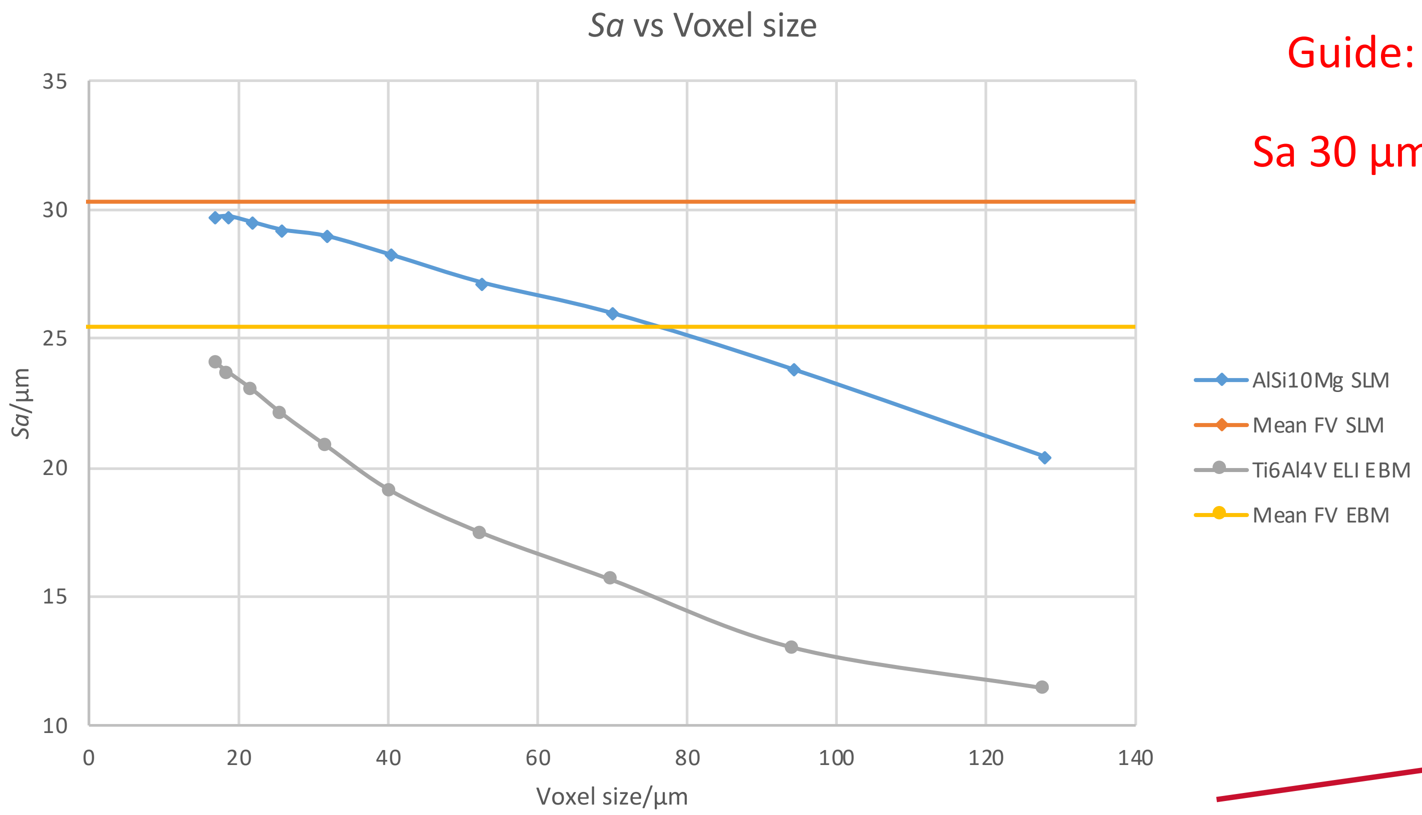
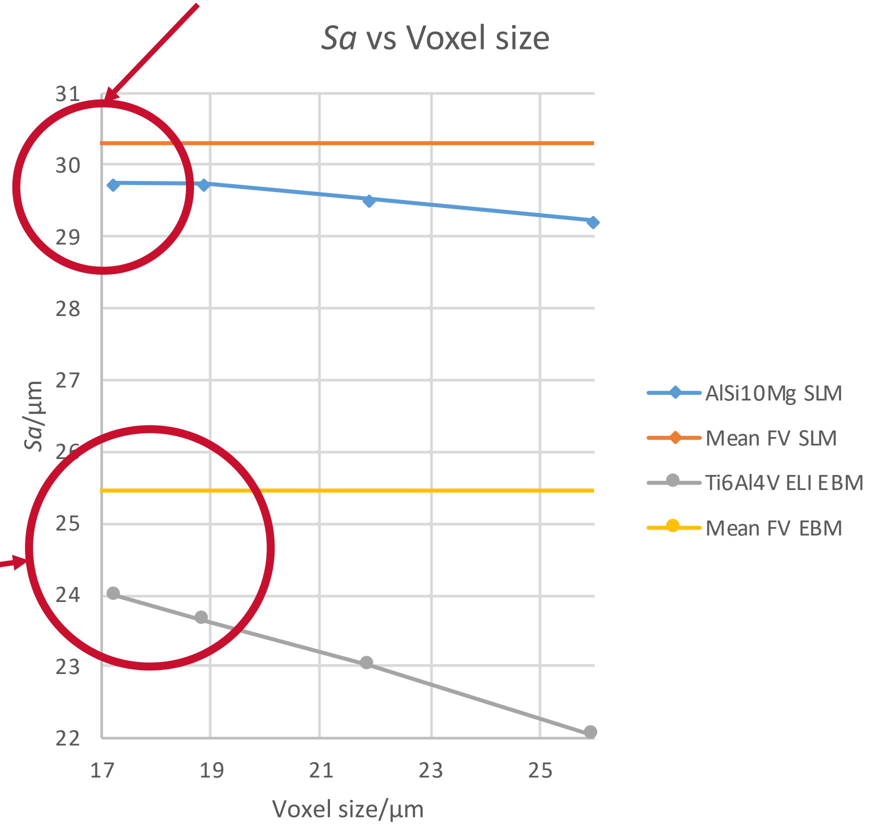


Guide: maximum voxel size half the *Sa* value?

Sa 30 µm Voxel size 17 µm and below OK (line flat)



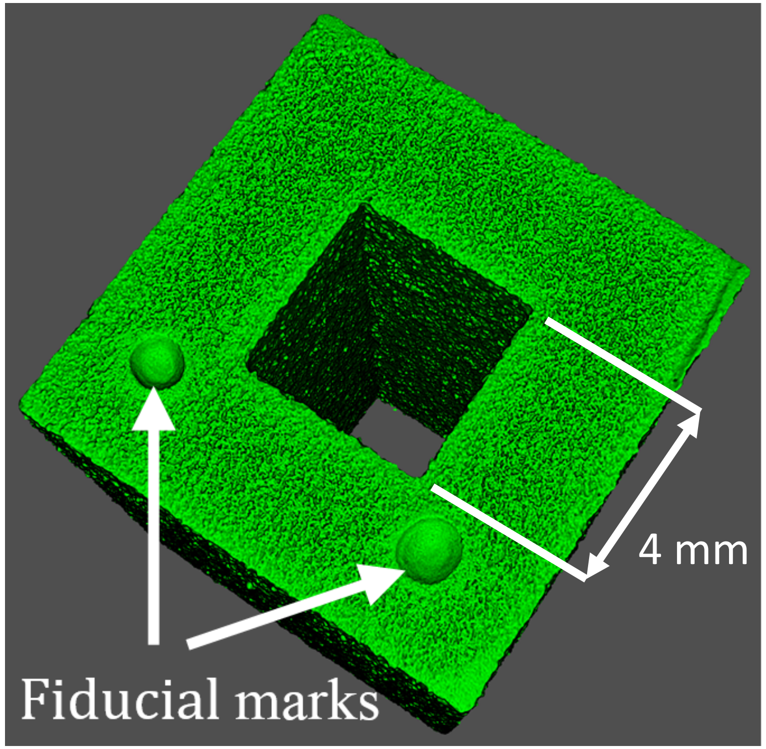
Sa 25 µm Voxel size 17 µm NOT OK?

Filtering per ISO 25178-3
L-filter nesting index (hi-pass) 8 mm
S-filter nesting index (low-pass) 0.025 mm

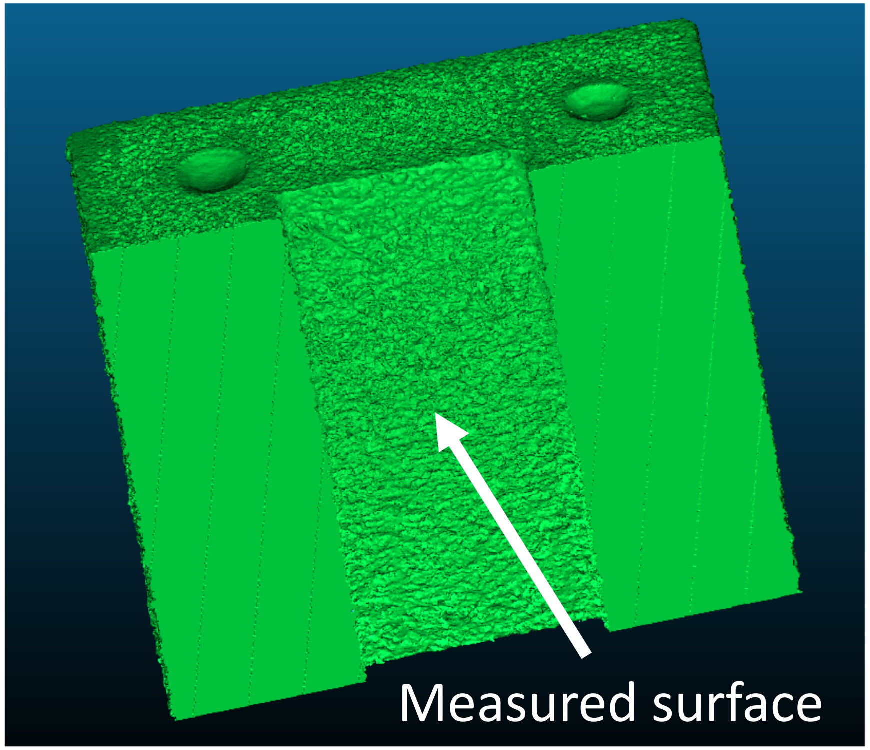
Factors affecting the accuracy of Surface-from-CT
Internal and external surfaces

10 mm x 10 mm Ti6Al4V SLM bar. 4 measurements 3 mm x 3 mm

Nikon XT H 225 CT. Voxel size 15.9 µm
(iterative surface determination)



Complete part
Measured surface internal



Mechanically sectioned
Measured surface external

Factors affecting the accuracy of Surface-from-CT Internal and external surfaces

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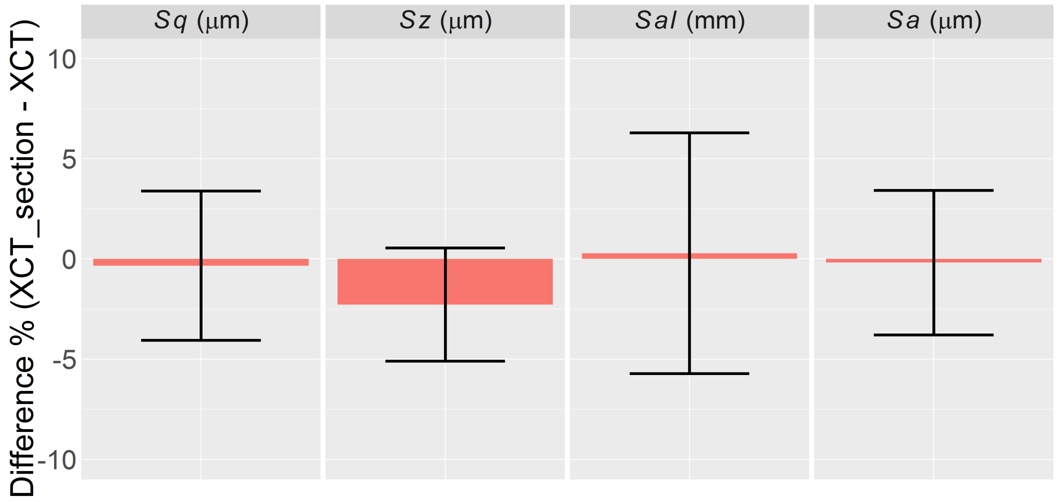
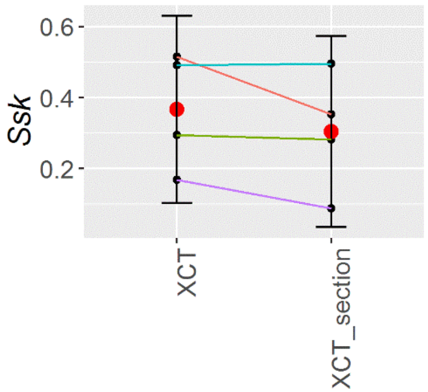
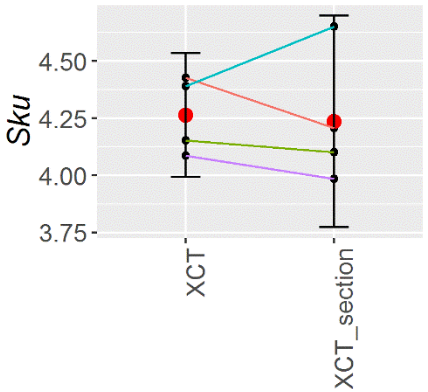


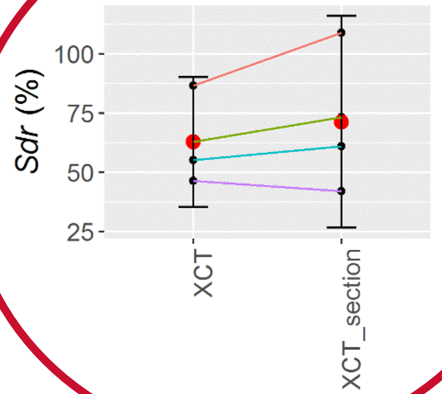




Filtering per ISO 25178-3

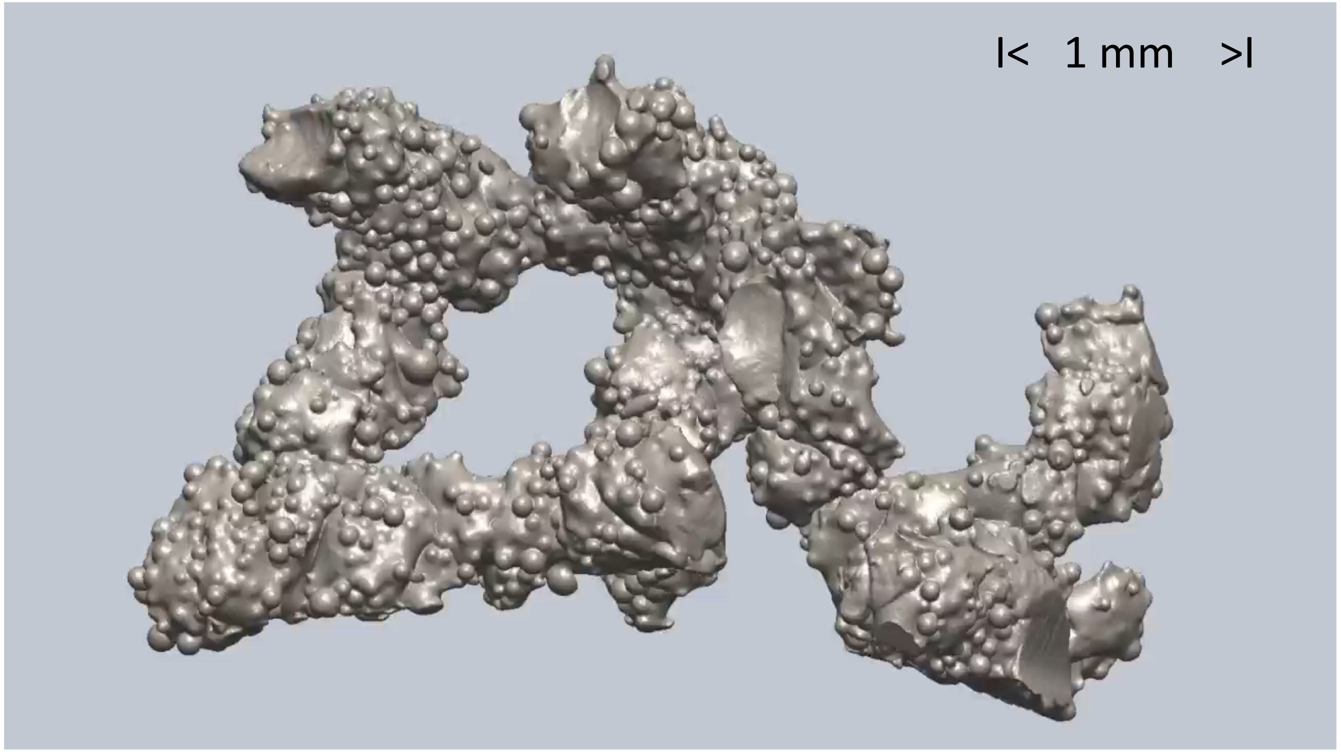
L-filter nesting index (hi-pass) 2 mm

S-filter nesting index (low-pass) 0.005 mm

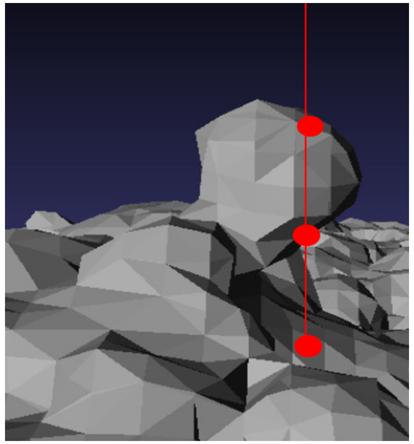


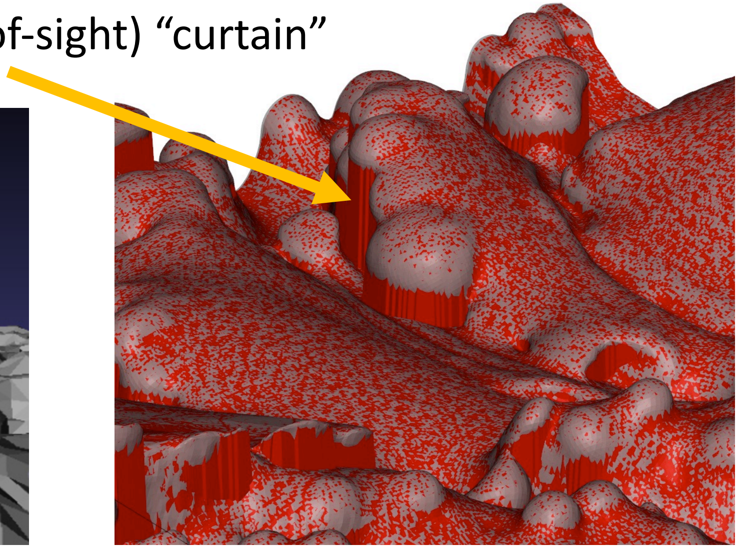
Insignificant difference in parameters between a similar internal and external surface

CT measurement of re-entrant surfaces *Sdr*$_{prime}$ and ISO 25178-2 parameter *Sdr*



Projection (line-of-sight) “curtain”





Re-entrant surface features: ≥2 registered z points for any x,y position.

Sdr is NOT applicable to true 3D (*x,y,z*) data, such as CT scans of re-entrant features. Introduce proposed parameter: *Sdr*$_{prime}$ which IS applicable to true 3D data, including data from re-entrant features.

The ISO 25178-2 hybrid parameter *Sdr* is the developed interfacial area ratio. This is the percentage of additional surface area contributed by the texture as compared to a plane the size of the measurement area.

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Surface-specific AM artefacts and AM chamber characterisation

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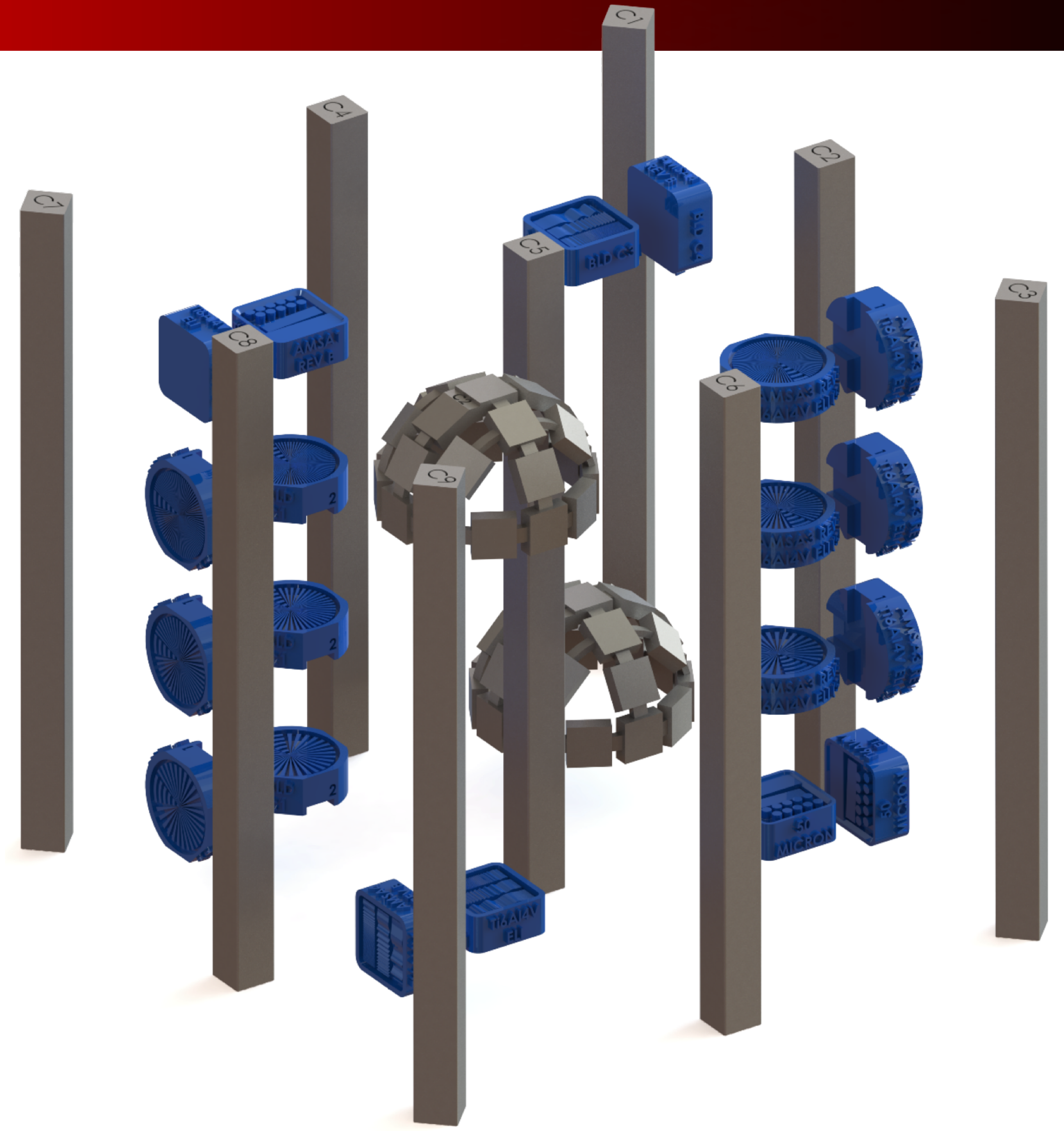
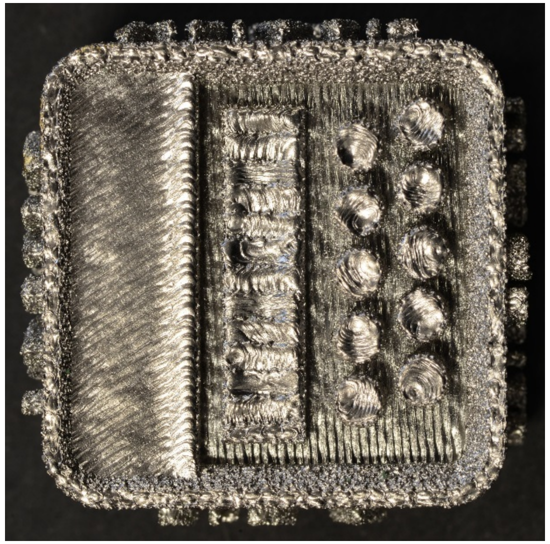
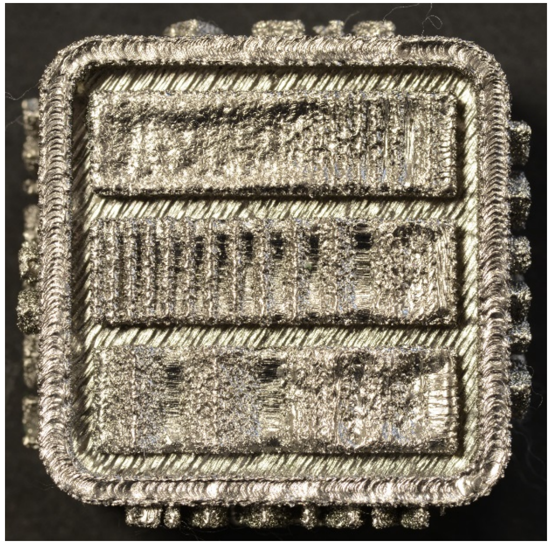


AMSA1



AMSA3

AMSA4



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Conclusions

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- Extraction of areal surface texture data per ISO 25178-2 from CT measurements possible
- Dimensional artefact in CT scans will permit discrimination between voxel scaling errors and surface determination errors
- Interlaboratory comparison of surface-from-CT measurements showed good repeatability and reproducibility. 0.5% *Sa* value difference between CT (MCT225) and FV measurements
- Investigation of the affects of selected measurement and processing parameters on the accuracy of surface-from-CT measurements: Local surface determination superior to global, consider re-cal after filament change, voxel size maximum 0.5 x *Sa*, internal / external similar results
- Proposal of surface texture parameter (Sdr_{prime}) to allow inclusion of re-entrant features in surface texture measurements
- Surface-texture-specific artefact set for inclusion in AM builds for process analysis and control

Future work

- Automated surface-from-CT. This is now on-going with an Innovate UK project
- Scaling and surface determination correction, based on dimensional measurements, applied to CT surface data
- CT-STARR Stage 2, including a larger variety of CT technologies and manufacturers
- Further characterisation of the CT chamber including further voxel-size and resolution effects on the extracted surface
- Function! Projects relating AM surfaces, including re-entrant features, to function, such as bio-attachment, coating adhesion, heat transfer
- Continued surface-specific artefact development and AM build process tracking

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Publications

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Journal papers

A. Townsend, N. Senin, L. Blunt, R. K. Leach and J. S. Taylor, "Surface texture metrology for metal additive manufacturing: a review“, *Precision Engineering,* vol. 46, pp. 34-47, 2016.

A. Townsend, L. Pagani, P. Scott and L. Blunt, "Areal surface texture data extraction from x-ray computed tomography reconstructions of metal additively manufactured parts“, *Precision Engineering,* vol. 48, pp. 254-264, 2016.

A. Townsend, L. Pagani, L. Blunt, P. J. Scott and X. Jiang, "Factors affecting the accuracy of areal surface texture data extraction from X-ray CT“, *CIRP Annals - Manufacturing Technology,* 2017.

A. Townsend, R. Racasan, and L. Blunt, "Surface-specific additive manufacturing test artefacts", *Surface Topography: Metrology and Properties*, *6*(2), p.024007, 2018.

A. Townsend, R. Racasan, R. K. Leach, N. Senin, A. Thompson, A. Ramsey, D. Bate, P. Woolliams, S. Brown, L. Blunt, "An interlaboratory comparison of X-ray computed tomography measurement for texture and dimensional characterisation of additively manufactured parts", *Additive Manufacturing*, vol. 23, pp. 422-432, 2018.

Conference papers and presentations

A. Townsend, R. Racasan, P. Bills and L. Blunt, "Development of an interlaboratory comparison investigating the generation of areal surface texture data per ISO 25178 from XCT“, presented at the 7th conference on industrial computed tomography, Leuven, Belgium, 2017.

A. Townsend, R. Racasan, P. Bills, A. Thompson, N. Senin, R. K. Leach and L. Blunt, "Results from an interlaboratory comparison of areal surface texture parameter extraction from X-ray computed tomography of additively manufactured parts“, presented at the 17th int. euspen Conference, Hannover, Germany, 2017.

A. Townsend, L. Blunt, and P. Bills, "Investigating the capability of microfocus x-ray computed tomography for areal surface analysis of additively manufactured parts“, in *Dimensional accuracy and surface finish in additive manufacturing, ASPE 2016 Summer Topical Meeting*, Raleigh, NC., 2016.

A. Townsend, L. Pagani, P. J. Scott and L. Blunt, "Measurement and charcterisation of additively manufactured re-entrant surfaces“, presented at the Joint special interest group meeting between euspen and ASPE, Dimensional accuracy and surface finish in additive manufacturing, KU Leuven, Belgium, 2017.

A. Townsend, L. Pagani, P. J. Scott and L. Blunt, "CT measurement of re-entrant additively manufactured surfaces“, presented at the 8th conference on industrial computed tomography (iCT 2018), Wels, Austria, 2018.

A. Townsend and L. Blunt, "Surface-specific additive manufacturing test artefacts“, presented at the 16th international conference on metrology and properties of engineering surfaces, Gothenburg, Sweden, 2017.

A. Townsend, L. Pagani, P. Yin, P. J. Scott and L. Blunt, "Areal surface texture measurement of additively manufactured parts“, presented at the ASTM committee F04 Workshop on additive manufacturing for medical applications, San Antonio, TX, USA, 2016.

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Quantitative surface texture data extraction from X-ray CT scans of additively manufactured parts

Andrew Townsend and Jefferson Cuadra

September 12, 2018

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