Development of an interlaboratory comparison investigating the generation of areal surface texture data per ISO 25178 from XCT

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Abstract

A significant advantage of additive manufacturing (AM) techniques is the ability to design and manufacture parts without the tool-path limitations inherent when using subtractive techniques, such as milling, turning and grinding. This capability of AM enables the production of components with surfaces (such as internal features) that cannot be inspected using standard surface inspection techniques, for example stylus or optical methods. Measurement and characterisation of these surfaces may be vital for component function, whether it be for fluid flow, coating adhesion or bio-attachment. X-ray computed tomography (XCT) has been investigated as a tool for form and dimensional measurement of AM parts; however there has been little research into the ability of XCT for surface texture (particularly areal) measurement and characterization. This paper discusses the initial work performed on producing parameter data per ISO 25173-2 from XCT scans and the rationale employed in the development of a round robin interlaboratory comparison based on this work. Initial round robin data will be discussed.

Keywords: Additive manufacturing, ISO 25178 surface texture, interlaboratory comparison.

1 Introduction - Why AM surface from XCT?

Additive manufacturing (AM) provides the engineer with design flexibility not available when manufacturing is constrained by the tool-path requirements of conventional subtractive techniques such as milling, turning and grinding. Additionally, the ability to use high performance engineering metals, such as titanium Ti6Al4V, 316 stainless steel and cobalt chrome in the AM process provides the aerospace, medical and automotive industries with a new manufacturing toolbox and these industries have seen the potential and are actively engaged with the AM manufacturing industry. However, AM presents many challenges at this early stage of integration into the manufacturing landscape. These quality-driven industries require defined accept-reject requirements for all measurements. A component manufactured using AM is not exempt from the stringent quality requirements that apply to other manufacturing processes. Surface texture requirements will need to be incorporated into drawings and specifications and imposed by customers onto suppliers, using a common language and standards. Verification of compliance with these requirements will be mandatory for AM components.

The exciting design-flexibility of AM will often result in components with sections, such as internal features, that cannot be inspected using standard measurement systems; this applies to dimensional, form and surface texture measurements. Currently, the only practical method available for extracting dimensional and surface texture information from the internal features of metal AM components is X-ray computed tomography (XCT).

The importance of XCT for the measurement of the surface texture of additively maunufactured parts has been recognised [1, 2], but, until recently, the extraction of quantitative surface information from XCT scans of AM surfaces has been limited to profile analysis of lattice structures [3, 4]. Recent development of techniques to extract and analyse areal surface texture data and produce quantitative numbers for all surface texture parameters per ISO 25178-2 [5] has the potential to provide industry and the research community with significant analysis and inspection capability [6]. This methodology has shown remarkably good results for the extraction and characterization of AM surfaces from metal AM surfaces. The results presented indicated that, for the surface of the ALSi10Mg selective laser melting (SLM) component evaluated, the difference between the *Sa* (arithmetic mean height of the scale-limited surface) values obtained from XCT when compared to a focus variation (FV) instrument was less than 2.5%. However, it should be made clear that surfaces that *can* be measured using other techniques (outside surfaces) generally *should* be measured using the standard techniques. The current resolution of XCT, and hence the basic quality of the surface extracted, lags significantly behind other techniques. Additionally, the estimation of measurement uncertainty for XCT is complex and has not been fully addressed in the research community, leading to potential traceability issues. However, just as the AM process itself presents many challenges, XCT surface measurement has challenges that will be faced and hence need to be resolved because of the unique advantages that XCT provides, particularly for the AM sector.

2 Why a round robin?

The results of the referenced research showed that XCT is a viable technique for surface texture measurement. However, all the measurements taken in the reported research were taken on one XCT machine: the Nikon XT H 225 Industrial CT. Because this technique may have industrial and academic research application it is important to assess machine-to-machine variability, and so an iterlaboratory comparison (round robin) has been developed: CT-STARR.

CT-SURFACE TEXTURE FOR ADDITIVE ROUND ROBIN

The round robin will consist of two stages: Stage 1 discussed in this paper, is to be a tightly controlled, rigorous and expeditious investigation. The format of Stage 2 will be finalized based on the results and lessons learned from Stage 1. Stage 2 will include a significantly larger number than the four laboratory participants for Stage 1.

3 Round robin Stage 1 methodology

CT-STARR Stage 1 is designed to gauge the repeatability and reproducibility of measurements from closely related XCT machines, using tightly controlled measurement settings and data analysis. The four round robin participants and the XCT machines of each participant are shown in Table 1.

Laboratory	Responsible	XCT machine
University of Huddersfield, UK	Andrew Townsend	Nikon XT H 225 Industrial CT
University of Nottingham, UK	Richard Leach	Nikon MCT225 Metrology CT
National Physical Laboratory, UK	Peter Woolliams	Nikon MCT225 Metrology CT
Nikon Metrology, UK	David Bate	Nikon MCT225 Metrology CT

Table 1: Round robin participating laboratories

3.1 Measurement artefacts

Two artefacts were chosen for the round robin: one AM artifact with a square planar surface area used for all surface measurements and one turned artefact designed for the assessment of scaling and surface determination errors. The same material was used to manufacture both artefacts. This was done to present similar challenges for surface determination during the surface extraction process. Both artefacts were manufactured from titanium Ti6Al4V ELI (extra-low interstitial). This is a high-purity version of Ti6Al4V with lower specified limits on iron, nitrogen, carbon and oxygen. This grade of titanium is commonly used in medical and dental applications because of its excellent bio-compatibility. The ELI grade (Grade 23) has superior damage tolerance (fracture toughness, fatigue crack growth rate) and better cryogenic mechanical properties than Grade 5 Ti6Al4V.

3.1.1 AM artefact

The AM artifact was manufactured on an ARCAM Q10 electron beam melting (EBM) machine. The nominal powder size was 45 -100 µm. A vertical (side) surface was used for all round robin measurements. The required size of the AM surface to be measured was calculated using the profile roughness (*Ra*) of the surface. Areal standard ISO 25178-3 [7] defines the L-filter nesting index based on the scale of interest. As this is an arbitrary judgment and surface specific, the required filtering and measurement size were based on the profile measurement standard set. The measured roughness (*Ra*) was approximately 30 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 an areal measurement area of 8 mm x 8 mm per ISO 25178-3 [15]. The artifact was manufactured as a cube of side lengths 10 mm. This provided suitable extra area for aligning and cropping to a "clean" 8 mm x 8 mm surface area.

3.1.2 Surface determination and scaling artifact

The machined artifact used to assess surface determination and dimensional scaling is shown in Figure 1.

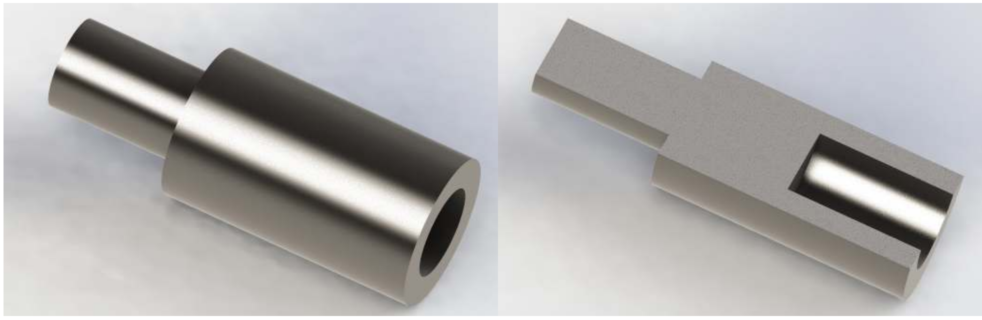

Figure 1: Dimensional and surface determination scaling artefact

The overall size of this artefact (13 mm long), manufactured from the same material as the AM surface artefact, was designed to produce similar X-ray attenuation as the AM surface artefact, therefore making it possible to optimise XCT settings for both artefacts simultaneously. Three dimensions were measured during the round robin: The step-length between two parallel faces, one outside diameter (OD) and one inside diameter (ID). The OD and ID were machined to the same nominal dimension (3 mm). These three dimensional configurations were designed to enable the analysis of possible surface determination and global scaling errors. If the surface determination were to calcluale and position the generated surface outside the part surface then the ID would tend to be undersized and the OD would tend to be oversize. Surface determination errors would have negligible effect on the length mesaurement.

3.2 Fixture design

Both artefacts were mounted in an additively manufactured acrylonitrile butadiene styrene (ABS) polymer fixture, see Figure 2. The fixture includes nylon slot-headed set screws to positively retain both artefacts. The surfaces to be measured on both atefacts were not in direct contact with the polymer. The air gap around all these surfaces, producing an air-Ti boundary, was designed to provide optimum surface determination conditions. The fixture design allowed the surface-of-interest of the AM component and the machined artifact to fill the projected image field, therefore maximizing pixel size. The fixture includes a necked-down section that allows line-of-sight between the XCT gun and detector panel at all times during the scan. The flux-normalization area was placed in this area. The brightness within this area for every projected image is compared and normalized to compensate for system variations during the scan.

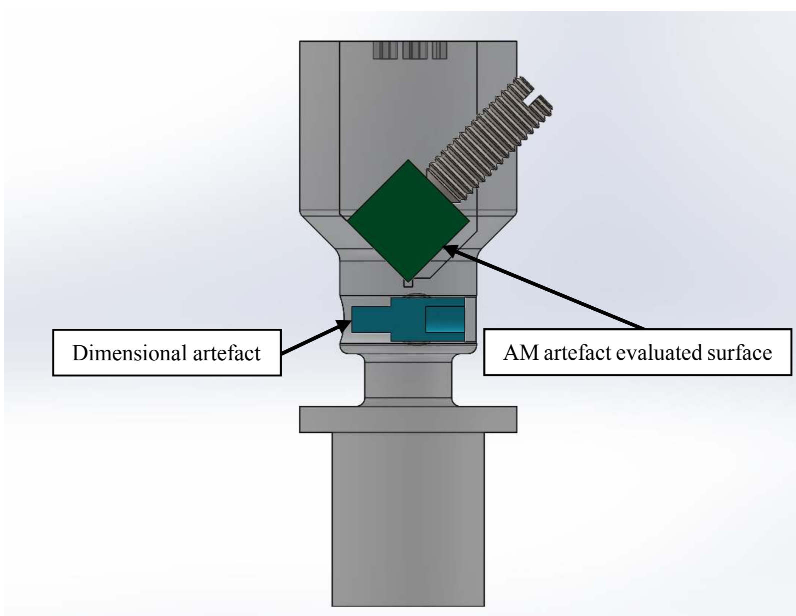

Figure 2: CAD section view of the XCT measurement fixture

3.3 XCT measurement settings

The measurement settings for the XT H 225 are shown in Table 2. These settings were chosen to optimize the exposure contrast while allowing the use of a fully-focused electron beam. The power was kept below 10 W, with the normal focusing setting used on the XCT for all measurements. Above this power the auto-defocus setting is used to keep the energy per unit area of the electron beam target below a safe level, avoiding possible damage to the target. This auto-defocussing effectively blurs the projected images. The artefacts were not removed from the fixture between measurements. The AM surface texture artefact had been removed and replaced in previous work [6] and the results showed no significant difference in the values of extracted surface texture parameters form those obtained when the artifact was not disturbed between scans. Not disturbing the artefacts between measurements will minimize the possibility of damage to the artefacts during the round robin.

Parameter	Value	Parameter	Value
Filter material	Copper	Voxel size	17.3 µm
Filter thickness	1.0 mm	Source to object distance	84.2 mm
Acceleration voltage	160 kV	Source to detector distance	972 mm
Filament current	62 µA	Number of projections	1583
Exposure time	2829 ms	Detector size (pixels)	1008 x 1008

Table 2: Nikon XT H 225 measurement settings

Reconstruction was performed using Nikon CTPro 3D [8] and surface determination was performed using VGStudio MAX 3.0 [9]. Local iterative surface determination was performed with a search distance of 4.0 voxels. Two regions of interest (ROI) were extracted: the dimensional artefact and the AM surface section. The ROI were then converted to a mesh using the VGStudio MAX “Super Precise” setting. A photograph of the fixture within the XT H 225 is shown in Figure 3.

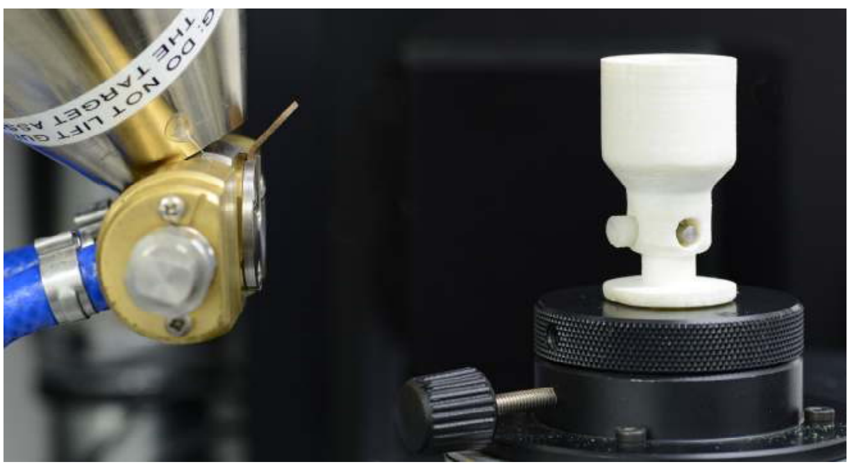

Figure 3: Fixture with artefacts mounted within the XT H 225

3.4 Comparative measurements

Initial results of surfaces and dimensions extracted from the XT H 225 round robin measurements were compared to measurements from an Alicona G4 focus variation instrument and a Zeiss Prismo coordinate measurement machine (CMM) respectively. The extraction and analysis methodology is reported in [6]. The Alicona measurement settings were selected based on ISO 25178-3 requirements. An L-filter nesting index of 8 mm (as discussed in para. 3.1.1) resulted is the selection of an S-filter nesting index value of 0.025 mm per ISO 25178-3 Table 1. The ratio between the S-filter nesting index value and the measurement sampling distance is required to a minimum of 3:1 for optical instruments per ISO 25178-3 table 3. The measurement sampling distance of 2.33 µm used here gives a ratio of greater than 10:1. All XCT data was levelled and filtered using the same filter settings.

4 Surface artefact results

A comparison of the values of areal parameters per ISO 25178-2 from the same surface area measured on the XT H 225 CT and the Alicona G4 is shown in Table 3.

Parameter per ISO 25178-2	Mean Alicona (5 meas.)	Alicona standard deviation	Mean XT H 225 CT (5 meas.)	XCT standard deviation	Percentage difference, XCT in relation to Alicona [(Δ) is absolute difference]
Height parameters					
Sq / µm	32.40	0.001	30.77	0.036	-5.0
Ssk	0.25	<0.001	0.08	0.016	(Δ) -0.17
Sku	3.70	<0.001	3.67	0.009	-0.8
Sp /µm	192.00	0.132	187.20	1.352	-2.5
Sv / µm	138.59	0.186	135.07	2.188	-2.5
Sz / µm	330.59	0.306	322.27	2.889	-2.5
Sa / µm	25.33	0.001	24.05	0.031	-5.1
Spatial parameters					
Str	0.79	<0.001	0.80	0.002	1.3
Sal / mm	0.12	<0.001	0.12	<0.001	0.0
Hybrid parameters					
Sdq	1.00	<0.001	0.81	0.002	-19.0
Sdr / %	39.90	0.013	28.26	0.123	(Δ) -11.64
Volume parameters					
Vmp / (µm³/µm²)	1.93	<0.001	1.73	0.011	-10.4
Vmc / (µm³/µm²)	28.21	<0.001	27.07	0.071	-4.0
Vvc / (µm³/µm²)	38.47	0.005	35.03	0.081	-8.9
Vvv / (µm³/µm²)	34.72	<0.001	35.93	0.027	3.5
Sk family parameters					
Spk / µm	39.95	0.005	36.14	0.198	-9.5
Sk / µm	81.17	0.009	76.36	0.070	-5.9
Svk / µm	30.07	0.009	31.52	0.338	4.8
Material ratio parameters					
Smr1 / %	10.00	<0.001	8.96	0.089	(Δ) -1.04
Smr2 / %	90.40	<0.001	88.88	0.130	(Δ) -1.52

Table 3: Comparison of mean Alicona and XCT ISO 25178-2 parameter results

Charts for the selected areal parameters are shown in Figure 4. The charts include the data for the Alicona and XCT with the 95% confidence interval for the mean for both.

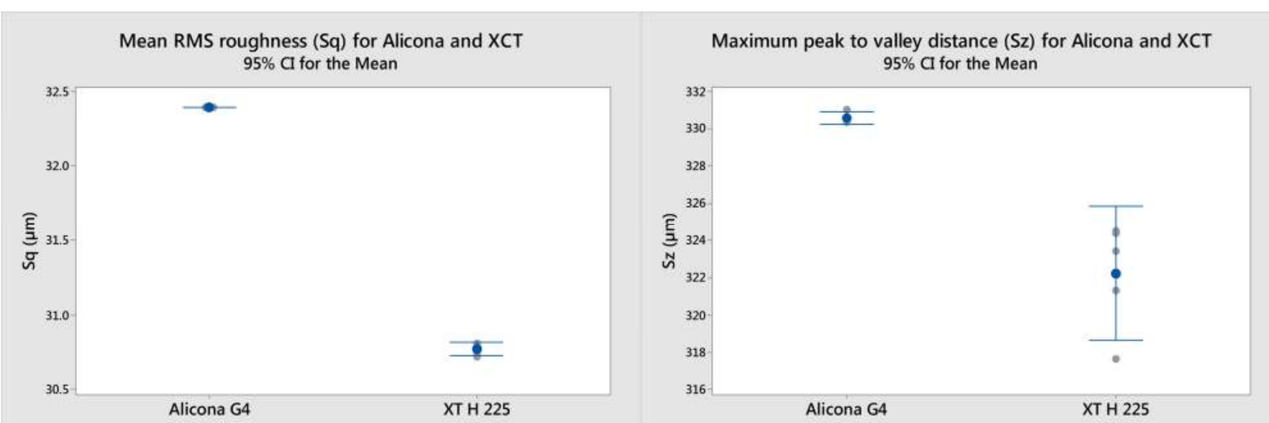

Figure 4: Dimensional and surface determination scaling artefact. The error bars are the 95% confidence interval for the mean. The blue markers are the mean value, the grey markers are each individual value

The false colour height maps for one of the Alicona measurements and one of the XCT measurements are shown in Figure 5. It can be seen that the height maps are visually very similar.

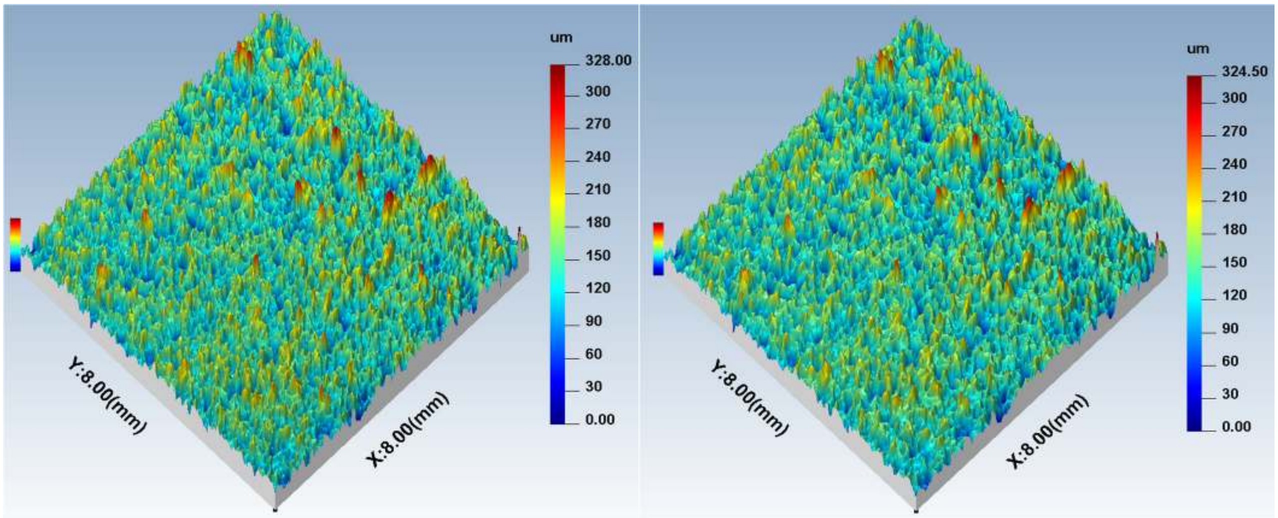

Figure 5: False colour height maps of the extracted surface (a) Alicona, (b) XT H 225

5 Dimensional artifact results

The results of the CMM and XCT measurements of the OD, ID and Length are shown in Table 4 and Figure 6. The mean difference between the XCT and CMM measurements of the OD, ID and Length were -0.27%, -0.83% and -0.54% respectively. A compensation for surface determination can be made for the dimensional artifact. Applying a compensation of 4.1 µm (moving the determined surface toward the part material) makes the OD smaller, the ID larger; the Length dimension remains unchanged. The percentage differences between the XCT measurements and CMM measurements for OD, ID and Length then become -0.55%, -0.55% and -0.54% respectively.

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.)	2.97345	0.00005	2.98457	0.00005	4.62400	<0.00005
XCT (5 meas.)	2.9654 [-0.27%]	0.00030	2.9599 [-0.83%]	0.00030	4.5990 [-0.54%]	0.00160
After compensating for possible surface determination error by removing 4.1 µm from the XCT surfaces						
XCT (comp.)	2.95724 [-0.55%]		2.96812 [-0.55%]		4.5690 [-0.54%]	

Table 4: Comparison of mean CMM and XCT dimensional results

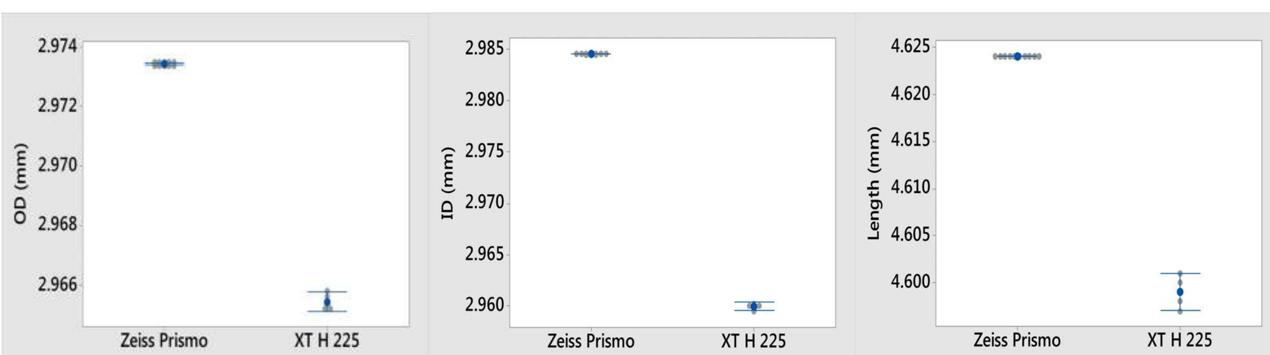

Figure 6: OD, ID and Length from CMM and XCT, showing 95% confidence interval for the mean

6 Discussion

The initial round robin XCT surface texture measurement results show good repeatability; for example, the mean *Sq* value was 30.77 µm with a sample standard deviation of 0.036 µm (five measurements). The difference between the mean Alicona measurement and the mean XCT measurement was approximately 5% for *Sq*. The dimensional artefact was used for analysis of scaling and surface determination and showed that, if compensation for surface determination was applied (by "moving" the determined surface 4.1 µm toward the part material), then the ID, OD and Length were consistently 0.54% - 0.55% smaller than the CMM measurements. A global (x,y,z) compensation could then be applied to approximate the measured CMM dimensions. The resultant effect of the AM surface parameter data from the post-measurement scaling will be investigated, but an indication of the difference produced by scaling differences has been reported [6]. In this study the scaling difference was as a result of changing the XCT tungsten filament. The results showed that a scaling difference of approximately -0.75% (x,y,z) produced a difference in *Sa* for the aliminium AlSi10Mg sample of -0.83% and *Sq* of -0.97%. One note about scaling changes produced when the XCT filament is changed: the Nikon MCT225 metrology CT includes a measurement artefact and protocol for calibration after each filament change. This Nikon MCT225 metrology CT will be used by the remaining three round robin participants and will be compared to the results presented here for the Nikon XT H 225 industrial CT. The metrology CT will produce reconstructions with a smaller voxel size: the XT H 225 has a 1008 x 1008 pixel detector, whereas the MCT225 has a 2000 x 2000 pixel detector. Therefore, with correct magnification adjustments, the voxel size for the metrology CT will be approximately one half the voxel size for the industrial CT. This will produce eight times as many voxels for each scan. The resultant effect on the values of surface texture parameters and dimensional artifact will be reported in the final round robin report.

7 Conclusions

Methodology for an inter laboratory comparison of areal surface texture extraction from XCT has been presented and discussed. Measurement artefacts, fixturing, inspection parameters, comparative measurements and initial results have been presented. The results obtained from one of the four round robin participants using a Nikon XT H 225 industrial CT show good repeatability results for the Ti6Al4V ELI scaling artifact and surface texture surface, with a surface texture *Sq* value difference between XCT and an Alicona G4 focus variation instrument, of 5%. It is considered that the methodology presented here provides a sound basis for the initiation of the interlaboratory comparison.

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References

[1] Thompson A., Senin N., and Leach R.K., Towards an additive surface atlas. in Proceedings of dimensional accuracy and surface finish in additive manufacturing, ASPE 2016 Summer Topical Meeting. Raleigh, NC, 2016.

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

[3] Pyka G., Kerckhofs G., Papantoniou I., Speirs M., Schrooten J., and Wevers M., Surface Roughness and Morphology Customization of Additive Manufactured Open Porous Ti6Al4V Structures. Materials. **6**(10): p. 4737-4757, 2013.

[4] Kerckhofs G., Pyka G., Moesen M., Van Bael S., Schrooten J., and Wevers M., High-Resolution Microfocus X-Ray Computed Tomography for 3D Surface Roughness Measurements of Additive Manufactured Porous Materials. Advanced Engineering Materials. **15**(3): p. 153-158, 2013.

[5] ISO_25178-2 B.E., BS EN ISO_25178-2, in Geometrical product specifications (GPS) Surface texture: Areal 2: Terms, definitions and surface texture parameters. British Standards Institute, 2012.

[6] Townsend A., Pagani L., Scott P., and Blunt L., Areal surface texture data extraction from x-ray computed tomography reconstructions of metal additively manufactured parts. Precision Engineering, http://dx.doi.org/10.1016/j.precisioneng.2016.12.008, 2016.

[7] ISO_25178-3 B.E., BS EN ISO_25178-3, in Geometrical product specifications (GPS) Surface texture: Areal Part 3: Specification operators. British Standards Institute, 2012.

[8] Nikon metrology NV, Nikon CT-Pro.

[9] Volume Graphics GmbH, VGStudio MAX.