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Investigating the capability of micro-focus x-ray computed tomography for areal surface analysis of additively manufactured parts

June 30, 2016

A. Townsend, L. Blunt, P. Bills
EPSRC Centre for Innovative Manufacturing in Advanced Metrology, University of Huddersfield, UK.
Nationally funded centre of excellence in advanced metrology. 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:

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

University of Huddersfield, UK
• Importance of surface texture measurement for Additive Manufacturing (AM)

• Surface characterisation choices

• X-ray computed tomography (XCT) for AM surfaces
  • Rubert comparator plates
  • AlSi10Mg AM component

• Conclusions and future work
Embedded surface example (powder bed fusion)

- 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?
Comparing \( Ra \) values for the profile of different surfaces

- **Honed**: \( Ra = 2.4 \text{ \( \mu \)m} \)
- **Turned**: \( Ra = 2.5 \text{ \( \mu \)m} \)
- **Ground**: \( Ra = 2.4 \text{ \( \mu \)m} \)

The \( Ra \) value does not provide any information as to the shape of the irregularities on the surface. It is possible to obtain similar \( Ra \) values for surfaces having very different profiles.

Surface characterisation choices
Profile or areal measurements?

Pit or valley?
AM surfaces are complex!
Simple profile roughness measurements may not be enough!
XCT for AM surfaces
Areal surface texture data from XCT

Moth head section (Nikon XT H 225).
Rubert comparator plates.

Focus variation.  
Alicona G4.

X-ray computed tomography.  
Nikon XT H 225.

Rubert & Co. Microsurf 334 comparator plate.  
(Casting).
Rubert comparator plates.

Ra 25 µm sample.

Rubert & Co. Microsurf 334 comparator plate. (Casting).
XCT for AM surfaces
Areal surface texture data from XCT

Rubert $Ra$ 25 $\mu m$ comparator plate.

$Ra$ 25 $\mu m$ focus variation mesh. 
(CloudCompare).
XCT for AM surfaces
Areal surface texture data from XCT

Rubert $Ra$ 25 µm comparator plate.

$Ra$ 25 µm focus variation mesh and XCT mesh. (CloudCompare).
XCT for AM surfaces
Areal surface texture data from XCT

Rubert Ra 25 µm comparator plate.

Selection of points (minimum three) for initial mesh alignment. (CloudCompare).
XCT for AM surfaces
Areal surface texture data from XCT

Rubert Ra 25 µm comparator plate.

Manual, followed by ICP alignment.
XCT for AM surfaces
Areal surface texture data from XCT

Rubert $Ra$ 25 $\mu$m comparator plate.

Cropped meshes prior to conversion to height map (SDF) format (in Matlab).
Rubert $Ra$ 25 µm comparator plate.

10 mm x 11 mm
Mesh – mesh distance +40 µm – -30 µm.

Mesh – mesh distance distribution.
Rubert $Ra$ 25 µm comparator plate.

Focus variation mesh (red).
XCT mesh (green).
XCT for AM surfaces
Areal surface texture data from XCT

Rubert Ra 25 µm comparator plate.

Focus variation.
Alicona G4.
False color height map.
(SurfStand)

X-ray computed tomography.
Nikon XT H 225.
False color height map.
(SurfStand)
Rubert comparator plates.

<table>
<thead>
<tr>
<th>Nominal Rubert plate Ra (µm)</th>
<th>Mean FV Sa (µm)</th>
<th>Mean XCT Sa (µm)</th>
<th>Difference between mean XCT and FV Sa (% of FV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>51.1</td>
<td>55.6</td>
<td>8.8 %</td>
</tr>
<tr>
<td>25</td>
<td>27.4</td>
<td>31.3</td>
<td>14.5 %</td>
</tr>
<tr>
<td>12.5</td>
<td>12.4</td>
<td>14.6</td>
<td>17.2 %</td>
</tr>
<tr>
<td>6.3</td>
<td>6.6</td>
<td>9.0</td>
<td>34.5 %</td>
</tr>
<tr>
<td>3.2</td>
<td>4.0</td>
<td>5.6</td>
<td>40.5 %</td>
</tr>
<tr>
<td>1.6</td>
<td>2.5</td>
<td>3.5</td>
<td>43.1 %</td>
</tr>
<tr>
<td>0.8</td>
<td>0.56</td>
<td>1.09</td>
<td>95 %</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rupert Ra (µm)</th>
<th>ISO 25178-3 Gaussian L filter nesting Index (mm)</th>
<th>ISO 25178-3 Gaussian S filter nesting Index (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>25</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>12.5</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>6.3</td>
<td>2.5</td>
<td>8</td>
</tr>
<tr>
<td>3.2</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>1.6</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>0.8</td>
<td>0.8</td>
<td>2.5</td>
</tr>
</tbody>
</table>
XCT for AM surfaces
Areal surface texture data from XCT

Rubert comparator plates.

XCT for surface inspection - XCT limited use when Sa less than XCT voxel size?
XCT for AM surfaces
Areal surface texture data from XCT

AlSi10Mg SLM AM sample.

AlSi10Mg sample, Renishaw AM250 SLM.
Top surface.
AISi10Mg SLM AM sample.

Focus variation.  
Alicona G4.  
False color height map.

X-ray computed tomography.  
Nikon XT H 225.  
False color height map.

Gaussian L-filter nesting index: 5.0 mm  
S filter nesting index 0.02 mm (per ISO 25178-3:2012)
XCT for AM surfaces
Areal surface texture data from XCT

AlSi10Mg SLM AM sample.

Mesh – mesh distance distribution.

5.6 mm x 5.8 mm sample.
Mesh – mesh distance ± 40 µm.
**XCT for AM surfaces**

Areal surface texture data from XCT

**AlSi10Mg SLM AM sample.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>FV</th>
<th>CT</th>
<th>Delta (% of FV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_a$</td>
<td>Arithmetic mean height</td>
<td>31.7 μm</td>
<td>40.7 μm</td>
<td>28.4%</td>
</tr>
<tr>
<td>$S_q$</td>
<td>Root mean square height</td>
<td>44.5 μm</td>
<td>53.2 μm</td>
<td>19.6%</td>
</tr>
<tr>
<td>$S_{sk}$</td>
<td>Skewness</td>
<td>1.72</td>
<td>1.13</td>
<td>-34.3%</td>
</tr>
<tr>
<td>$S_{ku}$</td>
<td>Kurtosis</td>
<td>10.7</td>
<td>6.6</td>
<td>-38.3%</td>
</tr>
<tr>
<td>$S_z$</td>
<td>Maximum height</td>
<td>470 μm</td>
<td>477 μm</td>
<td>1.5%</td>
</tr>
<tr>
<td>Spatial</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_{al}$</td>
<td>Fastest decay autocorrelation length</td>
<td>0.27 mm</td>
<td>0.28 mm</td>
<td>3.7%</td>
</tr>
<tr>
<td>Hybrid</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_{dr}$</td>
<td>Developed interfacial area ratio</td>
<td>21.0%</td>
<td>21.4%</td>
<td>1.9%</td>
</tr>
<tr>
<td>Functional</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_{mr2}$</td>
<td>Areal material ratio (dales)</td>
<td>90.8%</td>
<td>93.5%</td>
<td>3.0%</td>
</tr>
</tbody>
</table>

Areal parameters per ISO 25178-2.  
(After filtering per ISO 25178-3).
XCT for AM surfaces
Areal surface texture data from XCT

<table>
<thead>
<tr>
<th>Test sample</th>
<th>FV Sa (µm)</th>
<th>XCT Sa (µm)</th>
<th>Voxel Size (µm)</th>
<th>Percentage difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlSi10Mg SLM</td>
<td>31.7</td>
<td>40.7</td>
<td>17</td>
<td>28.4 %</td>
</tr>
<tr>
<td>25 µm Ra Rubert plate</td>
<td>27.4</td>
<td>31.3</td>
<td>12.9</td>
<td>14.5 %</td>
</tr>
</tbody>
</table>

Gaussian L-filter nesting index: 5.0 mm
S filter nesting index 0.02 mm (per ISO 25178-3:2012)

AlSi10Mg AM part and Rubert 25 µm Ra plate XCT – FV mean Sa comparison
Future work

XCT surface determination

Rubert 25 µm $Ra$ plate ISO50 (A&B) and manual (C&D) surface determination. (VGStudio MAX). Local adaptive surface determination?
Future work
Medical lattice structures

Ti6Al4V orthopaedic prototype component.
XCT reconstruction
Conclusions

• Large surface area produced during AM manufacturing – most is “embedded”
• Areal surface texture measurements provide advantages over profile
• Not just $Ra$ - spatial, hybrid, functional parameters
• XCT can be a good match for AM component inspection
  • NDT of internal or overhanging surfaces
• Fluid channels, coating adhesion, bio-attachment + cryostat tubes
• Have shown the extraction of areal surface texture data (per ISO 25178-2) from XCT
Future work

• Surface determination effects and solutions to be investigated
• Investigate causes of differences between XCT and FV results
• Compare with raster scan stylus measurements
• Calibration
• Material and AM build effects
• Investigate XCT part position effects – map the chamber
• Medical lattice structures
• Surface-specific artefacts
• Round robin project – XCT / surface texture capability analysis
Future work

TEAM ASPE
XCT
CHALLENGE
2016
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Thank you!

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