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Areal surface texture data extraction from X-ray computed tomography reconstructions of metal additively manufactured parts

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ABSTRACT

Many applications that exploit the manufacturing flexibility of additive manufacturing (AM) produce surfaces, primarily internal features, which cannot be measured using conventional contact or line-of-sight optical methods. This paper evaluates the capability of a novel technique to extract areal surface data from micro-focus X-ray computed tomography (XCT) from AM components and then generate surface parameter data per ISO 25178-2. This non-destructive evaluation of internal features has potential advantages during AM product research and commercial production. The data extracted from XCT is compared with data extracted using a focus variation instrument. A reference dimensional artefact is included in all XCT measurements to evaluate XCT surface determination performance and dimensional scaling accuracy. Selected areal parameters generated using the extraction technique are compared, including *Sa*, for which the nominal difference between the value obtained using XCT and used the focus variation method was less than 2.5%.

1. Introduction

Additive Manufacturing (AM) has emerged as the new paradigm in manufacturing. AM enables the production of geometrically complex components, by manufacturing them in a layer-by-layer manner using a variety of techniques from powder bed fusion of topologically optimized metal components [1] to the fused deposition modeling of scaffold architecture for tissue engineering applications [2]. AM has the potential for dramatically shorter development cycles and enables previously complex assemblies to be made in one piece. AM is now being used to make production parts in high-value applications such as aerospace, the automotive sector, the energy sector and medical engineering, where part complexity and customizability are key advantages.

Two of the limiting factors of AM however are a lack of precision in terms of achieving many required tolerances on engineering parts [3] and a lack of an infrastructure for the implementation of geometrical product specifications (GPS). In terms of accurate tolerancing and developing the use of metal powder based AM within the wider manufacturing framework, there are significant issues that remain to be answered concerning the optimal traceable metrology techniques used to assess AM parts for geometry and surface texture. This is especially problematic when parts need to be mated on assembly or require a specific surface roughness. The published information on the development of post-process techniques to measure and characterize complex part surface topography produced by AM are limited and shows a dearth of advanced techniques (e.g. the use of areal topography parameter) to assess the relatively high surface roughness of AM parts.

A recent review has been carried out to highlight the most commonly used surface metrology systems and quantitative topography parameters used to assess part quality [4]. This review showed focus variation, along with confocal microscopy, have become popular methods of measurement of the complex, three-dimensional surfaces of metal AM parts. Areal measurement and characterization (for example, as defined in ISO 25178-2 [5] and ISO 25178-3 [6]) is seeing more widespread adoption as the advantages over contact profile measurements are becoming apparent. Surface topography is three dimensional in nature and areal surface measurements are generally more representative of the functional surface than profile measurements [5]. Similarly, areal measurements will tend to provide greater understanding of AM manufacturing process performance than profile measurements [6].

Additionally, it has become clear that due to the complexity of AM part geometry XCT has an increasingly important role in assessing part geometry [7–10]. XCT has the ability to measure internal and recessed surfaces which would be impossible to access using

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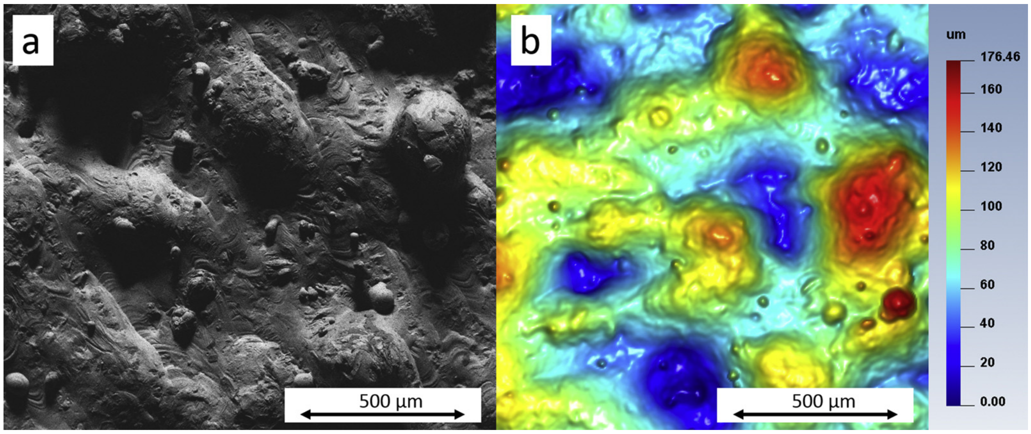

Fig. 1. (a) SEM secondary electron mode micrograph of the AlSi10Mg AM upskin surface (b) Alicona FV surface map of the AM surface.

conventional surface metrology techniques. Unfortunately the data produced by XCT systems in not in the form that is easily useable to enable quantitative surface assessment to be carried out and its accuracy, repeatability and resolution in terms of reproducing useful topography data has yet to be established.

With reference to metal powder based AM techniques, the present paper seeks to address these issues by providing a methodology to capture XCT data and transform it into a format that allows quantitative surface assessment. Additionally the data produced from XCT is verified in terms of its ability to characterize surface topography by comparing the XCT information to surface metrology data captured by a commercial focus variation (FV) surface metrology instrument (Alicona Infinite Focus G4). Issues such as surface determination techniques, scaling errors, instrument stability and repeatability are considered in the context of using an XCT instrument as an effective metrology tool. The aim of the paper is to highlight the efficacy of using XCT systems to produce standard (ISO 25178) surface texture parameter data. This is of particular relevance where the surface topography of internal or recessed surfaces needs to be established without destructively testing the part.

2. Methodology

The methodology used in the present study consists of the measurement and analysis of two artefacts: one additively manufactured artefact with a specific surface zone to be measured for surface texture comparison purposes (AM artefact) and a second artefact, manufactured from a similar material, used to assess and compensate for surface determination [11] and XCT measurement scaling errors (Dimensional artefact).

2.1. Artefact design

2.1.1. AM artefact

The AM artefact is a cube with 10 mm sides. The cube was manufactured on a Renishaw AM250 SLM machine using AlSi10Mg aluminium alloy powder. The AM component top (upskin) surface was used throughout the evaluation. Fig. 1a shows a scanning electron microscope (SEM) micrograph of a part of the surface. Fig. 1b shows a surface map of the same surface captured using an Alicona G4 focus variation instrument.

2.1.2. Dimensional artefact

The dimensional artefact was machined from Aluminium alloy (6082 T6 temper). The material type and overall size, both similar to the AM artefact, were chosen to provide similar X-ray absorption characteristics and surface determination challenges as the AM artefact. Three dimensions were measured during the analysis: An outside diameter (OD) and an inside diameter (ID) of similar size (approx. 3 mm) and a step length between two parallel faces of approximately 4 mm, see Fig. 2.

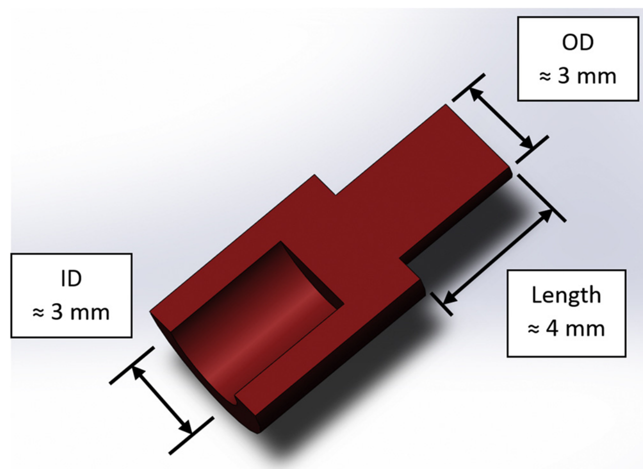

Fig. 2. CAD cross-section view of the dimensional artefact showing the measurement distances.

These measurement dimensions were chosen to highlight possible XCT surface determination problems. If, for example, the surface determination were to position the calculated surface inside the actual part surface, then the OD would tend to be undersized compared to the reference dimension and the ID would tend to be oversize. Surface determination position should have negligible effect on the length measurement because the measurement is between surfaces that are parallel and facing the same direction. Surface determination defines the material boundary based on grey scale (density) values between background and object material. The constructed surface using standard surface determination and iterative local surface determination implemented in commercial software, VGStudio MAX 2.2 [12] are shown in Fig. 3. The result of standard surface determination is a material boundary defined by one grey value applied globally to the object. Iterative local surface determination produces a material boundary based on local surrounding voxels, which largely compensates for any local deviations produced during the acquisition process, such as beam hardening. In this section example it can be seen that the standard surface determination would produce a calculated surface approximately 10–40 µm outside the actual surface. Local iterative surface

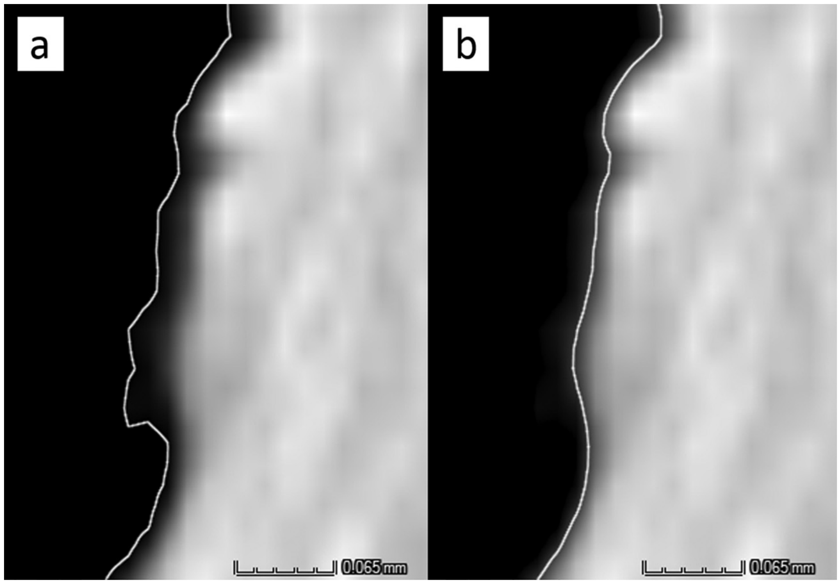

Fig. 3. Surface determination (VGStudio MAX 2.2 [12]) (a) Standard surface determination (b) local iterative surface determination.

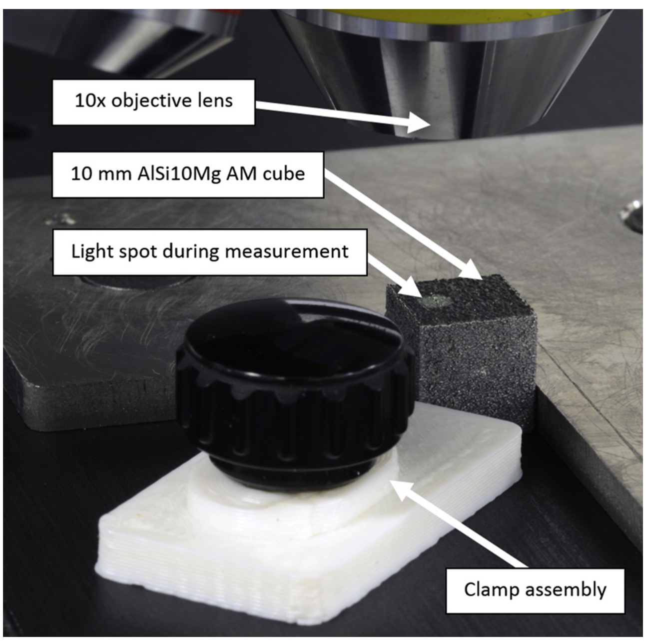

Fig. 4. Focus variation test fixture.

determination was used for all XCT measurements in the current work.

By evaluating these three types of measurements, possible errors due to surface determination can be evaluated and compensated for as necessary. The surface determination evaluation, in combination with information gained by comparing XCT nominal OD, ID and Length dimensions with the measurement results from the CMM, will provide scaling correction factors, as necessary, to be applied to the AM surface texture XCT measurement.

2.2. Measurements

The AM artefact surface reference measurements were taken using a focus variation instrument (Alicona G4) and the dimensional artefact reference measurements were taken using a coordinate measurement machine (CMM) (Zeiss Prismo). Both artefacts were then assembled into a 3D printed acrylonitrile butadiene styrene (ABS) polymer fixture and were measured together on a Nikon XT H 225 industrial XCT machine.

2.2.1. AM artefact focus variation measurements

All measurements were performed with a 10x objective lens on the Alicona G4. With this lens installed the system step height accuracy, with a 1 mm step, is 0.05%; maximum system lateral resolution is 1.75 μm; the maximum system vertical resolution is 100 nm with a repeatability of 30 nm. The Alicona focus variation system was chosen for its ability to image surfaces with high slope angles [13], together with its z-axis height range capable of measuring the tall structures present on the AM surface. The reference AM surface was measured 10 times. The component was removed from the fixture between each measurement and then replaced. This removal and replacement protocol was initiated to give an indication of measurement repeatability obtainable in an "industrial" scenario where a series of parts from a batch are measured consecutively using the same instrument, fixture or jig.

The measurement area was approximately 10 mm × 10 mm (later cropped to 8 mm × 8 mm for analysis). The measurement consisted of 8 by 10 stitched areas. The lateral sampling distance was 2.33 μm for all measurements. These measurement parameters were chosen based on the roughness of the surface. An initial profile roughness *Ra* value for the surface obtained was approximately 40 μm. Per ISO 4288 Table 1 requirements [14] this would then require a roughness sampling length and λc cut-off wavelength of 8 mm. This would suggest a similar L-filter nesting index (8 mm) and a measurement area of 8 mm × 8 mm per ISO 25178-3 [15]. The S-filter nesting index value of 0.025 mm was selected from Table 1 of ISO 25178-3. The ratio between the S-filter nesting index value and the measurement sampling distance is required to be a minimum of 3:1 for optical instruments per ISO 25178-3 Table 3. The actual measurement sampling distance of 2.33 μm gives a ratio of greater than 10:1. The Alicona G4 surface data was saved with an STL file format to allow simultaneous processing with the XCT surface data.

2.2.2. Dimensional artefact CMM measurements

The dimensional artefact was measured using a Zeiss Prismo CMM. The CMM maximum permissible error (MPE) is (1.9 + L/300) μm (L in meters). A 1.0 mm diameter ruby probe tip was used for

Table 1
Nikon XT H 225 settings used for all measurements.

Parameter	Value	Parameter	Value
Source to object distance	84.2 mm	Filter material	Copper
Source to detector distance	972 mm	Filter thickness	0.5 mm
Acceleration voltage	150 kV	Number of projections	1583
Filament current	67 μA	Detector pixels	1008 × 1008
Exposure time	2829 ms	Voxel size	17.3 μm

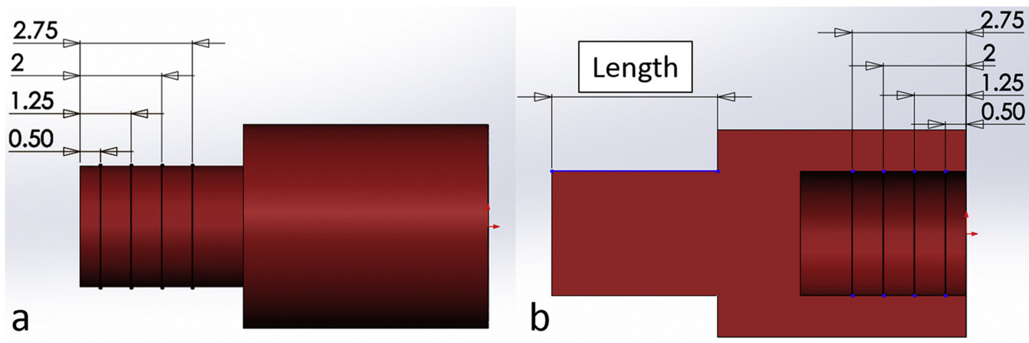

Fig. 5. Location of CMM measurements (a) OD, (b) ID and Length. All dimensions in mm.

all measurements. CMM scanning mode was used whereby the probe traverses the surface, remaining in contact with the surface. The ID and OD were measured at four locations along the length of the artefact; measurements were taken at distances 0.5 mm, 1.25 mm, 2.0 mm and 2.75 mm from the respective end faces, see Fig. 5. 100 measurement points per circle were taken. The dimensional artefact was not removed from the fixture between CMM measurements.

2.2.3. XCT measurements

2.2.3.1. XCT measurement conditions. Fig. 6 shows a CAD cross-section view of the AM artefact and dimensional artefact mounted within the 3D printed fixture. Both artefacts were retained within the fixture using nylon slotted studs. This configuration was used for all of the XCT measurements. The upskin surface of the AM artefact, Fig. 6a, was mounted in the fixture facing downwards, 45 ° to the horizontal. The fixture was designed such that none of the surfaces of the AM artefact or dimensional artefact to be measured were in direct contact with the plastic of the fixture. This was to optimise surface determination as there is only a two-material interface to consider (artefact to air).

After assembly into the fixture the assembly was mounted on the rotary stage of the Nikon XT H 225, see Fig. 7.

The machine parameter settings were consistent for all XCT measurements, see Table 1.

Reconstruction, from the 1583 TIFF images was performed in Nikon CTPro 3D [16]. Surface determination was performed in VGStudio MAX 2.2. Air was selected and defined as the background material. A volume from the dimensional artefact was selected and defined as the material of interest. An initial surface histogram was generated based on these selections. Iterative surface determination was used, with a (default) search distance of 4.00 voxels for all measurements, with the starting determination based on the initial histogram. Two regions of interest (ROI) were extracted from each measurement: the AM component upskin surface and the entire dimensional artefact. The surfaces of these two ROI were extracted and saved with an STL mesh format, using the VGStudio MAX 2.2 “Super Precise” setting, which provides highest available resolution with no simplification of the mesh.

2.2.3.2. XCT measurement data sets. The XCT measurements consisted of three sets, each of five measurements.

2.2.3.2.1. Set 1. Five measurements were taken with the AM artefact and dimensional artefact in the 3D printed fixture. The fixture was not removed from the rotary stage and the artefacts were not removed from the fixture between measurements.

2.2.3.2.2. Set 2. After the initial five measurements the XCT filament was replaced. Five measurements were taken with the AM artefact and dimensional artefact in the 3D printed fixture. The fixture was not removed from the rotary stage and the artefacts were not removed from the fixture between measurements.

2.2.3.2.3. Set 3. After completion of measurement set 2 the fixture was removed from the XCT rotary stage. The AM component was removed from the fixture and rotated 90 ° CCW (so the surface-of-interest remained facing downwards at an angle of 45 ° to the horizontal). Between every subsequent measurement the fixture was removed from the stage, the AM artefact was removed from the fixture, rotated 90°, replaced into the fixture and fixture then replaced onto the rotary stage. This removal and replacement is similar to the protocol followed for the Alicona G4 focus variation measurements and was performed to duplicate an “industrial” lot measurement scenario. The dimensional artefact was not removed between measurements. To allow alignment and cropping of the Alicona and XCT data the data format must be similar, so all files from XCT and Alicona were saved with an STL format.

2.3. Surface data processing for the AM surface

The data processing performed aligns all surfaces to ensure all quantitative data is generated from similar surface areas of the part. The data is converted to a form that allows analysis using standard surface software packages, such as MountainsMap [17] and SurfStand [18]. This processing is a ten-stage sequence incorporating custom computational processing combined with the use of commercially available software. This protocol was used to process all the surface data STL files, from the XCT and the Alicona (this is similar to the process performed in [19]):

2.3.1. Trim data

The STL from the Alicona contains the edges of the top surface and the XCT measurements of the surface also includes the sides

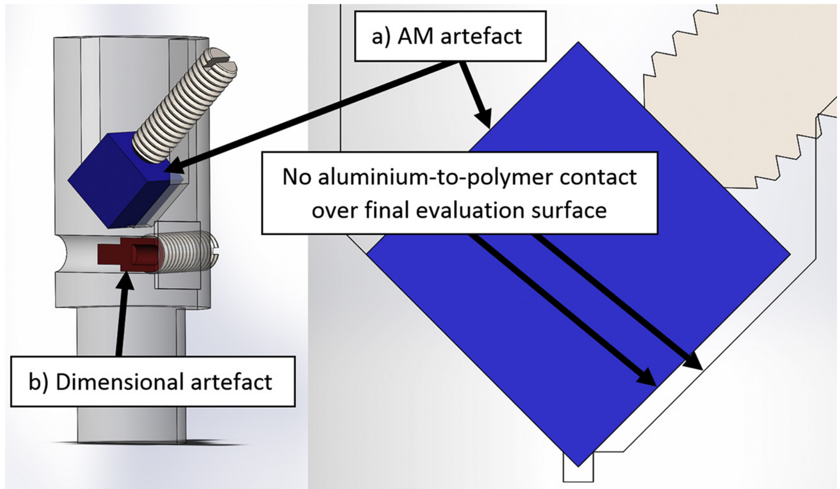

Fig. 6. XCT measurement fixture showing (a) AM artefact (b) dimensional artefact.

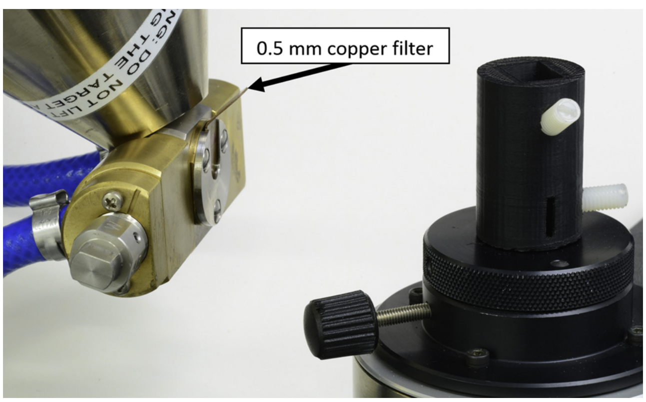

Fig. 7. Fixture containing two artefacts, shown at the measurement position in the Nikon XT H 225.

of the sample. These area were removed by cropping the surface area to approximately 9 mm × 9 mm, centred on the middle of the 10 mm × 10 mm cube surface.

2.3.2. Convert STL to PLY

PLY file format contains just the vertices and not the triangle information. The file size is approximately a third the size of the STL and allows for faster data computation.

2.3.3. Align surfaces

One surface measurement was chosen as the master for all alignment and cropping purposes. This master was one of the Alicona measurement files. The surface of the master file was not trimmed (per step 1) and so was slightly larger than the files to be aligned to it. This allowed the maximum area of each of the measurement sets to be used for the alignment process. Least squares alignment was performed between all measurement sets and the master surface.

2.3.4. Perform deviation analysis

Deviation analysis is not required during processing but provides verification that alignment has been performed correctly.

2.3.5. Crop to 8.4 mm × 8.4 mm PLY

After alignment to the master, each surface was cropped to 8.4 mm × 8.4 mm, in the same coordinate system as the master so, for example, the XY coordinate values for the corners for all the samples will be identical. The 8.4 mm × 8.4 mm cropped files were saved with a PLY format.

2.3.6. Clean the mesh

This step is only required for the XCT mesh files, not for the Alicona G4 mesh files. Converting the point cloud to a height map (step 7) involves projecting the point cloud onto a plane and assigning a Z height value to each of the height map matrix squares. Errors will occur if there is more than one point cloud surface to be projected onto the plane at the same XY location, such as would be the case with a re-entrant feature. To avoid this the mesh has to be cleaned by removing all non-visible re-entrant features followed by repairing the mesh to make it continuous. This step is performed after alignment to the master (Alicona) mesh because the non-visible areas should correspond to the surface areas not in line-of-site for the Alicona measurement.

2.3.7. Convert to a height map

The 8.4 mm × 8.4 mm PLY files (point cloud) were then converted to SDF (height map) format by linear interpolation and projection onto a plane, using a 2.5 μm grid spacing.

2.3.8. Crop to 8 mm × 8 mm per ISO 25178-3

The height map was then cropped to 8 mm × 8 mm (per ISO 25178-3 requirements, discussed above) and saved as a SDF file format.

2.3.9. Filter per ISO 25178-3

Levelling and filtering was then performed. A Gaussian regression L-filter nesting index of 8 mm and an S-filter nesting index of 0.025 mm, per ISO 25178-3, were applied to each surface.

2.3.10. Generate parameter data per ISO25178-2

Surface parameter data per ISO 25178-2 [20] was then generated.

2.4. Processing of the dimensional artefact data

Best-fit cylinders were generated for the OD and ID using the datum faces used for CMM measurement. Both cylinders extended 0.5 mm to 2.75 mm inward from the respective datum face of the artefact. The Length dimension was calculated as the distance between two planes generated from the small diameter end face and the step face, see Fig. 5.

Table 2
Master sample and copy ISO 25178-2 data comparison.

Parameter per ISO 25178-2	Master	Copy of Master	Percentage difference (in relation to Master) [(Δ) is absolute difference]
Height parameters			
***Sq*/μm**	41.186	41.186	<0.001
Ssk	1.413	1.413	<0.001
Sku	9.297	9.297	<0.001
Sp/μm	342.593	342.601	0.002
Sv/μm	137.346	137.329	−0.012
***Sz*/μm**	479.939	479.93	−0.002
***Sa*/μm**	30.301	30.301	<0.001
Spatial parameters			
Str	0.77	0.77	<0.001
***Sal*/mm**	0.287	0.287	<0.001
Hybrid parameters			
Sdq	0.626	0.626	<0.001
***Sdr*/%**	15.895	15.894	(Δ) −0.001
Volume parameters			
Vmp/($\mu m^3/\mu m^2$)	3.44	3.44	<0.001
Vmc/($\mu m^3/\mu m^2$)	31.70	31.70	<0.001
Vvc/($\mu m^3/\mu m^2$)	47.60	47.60	<0.001
Vvv/($\mu m^3/\mu m^2$)	3.46	3.46	<0.001
Sk family parameters			
Spk/μm	66.229	66.230	0.002
***Sk*/μm**	90.248	90.253	0.006
Svk/μm	28.196	28.195	−0.004
Material ratio parameters			
Smr1/%	12.8	12.8	(Δ) <0.001
***Smr2*/%**	92	92	(Δ) <0.001

3. AM surface artefact results

3.1. Process verification

3.1.1. Computational alignment and parameter extraction process verification

The primary intention of this research is to investigate the capability of XCT for the measurement and characterisation of AM surfaces. Part of this process is validation of the data extraction and analysis process itself. An initial test was performed to verify the ten-step computation process. This consisted of making a copy of the master surface file then performing iterative closest point (ICP) alignment between the master and its copy with a threshold maximum RMS difference between consecutive iterations of 5 × 10–5 mm. The surface area was approximately 9 mm × 9 mm. A deviation analysis was then performed. The mean distance after alignment was less than 1 nm. The deviation standard deviation was 88 nm. The surfaces were then processed using the ten-stage protocol, resulting in two height maps, 8 mm × 8 mm, levelled and filtered. A set of parameters per ISO 25178-2 were then generated in SurfStand. The difference between the parameter values are reported in Table 2. The parameters highlighted in bold were selected as ones that have been shown in previous research to be sensitive to AM build and post-processing surface variations [4]. The complete parameter set is easily generated using standard software, such as MountainsMap or SurfStand, but just these selected parameters will be reported for the remainder of the paper.

The largest percentage difference between the copy and the master is 0.012% for *Sv* (the maximum pit height of the scale limited surface) with the majority having a difference of zero to three decimal places. The authors thus consider that this verification of the alignment and extraction process is suitably accurate for this XCT to Alicona G4 AM surface measurement comparison.

3.1.2. Alicona measurement and processing verification

This verification test was performed to verify the precision of the Alicona measurements, in combination with the extraction process verified earlier. All measurements performed on the Alicona were processed per the sequence discussed previously, including alignment with the master, conversion to a height map, cropping and filtering per ISO 25178-3. Parameter mean values and sample standard deviations were generated for the ten samples for a selection of parameters, see Table 3.

Table 3
Alicona G4 ten measurement mean and sample standard deviation.

Parameter	Mean	Sample standard deviation
Height parameters		
Sq/μm	41.19	0.0068
Ssk	1.41	0.0012
Sku	9.29	0.0090
Sz/μm	479.61	0.31
Sa/μm	30.31	0.0055
Spatial parameters		
Sal/mm	0.29	0.00050
Hybrid parameters		
Sdr/%	15.92	0.012
Sk family parameters		
Sk/μm	90.25	0.025
Material ratio parameters		
Smr2/%	91.98	0.042

These numbers, as a typical example *Sq* mean value 41.19 μm, with a sample standard deviation of 0.007 μm, show the good repeatability of the Alicona measurement and data extraction process and repeatability is orders of magnitude better than the expected focus variation to XCT result differences.

3.1.3. Deviation analysis

The results of a deviation analysis between the master sample and another sample from the batch is shown in Fig. 8. The mean distance between the meshes is 4 nm, with a standard deviation of 250 nm. The primary purpose of alignment is to make sure measurements from the same area are compared for ISO 25178-2 parameter extraction. The alignment process performed here is significantly better than required for this purpose.

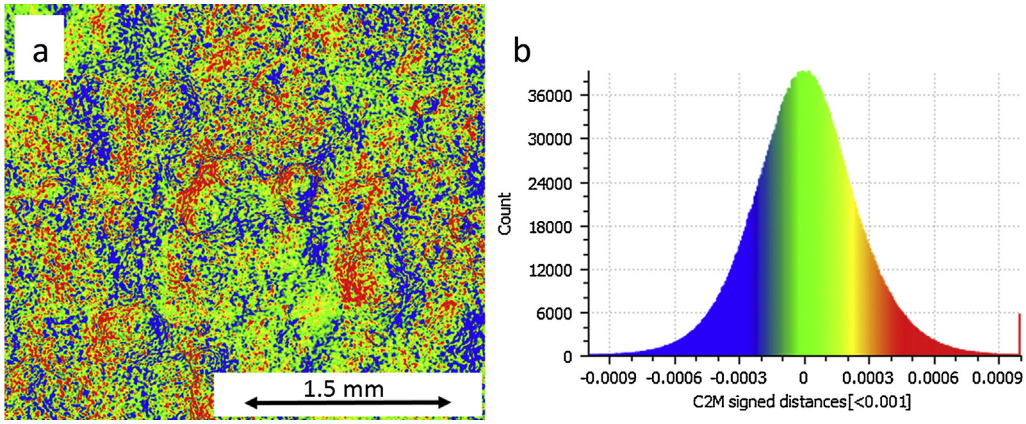

Fig. 8. Deviation analysis between two aligned Alicona measurements (a) deviation map (b) distance histogram (values in mm).

Table 4
XCT five sample mean and standard deviation, Set 1.

Parameter	Mean	Sample standard deviation
Height parameters		
Sq/µm	40.46	0.030
Ssk	1.35	0.0075
Sku	9.04	0.065
Sz/µm	479.07	1.76
Sa/µm	29.84	0.038
Spatial parameters		
Sal/mm	0.298	0.00090
Hybrid parameters		
Sdr/%	13.30	0.17
Sk family parameters		
Sk/µm	89.76	0.27
Material ratio parameters		
Smr2/%	91.70	0.071

Table 5
XCT five sample mean and standard deviation, Set 2.

Parameter	Mean	Sample standard deviation
Height parameters		
Sq/µm	40.07	0.056
Ssk	1.34	0.0039
Sku	8.98	0.028
Sz/µm	474.87	1.84
Sa/µm	29.59	0.045
Spatial parameters		
Sal/mm	0.29	0.00090
Hybrid parameters		
Sdr/%	13.09	0.24
Sk family parameters		
Sk/µm	89.01	0.18
Material ratio parameters		
Smr2/%	91.74	0.055

3.2. XCT

All XCT measurements were processed per the ten-step process outlined previously. Data for parameters per ISO 25178-2 were generated for all measurements. The measurement mean and sample standard deviation for the three sets of data is reported as follows.

3.2.1. Set 1: samples not disturbed between measurements

Set 1 consisted of five measurements on the XCT. The fixture was not disturbed between each of the measurements. The parameter mean and sample standard deviation values are shown in Table 4.

3.2.2. Set 2: after XCT filament change, samples not disturbed between measurements

Set 2 consisted of five measurements on the XCT. The XCT filament was changed prior to the first measurement. Automatic focus was performed after the filament change. No other XCT measurement settings were changed. The fixture was not disturbed between each of the measurements, see Table 5. There was a statistically significant difference in mean values measured prior and post filament change; for example, *Sq* mean 40.46 µm with a standard deviation of 0.03 µm prior to filament change. After the filament change the *Sq* mean was 40.07 µm with a standard deviation of 0.06 µm. The change was approximately 0.95%. To verify the only parameter that had been adjusted (auto focus) had not produced the difference, an additional test was run with the focus setting returned to the pre-filament change value. The *Sq* value for this individual measurement was 40.15 µm, which was slightly less than the maximum *Sq* value, 40.154 µm, obtained from Set 2 (auto focussed post filament change).

Table 6
XCT five sample mean and standard deviation, Set 3.

Parameter	Mean	Sample standard deviation
Height parameters		
Sq/µm	40.07	0.012
Ssk	1.35	0.0068
Sku	8.99	0.036
Sz/µm	472.53	1.88
Sa/µm	29.58	0.013
Spatial parameters		
Sal/mm	0.29	0.00050
Hybrid parameters		
Sdr/%	12.79	0.12
Sk family parameters		
Sk/µm	88.74	0.11
Material ratio parameters		
Smr2/%	91.74	0.055

3.2.3. Set 3: AM part rotated 90° between measurements

Set 3 consisted of five measurements on the XCT. The fixture was removed from the XCT rotary table and the AM component was removed from the fixture, rotated 90° CCW and replaced prior to the first Set 3 measurement. This removal and replacement process was repeated between each Set 3 measurement. The parameter mean and sample standard deviation values are shown in Table 6. Interestingly, the standard deviations values for this set of measurements is less than the standard deviations obtained for Set 1 and Set 2 measurements – sets for which the artefact was not disturbed between measurements.

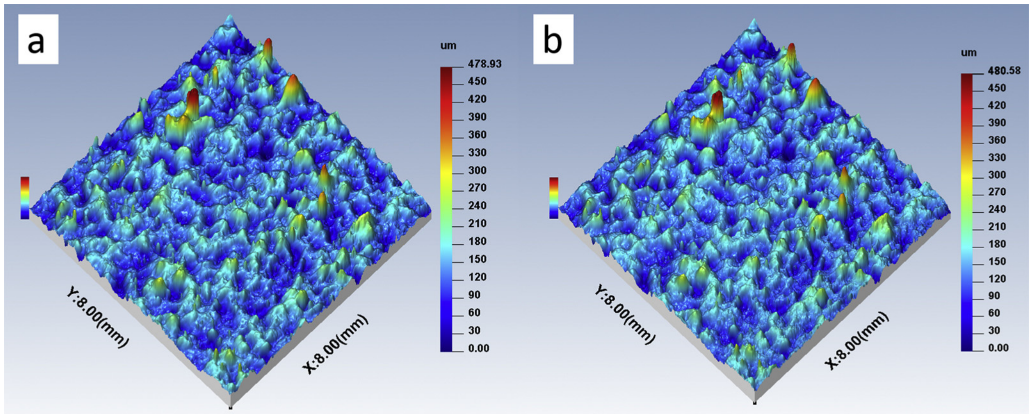

Fig. 9. False colour height maps (a) Alicona master (b) XCT reconstruction from Set 1.

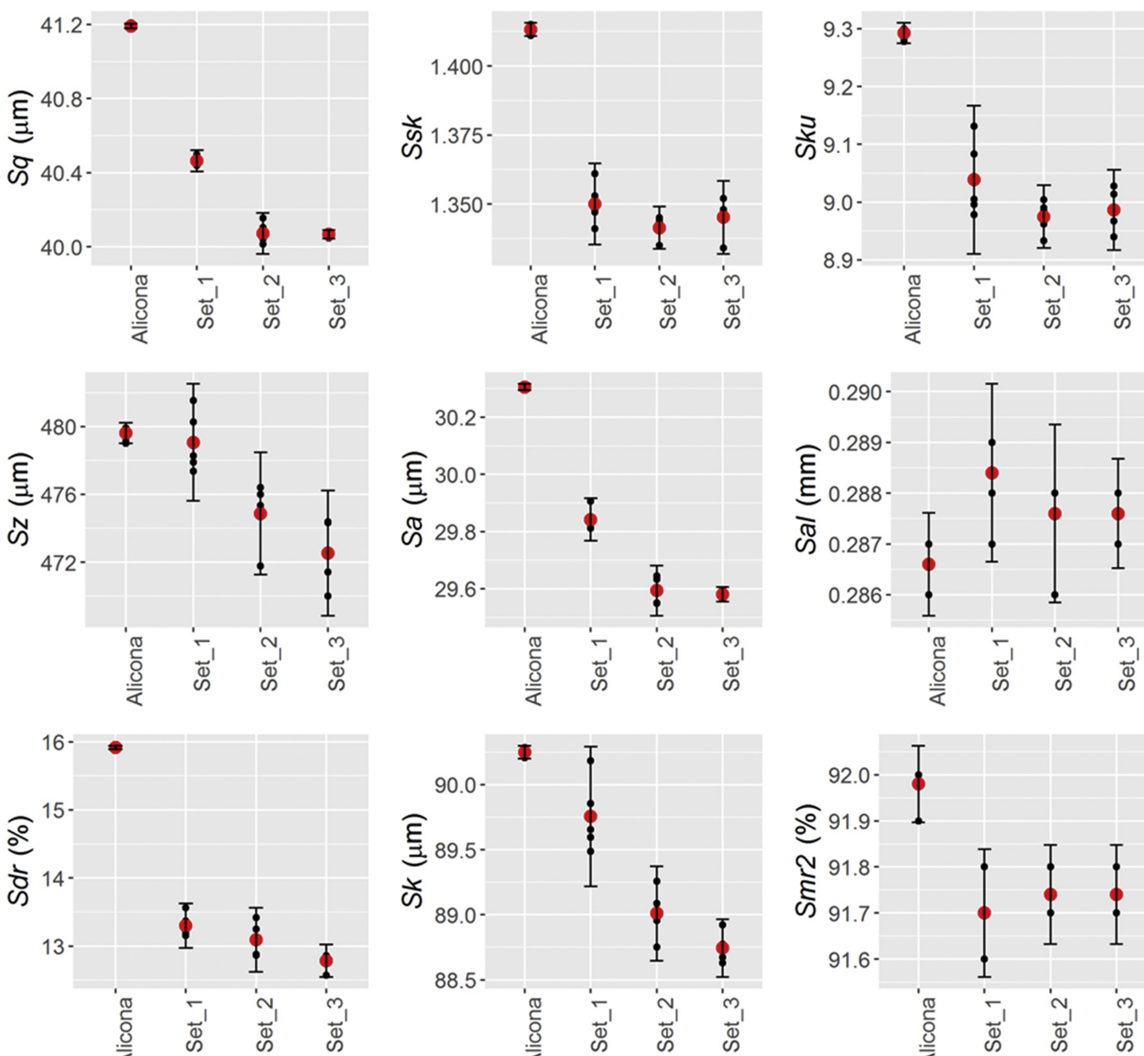

Fig. 10. ISO 25178-2 parameter Alicona to XCT comparison charts with 95% confidence interval.

3.3. XCT to focus variation measurement comparison

Fig. 9 shows false colour height maps for the master Alicona file and one of the measurements from XCT Set 1. The filtering, as with all data presented in this research, was 8 mm L-Filter nesting index and 0.025 mm S-Filter nesting index Gaussian regression filter per ISO 25178-3. The processed sample size was also 8 mm × 8 mm for all measurements. The surfaces show great visual similarity.

The percentage differences between the Alicona parameter mean value and the parameter mean value for the three sets of XCT data are shown in Table 7. The percentage difference between the mean values of *Sa* obtained for XCT measurement Set 1, Set

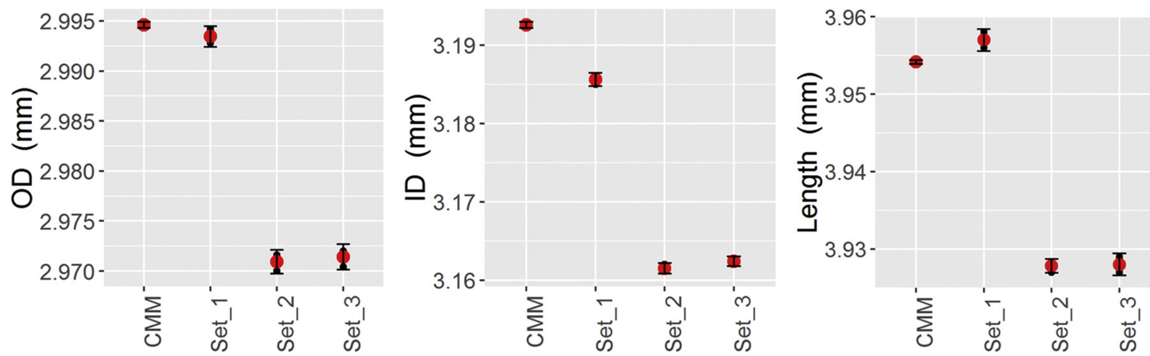

Fig. 11. OD, ID and length CMM and XCT dimensional data.

Table 7
Percentage difference between the XCT mean and the Alicona mean values [(Δ) is absolute difference].

Parameter	Alicona mean value	Set 1 mean value	Set 2 mean value	Set 3 mean value	Percentage difference, Set 1 to Alicona	Percentage difference, Set 2 to Alicona	Percentage difference, Set 3 to Alicona
Height parameters							
Sq/µm	41.19	40.46	40.07	40.07	−1.8	−2.7	−2.7
Ssk	1.41	1.35	1.34	1.35	−4.5	−5.1	−4.8
Sku	9.29	9.04	8.98	8.99	−2.7	−3.4	−3.3
Sz/µm	479.61	479.07	474.87	472.53	−0.1	−1.0	−1.5
Sa/µm	30.31	29.84	29.59	29.58	−1.5	−2.3	−2.4
Spatial parameters							
Sal/mm	0.29	0.29	0.29	0.29	0.6	0.3	0.3
Hybrid parameters							
Sdr/%	15.92	13.30	13.09	12.79	(Δ) −2.6	(Δ) −2.8	(Δ) −3.1
Sk family paramters							
Sk/µm	90.25	89.76	89.01	88.74	−0.5	−1.4	−1.7
Material ratio parameters							
Smr2/%	91.98	91.70	91.74	91.74	(Δ) −0.3	(Δ) −0.2	(Δ) −0.2

2 and Set 3 and the Alicona G4 measurement set are 1.8%, 2.7% and 2.7% respectively. These differences are remarkably low considering the very different measurement technology employed. As reported previously, the change between 1.8% for Set 1 and 2.7% for Set 2 and Set 3 appears to be caused solely by the filament change.

Charts for the selected areal parameters are shown in Fig. 10. The charts show data for the Alicona and Sets 1, 2 and 3 with the 95% confidence interval (± 1.96 standard deviations of the repeatability measurements).

4. Dimensional artefact results

The dimensional artefact measurement results for the outside diameter, inside diameter and length (Fig. 5) are shown in Table 8. The table includes standard deviation values for each set of measurements, together with percentage differences between the mean value of the XCT data sets and the mean value of CMM data set for OD, ID and Length.

The dimensional change between XCT Set 1 and Set 2 (IE after changing the XCT filament) showed a consistent dimensional change for OD, ID and Length of −0.75%, −0.76% and −0.74% respectively. All dimensional results obtained from the XCT were within 1% of the dimension as measured on the CMM. Charts for OD, ID and length, including 95% confidence interval, clearly showing the XCT measurement change from Set 1 to Set 2, are shown in Fig. 11.

5. Discussion

There is no significant bias in the direction of the dimensional errors for OD, ID and Length that would suggest the iterative local surface determination is incorrect (Table 8). The mean of all the XCT OD measurement is −0.53% less than the mean CMM OD measurement. Similarly the mean XCT ID and Length measurements are −0.71% and −0.47% less than the corresponding CMM measurements. The filament change effectively resulted in a scaling difference of −0.75%; i.e. the XCT dimensional measurements all reduced by approximately 0.75%. This 0.75% scaling change produced the changes in XCT parameter data given in Table 9. All XCT measurements reported in this paper were taken on the Nikon XT H 225 industrial CT. It should be noted that The Nikon metrology XCT machine, MCT225, includes a protocol, and is supplied with an artefact, for performing post-filament-change calibration.

The initial test of alignment and data extraction for the master surface and a copy, together with the analysis of the ten sample Alicona data showed good repeatability of the Alicona measurements and the described extraction, alignment and parameter data extraction process. The dimensional artefact, easily included during the measurement stage, allows monitoring of the XCT measurement process. The filament change during the measurement process highlighted the need for this monitoring as the change produced differences in the dimensional artefact OD, ID and Length of −0.75%, −0.76% and −0.74% respectively. Correspondingly, statistically significant changes were observed in the areal parameter data sets after the filament change. Using a traceable artefact, manufactured from a similar material to the surface artefact, such as the dimensional artefact used here, as measured on a CMM, will provide valuable verification of scaling and surface determination for the XCT. Measurement uncertainty for AM surface measurements on the XCT (and indeed the Alicona) will be an ongoing area of research – there are a wide variety of AM surfaces and providing traceable calibration information will be difficult. The process used here describes the extraction of areal surface texture data from XCT

Table 8
CMM and XCT dimensional artefact data.

Measurement method	Mean OD (mm) [% dif. c.w. CMM]	Sample std. dev. (mm)	Mean ID (mm) [% dif. c.w. CMM]	Sample std. dev. (mm)	Mean Length (mm) [% dif. c.w. CMM]	Sample std. dev. (mm)
CMM (10 meas.)	2.9946	0.00016	3.1926	0.00019	3.9542	0.00013
XCT Set 1 (5meas.)	2.9934 [−0.04%]	0.00050	3.1856 [−0.22%]	0.00040	3.9570 [−0.07%]	0.00070
XCT Set 2 (5 meas.)	2.9709 [−0.79%]	0.00060	3.1615 [−0.97%]	0.00030	3.9278 [−0.67%]	0.00040
XCT Set 3 (5 meas.)	2.9714 [−0.77%]	0.00060	3.1624 [−0.95%]	0.00030	3.9280 [−0.66%]	0.00070

Table 9
Percentage change in mean parameter value after changing XCT filament.

Parameter	Set 1 mean value	Set 2 mean value	Percentage difference [(Δ) is absolute difference]
Height parameters			
Sq/μm	40.46	40.07	−0.97
Ssk	1.35	1.34	−0.64
Sku	9.04	8.98	−0.71
Sz/μm	479.07	474.87	−0.88
Sa/μm	29.84	29.59	−0.83
Spatial parameters			
Sal/mm	0.29	0.29	−0.28
Hybrid parameters			
Sdr/%	13.30	13.09	(Δ) −0.21
Sk family parameters			
Sk/μm	89.76	89.01	−0.83
Material ratio parameters			
Smr2/%	91.70	91.74	(Δ) 0.04

scans, but it should be noted that profile information, such as *Ra*, or any other parameter per ISO 4287 [21], may be simply extracted and compared from the aligned areal surface data. The authors consider this procedure a valid method for the extraction of areal (and profile) surface texture information from XCT data, applicable to additively manufactured parts but with potential applications beyond the AM field.

6. Conclusions

A method has been developed to extract areal surface information from XCT volume data and generate surface texture parameters per ISO 25178-2. It has been shown that with careful technique and processing the value of parameters obtained using XCT are remarkably similar to those obtained using conventional optical surface texture measurement techniques. Repeatability has been shown to be good, with the AM artefact removed and replaced between XCT measurements the mean *Sa* value for the sample was 29.6 μm with a sample standard deviation of less than 0.013 μm. The Alicona G4 measurement for the same surface area, also removing and replacing the artefact between measurements, was 30.8 μm with a sample standard deviation of 0.006. This is a difference between the *Sa* value of less than 2.5%. Additive components with internal features will become more commonplace in industrial applications, such as medical, aerospace and automotive. These industries will all need to have understandable, definable pass-fail requirements for internal surface texture. The methodologies illustrated in the current paper allows quantitative measurement of surfaces per existing areal and profile standards. If and when specific AM related standards are generated, this process will be fully adaptable to these.

7. Future work

The present work will be expanded to cover additional aspects of the XCT data transformation process and will include:

- Further investigation of the effects of surface determination on surface texture parameters.
- Development of stand-alone “one-click” software to perform the analysis and generate parameter data from the XCT volume data, either directly from the point cloud information, or extracted and projected onto a plane as a height map.
- Perform a round-robin investigation to compare XCT capability across different XCT platforms and highlight any potential problems for industry end users of this methodology.
- Map the capability across the XCT chamber.
- Investigate extraction of surface data from re-entrant features and free form surfaces.
- Perform wavelet decomposition of XCT and Alicona data sets to investigate the difference in capability in detecting a range of spatial wavelengths.

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