INVESTIGATING THE CAPABILITY OF MICROFOCUS X-RAY COMPUTED TOMOGRAPHY FOR AREAL SURFACE ANALYSIS OF ADDITIVELY MANUFACTURED PARTS

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INTRODUCTION

The ability to perform non-destructive areal surface analysis, for example of the internal surfaces of additively manufactured (AM) parts has potential advantages during product development and for production process control. This paper reports on the extraction of areal surface information from microfocus x-ray computed tomography (XCT) data. Using this novel technique a range of areal parameter values were generated from a surface section extracted from XCT scan data of an as-built (no post-processing) AlSi10Mg additively manufactured part. This was then compared with the parameter values generated from a focus variation scan of the same surface section. The data comparison method involving normalisation of data format to allow analysis using industry-standard software, such as MountainsMap (Digital Surf, Besançon, France) or SurfStand (The Centre for Precision Technologies UoH) is demonstrated. Importing the extracted surfaces into these powerful software packages allows one-click data filtering per ISO 25178-3 [1] and the generation of a comprehensive suite of areal surface parameter values. These include feature and field parameters, amplitude, spatial, hybrid and functional parameters, as defined in ISO 25178-2 [2]. A method for characterising the capability of XCT for areal surface measurement is demonstrated by comparing results obtained from samples taken from a Rubert comparator test panel, with sample surface *Ra* values between 0.8 µm and 50 µm.

XCT AND FOCUS VARIATION AM SURFACE COMPARISON

A cube, 10 mm per side, was manufactured using selective laser melting (SLM) on a Renishaw AM250 using AlSi10Mg powder. No post-processing, such as grit blasting, was performed after manufacture.

XCT Measurement

The cube was imaged using a Nikon XT H 225 microfocus CT. Nikon CT-Pro (Nikon metrology, Tring, UK) was used to perform reconstruction. Voxel size was 17 µm (x,y,z). Surface determination was performed in VGStudio MAX (Volume Graphics GmbH). Surface extraction (no simplification or downsampling, automatic surface determination) was performed in VGStudio MAX and the data was saved as an STL surface geometry (mesh) file. The surface was then imported into Meshlab (Visual Computing Lab ISTI-CNR), and area of interest (component upskin (top) surface) was aligned with the xyz coordinate system and then extracted and saved with a PLY file format.

Focus Variation

Focus variation (FV) instruments are commonly used to analyse the surface texture of additively manufactured parts and the FV results are used here as reference measurements. The upskin surface of the aluminium cube was measured using an Alcona G4 using a 10x objective lens. Vertical resolution was 0.2 µm and the lateral sampling distance was 2.3 µm. The data was saved as an STL file.

Areal Parameter Comparison

The XCT and FV STL surface sections were both imported into CloudCompare (version 2.6.3beta [GPL software] 2015). The areas were aligned using iterative closest point (ICP) and then both were cropped to give aligned, equal areas. No lateral or vertical scaling was performed during the alignment. Both areas were saved with PLY file formats. The XCT and FV PLY mesh files were levelled, projected onto a grid and converted to SDF (Surface Data Format) in Matlab (The MathWorks, Inc., Natick, Mass, USA. Release R2015b). Projected grid spacing was 2 µm (x and y), 1 nm vertical numerical resolution for both files.

A surface area of 5.6 mm x 5.8 mm, approximately 30% of the top surface area, was used for parameter generation, see Figure 1.

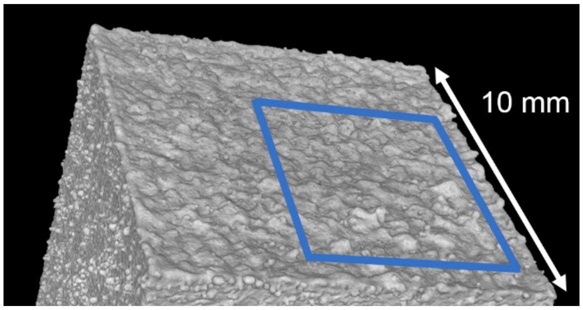

FIGURE 1. Top of AlSi10Mg part after XCT reconstruction, showing cropped surface area.

The XCT and FV SDF files were opened in SurfStand (V6.0) software. Based on the surface (no structure of interest with a scale (wavelength) larger than 1 mm) the Gaussian L-filter nesting index was set to 5.0 mm and the S-filter nesting index was set to 0.02 mm, per ISO 25178-3:2012 tables 1 and 3. The FV and XCT false colour height maps, generated in SurfStand, are shown in Figure 2. The correlation between the surface topography of the two height maps can be seen clearly. Areal surface parameter data (per ISO 25178-2), computed in SurfStand from the FV and XCT data for these aligned and cropped areas, are compared in Table 1.

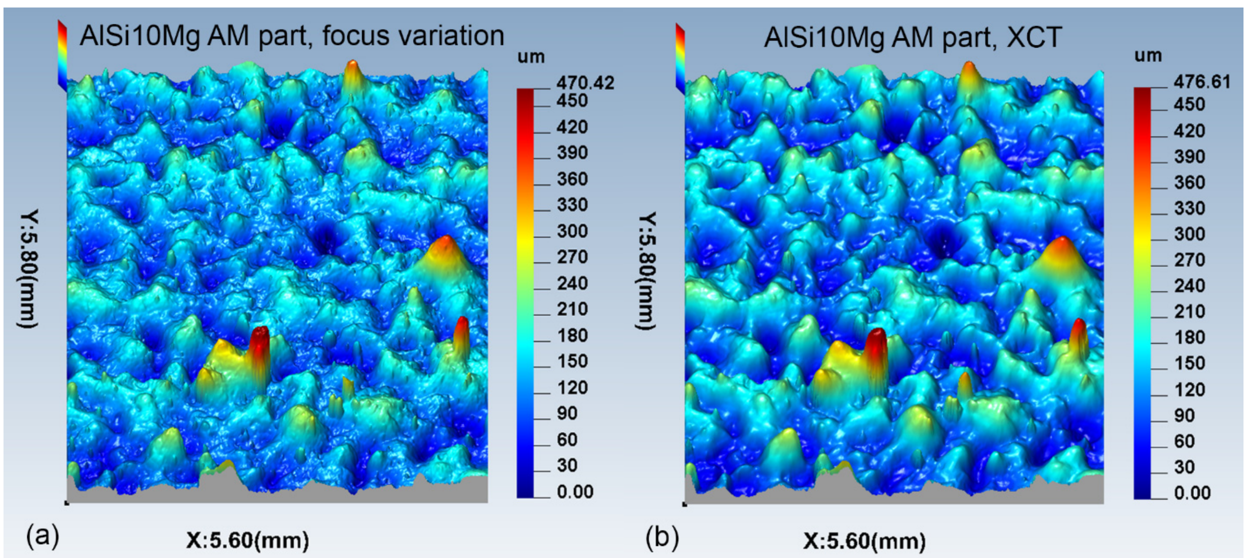

FIGURE 2. AlSi10Mg part false colour height map (a) FV, (b) XCT.

TABLE 1. AlSi10Mg part, FV and CT ISO 25178-2:2012 parameters.

Parameter	**Description**	**FV**	**CT**	**Delta (% of FV)**
Amplitude				
Sa	Arithmetic mean height	31.7 µm	40.7 µm	28.4%
Sq	Root mean square height	44.5 µm	53.2 µm	19.6%
Ssk	Skewness	1.72	1.13	-34.3%
Sku	Kurtosis	10.7	6.6	-38.3%
Sz	Maximum height	470 µm	477 µm	1.5%
Spacing				
Sal	Fastest decay autocorrelation length	0.27 mm	0.28 mm	3.7%
Hybrid				
Sdr	Developed interfacial area ratio	21.0%	21.4%	1.9%
Functional				
Smr2	Areal material ratio (dales)	90.8%	93.5%	3.0%

The surface parameters in Table 1 were chosen because they have all been shown to differentiate variations in AM build performance in response to changes in build parameters such as laser and electron beam spot size and power, build orientation and post-processing time [3]. The percentage variation between the XCT and focus variation measurements range between 1.5% for *Sz* (the sum of the maximum peak value and maximum pit height value) and -38% for *Sku* (kurtosis). The kurtosis for the XCT measurement is 38% less than that of the focus variation instrument. This is understandable as kurtosis is an indication of “peakedness” of the surface and XCT resolution is considerably less than that of the focus variation instrument and so would tend not to resolve narrow, sharp peaks. *Sa* and *Sq* have been the most widely used areal parameters for AM surface measurement [3]. The values of *Sa* and *Sq* from the XCT were 28% and 20% greater than the focus variation measurements for this particular AM sample.

Mesh Distance Analysis

The distance (closest points) between the two aligned and cropped meshes was calculated and plotted, see Figure 3. The distance analysis map shows the good lateral scaling of the XCT. The distance distribution was also plotted, showing an approximately Gaussian distribution, and giving a standard deviation of 11 µm, see Figure 4.

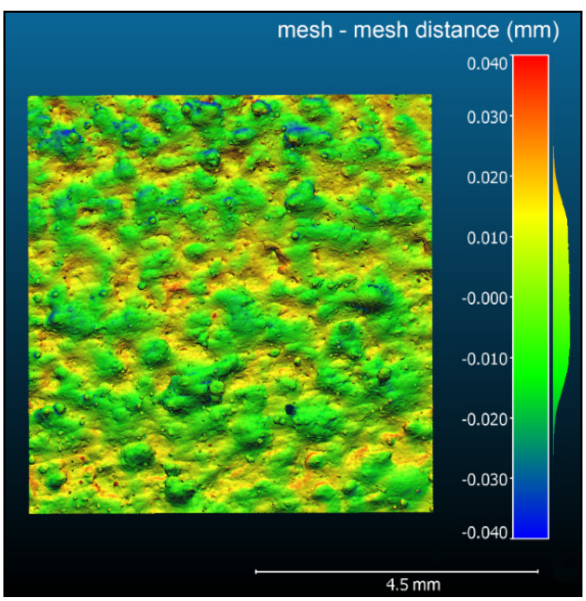

FIGURE 3. XCT to FV mesh difference map.

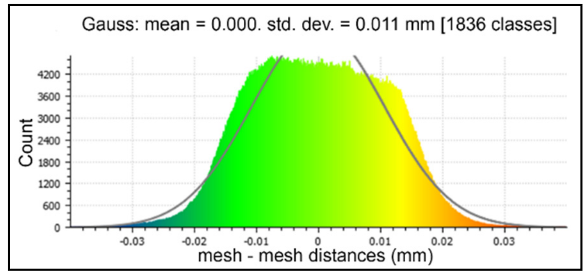

FIGURE 4. XCT mesh to FV mesh distance difference distribution.

XCT AND FOCUS VARIATION ROUGHNESS PLATE COMPARISON

The surfaces of powder bed fusion metal AM parts vary considerably with different manufacturing systems, powder configurations and build parameters. To give an indication of the limits of XCT to produce meaningful areal surface information a series of measurements were performed on test plates with roughness values encompassing those likely to be produced by metal powder bed fusion processes (nominal *Ra* 0.8 µm – 50 µm).

Rubert roughness comparison specimens

Seven plates, approximately 10 mm x 20 mm, were cut from a Rubert Microsurf 334 (casting) comparator test panel, see Figure 5.

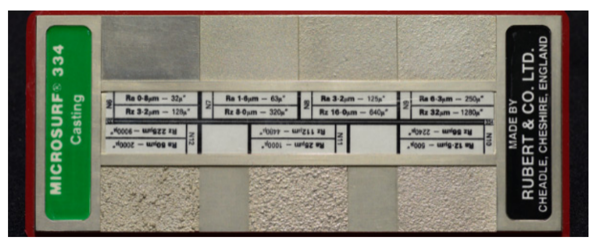

FIGURE 5. Rubert Microsurf 334 comparator test panel.

The casting panel was used as this surface most closely represents the powder bed fusion metal AM surface. No Rubert samples exist for AM surfaces at present.

Measurement and Analysis

XCT results were again compared to those obtained using the focus variation instrument. XCT voxel size for all plates was 12.9 µm (x,y,z). L-filter and S-filter nesting for indexes, based on plate *Ra* value, were generated using data from ISO 4287-1998 [4], ISO 4288-1998 [5] and ISO 25178-3:2012. The XCT and FV measured areas for each of the seven plates were aligned and cropped following the same procedure used for the AlSi10Mg AM sample. Nine square samples, with sample side lengths based on value of the L-filter nesting index, were extracted from the 0.8 µm – 6.3 µm *Ra* plates. Four samples were extracted from the 12.5 µm – 50 µm *Ra* plates (quantity limited by the plate sizes). The files were converted to SDF format, opened in SurfStand and the parameter set was generated. Table 2 shows the nominal *Ra* value together with the mean *Sa* value computed from the FV and XCT data for each of the seven plates.

TABLE 2. Rubert plate nominal Ra values, mean FV and XCT Sa values and percentage difference between mean XCT and FV values.

Nominal Rubert Plate *Ra* (µm)	Mean FV *Sa* (µm)	Mean XCT *Sa* (µm)	Difference between mean XCT and FV *Sa* (% of FV)
50	51.1	55.6	8.8 %
25	27.4	31.3	14.5 %
12.5	12.4	14.6	17.2 %
6.3	6.6	9.0	34.5 %
3.2	4.0	5.6	40.5 %
1.6	2.5	3.5	43.1 %
0.8	0.56	1.09	95 %

Figure 6a shows the four FV and corresponding XCT readings for the nominal 50 µm *Ra* plate. Figure 6b shows the nine FV and corresponding XCT readings for the nominal 0.8 µm *Ra* plate.

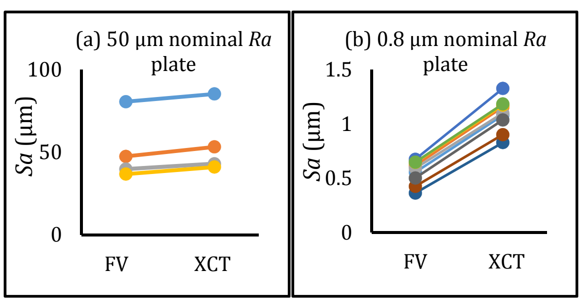

FIGURE 6. Comparison of FV and XCT results (a) 50 µm nominal Ra plate (b) 0.8 µm nominal Ra plate.

The lines on each chart are approximately parallel, illustrative of the correct FV to XCT mesh alignment. The gradients of the lines for the 0.8 µm *Ra* plate are greater, indicative of the larger percentage difference between the XCT and FV measurements than with the nominal 50 µm *Ra* plate. For each of the seven Rubert plates a paired t-test was performed. The null hypothesis being that the difference between the mean *Sa* as measured on the XCT and on the FV instrument was zero. The 95% confidence level was then generated for the data from each of the seven plates. The mean *Sa* difference between FV and XCT readings, together with the 95% confidence level of the mean *Sa* difference were plotted for each of the seven Rubert plates. The values plotted are percentages of the mean FV reading for each plate, see Figure 7.

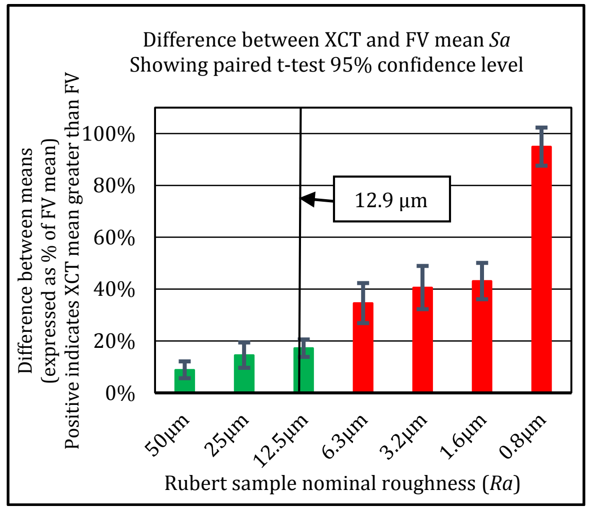

FIGURE 7. Chart of the mean Sa difference between FV and XCT for seven Rubert test plates.

The null hypothesis was rejected: for all seven plates there is greater than 95% probability the XCT measured roughness value is greater than the FV measured roughness value (none of the confidence interval bars cross the 0% line). The percentage difference between the XCT and FV measured roughnesses increases significantly as the absolute plate roughness value reduces (9% at nominal 50 µm *Ra* and 95% at nominal 0.8 µm *Ra*). There is a 2x step increase in percentage difference at an *Ra* value approximately equivalent to the 12.9 µm voxel size of the XCT. Mean differences between XCT and FV *Sa* measurements were 17% and 35% with sample roughness values (*Ra*) of 12.5 µm and 6.3 µm respectively. This significant increase in mean difference suggests an initial guideline that XCT areal surface measurements from surfaces with a reconstruction voxel size greater than the surface *Ra* or *Sa* should be avoided as errors increase significantly.

CONCLUSIONS

A novel first-step analysis technique has been developed to extract surface information from XCT data and configure this data to allow filtering and parameter generation, per ISO 25178-3 and ISO 25178-2 respectively, using commercially available software packages. Producing standard areal surface data from XCT would be particularly useful for the analysis of internal surfaces of additively manufactured parts, surfaces that up to now could only be analysed using destructive techniques. Initial characterisation of XCT surface measurement capability has been performed. These results show that, dependent upon voxel size and surface roughness, XCT is a viable method for areal surface analysis of AM components. Initial results show a marked decrease in accuracy when the voxel size exceeds the nominal surface *Ra* value. Additional applications of this technique beyond AM are expected.

FUTURE WORK

Currently there are no AM surface calibration or comparator test panels available and the results obtained for the single test of the AlSi10Mg AM surface produced a percentage difference for *Sa* values computed from XCT and FV (28.4%) higher than that of the approximately comparable Rubert casting plate, 25 µm nominal *Ra*, (14.5%), see Table 3.

TABLE 3. 25 µm Rubert plate and AlSi10Mg AM sample mean FV and XCT Sa values and percentage difference between mean XCT and FV values.

Test sample	FV *Sa* (µm)	XCT *Sa* (µm)	Voxel Size (µm)	Percentage difference
25 µm *Ra* Rubert plate	27.4	31.3	12.9	14.5 %
AlSi10Mg SLM	31.7	40.7	17	28.4 %

Future work will include measuring a selection of AM (and non-AM) surfaces to generate a more comprehensive understanding of XCT capability, including the relationship between voxel size and other factors such as surface determination, on measurement accuracy. Generation of a standard AM surface test plate will be investigated. Voxel size and resolution are dependent upon the position of the component being measured in the XCT chamber (in a cone-beam XCT machine a smaller voxel size will be generated the closer the component is to the x-ray source). The position is dictated by the size of the component. The larger the component is the further away from the x-ray source the component needs to be to be imaged correctly and, subsequently, the larger the voxel size. These factors will be investigated and it is planned to characterise a variety of XCT machines for surface extraction capability.

ACKNOWLEDGEMENTS

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