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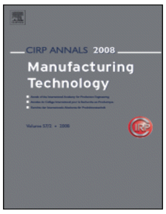

Factors affecting the accuracy of areal surface texture data extraction from X-ray CT

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The ability to perform non-destructive areal surface analysis of the internal surfaces of additively manufactured (AM) components would be advantageous during product development, process control and product acceptance. Currently industrial X-ray computed tomography (XCT) is the only practical method for imaging the internal surfaces of AM components. A viable method of extracting useable areal surface texture data from XCT scans has now been developed and this paper reports on three measurement and data processing factors affecting the value of areal parameters per ISO 25178-2 generated from XCT volume data using this novel technique.

X-ray, Metrology, Additive manufacturing

1. Introduction

Additive manufacturing (AM) techniques allow the manufacture of parts with geometries and features that cannot be manufactured using subtractive techniques such as milling and turning. This significant advantage of AM is primarily because this technique's layer-by-layer build method is not constrained by the machine tool access requirements of standard machining processes. Correspondingly, access limitations associated with complex geometries prevent standard inspection instruments and techniques from being used to verify dimensions and surface finishes of AM components. The aerospace, medical and automotive sectors have embraced the opportunities presented by AM and additive applications within these industries have seen rapid growth, particularly after the introduction of metals-fed AM machines [1]. These quality-driven industries require traceable verification of all specification and drawing requirements, including surface texture. The primary method used for measuring the internal features of AM components has been X-ray computed tomography (XCT). Significant research has been performed in relation to dimensional metrology using XCT. This dimensional research includes measurement accuracy [2, 3], scaling error compensation [4] and development of XCT measurement procedures and workflows [5, 6]. Surface texture-from-XCT extraction and characterisation, however, is in its infancy, but If XCT is to be used as an industrial inspection tool for component surface texture acceptance then this measurement and characterisation will need to be performed per accepted reference standards, such as ISO 25178. Surface texture data per ISO 25178-2 [7] has now been extracted from XCT scans of additively manufactured (AM) components, as described in Townsend et al. [8]. The authors' research forms a foundation for the current paper and the current paper addresses questions that had arisen during the measurement and characterisation work performed: factors affecting the accuracy of the extracted surface texture data. This paper reports on three factors: firstly, the effect of variation in XCT surface determination, which is the process of defining where the surface of an object is based on image grey-scale values. Surface determination was chosen for investigation because the user has to make a non-intuitive choice during surface extraction. The potential effect of this choice is reported here. Secondly, the effect produced by changing the XCT electron-generation filament. This was chosen as an area of investigation as a filament change during a production run will potentially be unavoidable and so the potential effects should be investigated. Thirdly, the differences between results obtained between one surface section measured as an internal and subsequently as an external feature. AM techniques now enable the manufacture of components with complex, critical internal features. It is important to verify that XCT surface data extracted from internal surfaces is *identical* to that extracted from identical external surfaces. Other potential areas of investigation, such as position within the XCT measurement chamber, variation in acceleration voltage, filament current and acquisition time are more measurement component dependent than the three more fundamental areas of investigation reported here.

2. XCT Surface determination

XCT surface determination defines the boundary between the component material and the background (usually air) based on the XCT image grey scale (density) values. The surface determination methods employed to determine which grey scale value is appropriate have been shown to have a significant effect on dimensional information extracted from XCT volume data [6, 9]. Here we apply four surface determination techniques to extract the surface (and subsequently generate and compare areal parameter data) from a metal Rubert comparator plate. Using the commonly available Rubert sample plates allows comparison of the effect of surface determination on surfaces with similar configuration but different roughness values when using similar XCT measurement settings and surface characterisation.

2.1. Measurement plates

Individual rectangular plates, approximately 10 mm x 20 mm, were cut from a Rubert Microsurf 334 (casting) test panel. The casting panel was used as this surface was considered to most closely represent the surface of a powder bed fusion (PBF) metal AM component. The nominal surface *Ra* values for the plates used for this work were 50 μm and 25 μm as these approximate the as-built PBF metal AM surface roughness [10]. The individual samples were imaged using a Nikon XT H 225 industrial CT machine. Acceleration voltage was 190 kV, filament current was 53 µA, with an acquisition time of 4000 ms. A 1 mm copper filter was used to reduce contrast and beam hardening. Auto-defocus was deactivated. The voxel size for all measurements was 12.9 µm (*x*, *y* and *z*). Measurement parameters were identical for both samples.

2.2. Surface determination methods

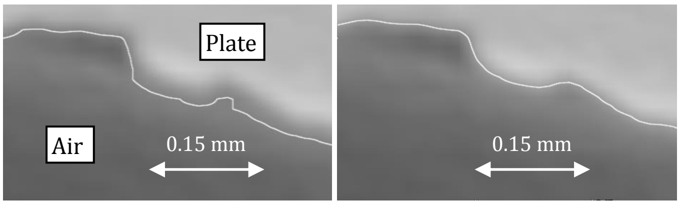
XCT surface determination was performed using four different methods, three global and one local.

"Manual" in which the global surface determination was set by the user by visually optimizing the surface location, implemented in VGStudio MAX 2.2 [11].

ISO 50 surface determination, is also implemented in VGStudio MAX 2.2. The ISO 50 method defines a global threshold which is computed as the mean of two peaks (background and material) of the grey value histogram.

The third global surface determination method is the Otsu method [12] implemented in ITK [13]. Otsu surface determination finds two clusters, in the grey value histogram, such that the sum of the within-class variances of the foreground and background is minimised.

The local iterative surface determination method, implemented in VGStudio MAX 2.2 performs surface determination based on the local surface grey values. Examples of surfaces created using ISO 50 and local iterative surface determination are shown in figure 1. The difference between the locations of the computed surface boundary (white line) can clearly be seen.



(a) (b)

Figure 1. Rubert 50 plate surface determination (VGStudio MAX 2.2 [13]). (a) ISO 50 surface determination (b) local iterative surface determination.

Surface conversion to a mesh (STL) format, following surface determination, was performed using the VGStudio MAX 2.2 "Super Precise" setting [10].

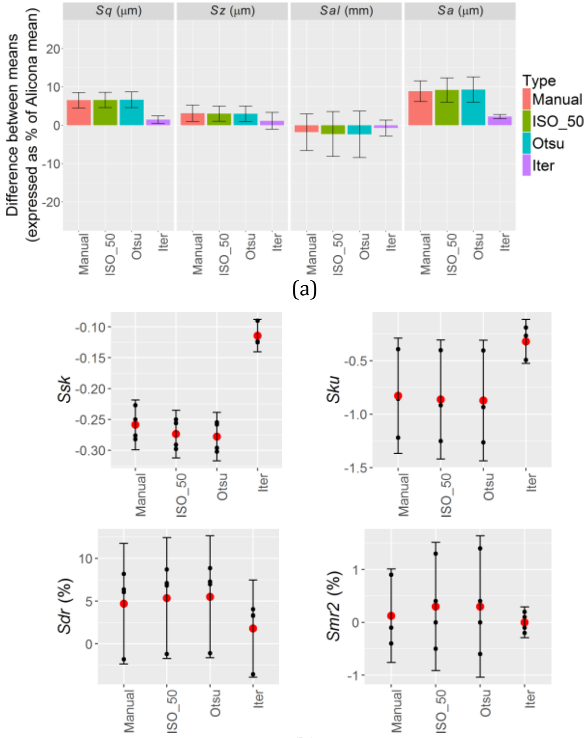
2.3. XCT-focus variation comparison

The XCT results were compared to those obtained using an Alicona G4 focus variation instrument. Focus variation (FV) has been one of the most widely used areal surface measurement technologies for AM research [10]. FV has a large measurement z-range suitable for tall AM structures, has the ability to measure surfaces with high slope angles [14], is well suited to the reflectivity of as-built AM components and is easily adaptable for a variety of roughness levels. The Alicona measurements were performed using a 5x objective lens. Lateral sampling distance was 5 µm; lateral resolution was 15 µm. Surface extraction and processing was performed as described in [8]. The XCT and FV measured areas for each of the Rubert samples were aligned using the ICP (Iterative Closest Point) algorithm and then cropped. Four sample areas, 5 mm x 5 mm were extracted from each of the 25 µm and 50 µm *Ra* samples. Both surfaces were levelled and filtering was performed using an L-filter nesting index (hi-pass filter) of 5 mm and an S-filter nesting index (low-pass filter) of 0.020 mm. A surface texture parameter set per ISO 25178-2 was generated using SurfStand [15].

2.4. Analysis of results

The stated Rubert plate profile *Ra* values were compared to the *Ra* values from profiles extracted from the Alicona areal measurements. Five measurements, each 5 mm long were extracted. Each of these measurements was the mean of five individual profiles. A λ_c cutoff of 8 mm was applied, per ISO 4288 (1996) [16]. The mean of the five measured *Ra* value for the 25 µm nominal *Ra* Rubert sample plate was 25.3 µm with a sample standard deviation of 1.8 µm. The mean measured *Ra* value for the 50 µm nominal *Ra* Rubert sample plate was 46.0 µm with a sample standard deviation of 3.7 µm. All subsequent analysis was performed using areal parameters per ISO 25178-2 [7, 17].

For each of the Rubert sections a paired t-test was performed; the null hypothesis being that the difference between the mean parameter as measured on the XCT and on the Alicona was zero. The 95% confidence interval of the mean was then generated for each of the samples. The percentage difference between the mean FV and XCT readings, together with the 95% confidence interval were plotted for each of the analysed parameters: *Sq*, *Sz*, *Sal* and *Sa* (figures 2(a) [50 µm *Ra*] and 3(a) [25 µm *Ra*]). The absolute differences between XCT and FV results for the parameters *Ssk*, *Sku*, *Sdr* and *Smr2* are shown in figures 2(b) [50 µm *Ra*] and 3(b) [25 µm *Ra*]. These selected parameters were chosen because they have been shown to be sensitive to AM build performance and post-processing surface changes [10].

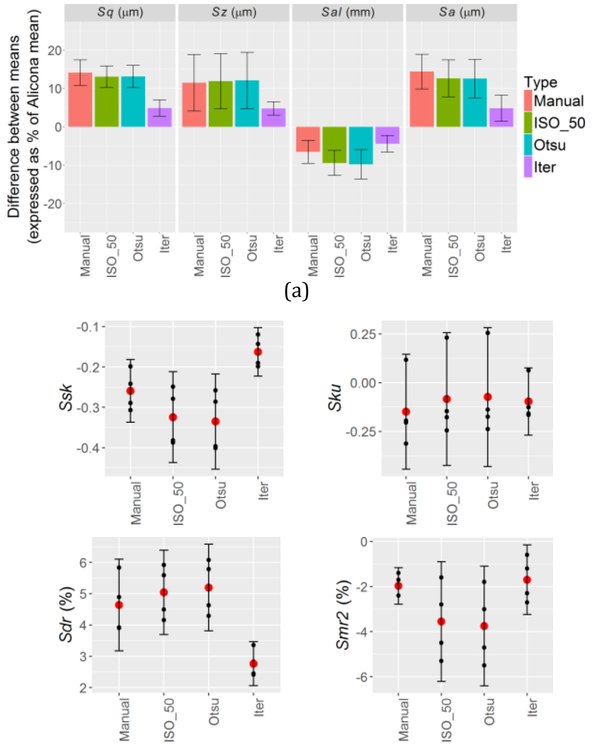


(a)

(b)

Figure 2. Areal parameters of the Rubert sample, nominal *Ra* of 50 µm.

The reconstructed surfaces using the global surface determination methods achieve generally similar results, in some instances the manual surface determination has slightly better parameter estimation than the other global methods. Comparing the local with the global surface determination methods for both the 50 µm *Ra* and 25 µm *Ra* plates it can be seen that the local iterative method achieves results significantly closer to those obtained using the Alicona G4.



(a)

(b)

Figure 3. Areal parameters of the Rubert sample, nominal *Ra* of 25 µm.

3. Electron-generation filament

The filament life for the Nikon machine used for these analyses has historically ranged from 20 hours to over 100 hours. The situation may arise during an industrial inspection process where the filament fails and has to be replaced mid-batch and so any variation in results due to filament change has the potential influence measurement accuracy, repeatability and batch acceptance.

3.1 Measurement artefacts

A 10 mm x 10 mm aluminium AlSi10Mg selective laser melting (SLM) AM cube was scanned five times using the Nikon XT H 225. Acceleration voltage was 150 kV, filament current was 67 µA, with an acquisition time of 2829 ms. A 0.5 mm copper filter was used. Auto-defocus was de-activated. Voxel size was 17.3 µm (*x*, *y* and *z*). The filament was then changed and the artefacts were again scanned five times using identical machine parameters. The top surface data was extracted [8]. The same surface was measured on the Alicona G4. The Alicona measurements were performed using a 10x objective lens. Lateral sampling distance was 2.33 µm; lateral resolution was 7 µm. The AM surfaces were levelled and filtered with an L-filter nesting index of 8 mm and an S-filter nesting index of 0.025 mm per ISO 25178-3 [18]. The results for the selected ISO 25178-2 parameters for the AM artefact surface are shown in figure 4.

3.2. Analysis of results

The values of *Sq* and *Sa* (mean of five measurements) changed by -0.97% and -0.83% respectively after changing the filament. This change, while not large, may be significant depending upon application and potential issues should be taken into consideration. The change in values for the remaining selected parameters is not significant. The XT H 225, the type used for these analyses, is an industrial machine. It should be noted that Nikon produces a metrology XCT machine, the MCT225, which does include a protocol and supplied artefact to be used post-filament change for system calibration.

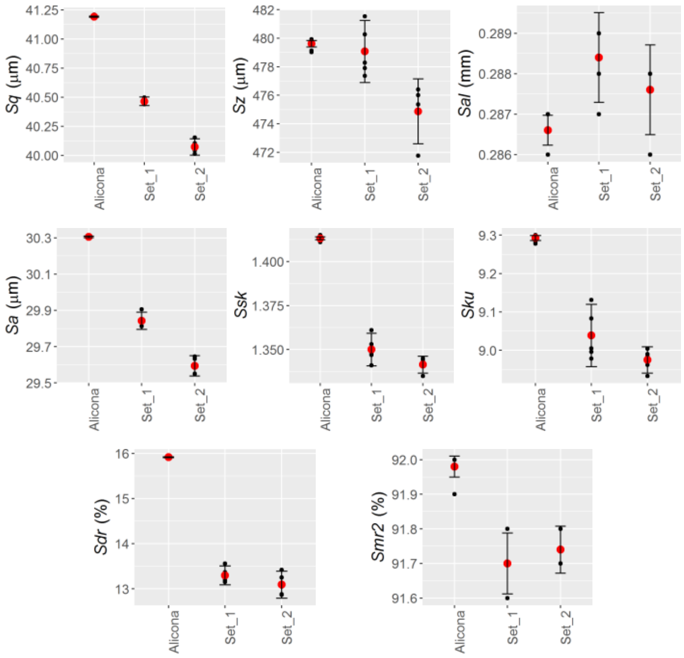


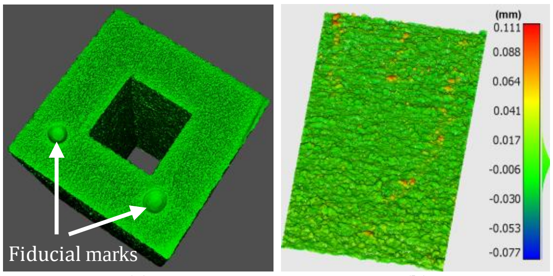
Figure 4. Areal parameters for the Alicona and Pre (Set 1) and Post (Set 2) filament change XCT.

4. Analysis of areal surface parameters of internal features

The most significant advantage of XCT over line-of-sight measurement systems is the ability of XCT to measure the internal features of an object, so potentially avoiding costly destructive testing. AM techniques now enable the manufacture of components with complex, critical internal features. However for the advantages of both XCT and AM to be realised it is important to verify that XCT surface data extracted from internal surfaces is no different to that extracted from identical external surfaces, that there are, for example, no artefacts generated during the XCT measurement process specifically on internal surfaces. This equivalency is important if, for example, a reference measurement is taken on an outside surface using a stylus or optical instrument and then compared to both external and internal surface data extracted from XCT scans of the same component. This investigation assesses whether a surface inside the part reconstructs and analyses differently from the same surface on the outside of the part. Focus variation measurements are not analysed since the aim of this section is to evaluate the reconstruction of the internal features compared to external features, not to quantify the XCT measurement deviations.

4.1. XCT measurement

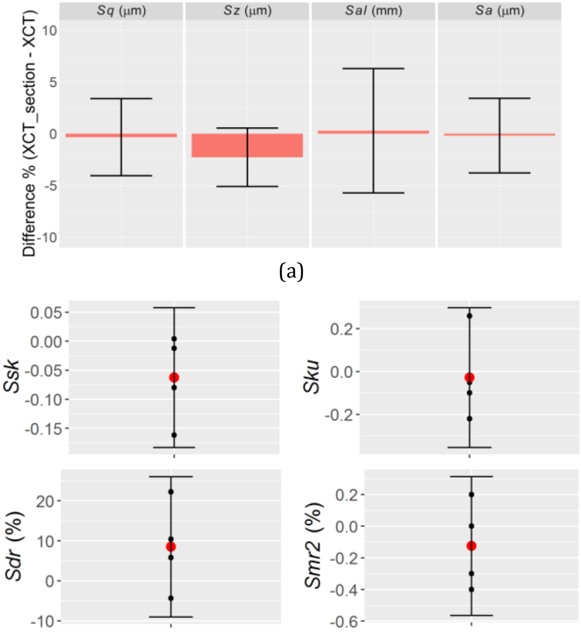
A titanium Ti6Al4V 10 mm square section SLM bar, 50 mm long with a 4 mm square internal bore, was imaged using the Nikon XT H 225. The component was then physically sectioned, the “internal” surface now becoming “external”, and the component was then re-imaged on the XCT. Measurement settings were identical for both scans. Acceleration voltage was 210 kV, filament current was 48 µA, with an acquisition time of 4000 ms. A 1.0 mm copper filter was used. Auto-defocus was de-activated. The voxel size of both reconstructed volumes was 15.9 µm (*x*, *y* and *z*). The surfaces were extracted using local iterative surface determination implemented in VGStudio MAX 2.2. Manual alignment of the surfaces from pre and post-sectioned scans was performed utilising the two fiducial marks, see figure 5(a). The ICP algorithm was used for final alignment. Data processing and parameter extraction was performed per [8]. Figure 5(b) shows the false colour height map for the deviation analysis between the two extracted surfaces. The deviation ranged from -0.08 mm to 0.11 mm.



(a) (b)

Figure 5. (a) XCT reconstruction (b) deviation analysis.

After the alignment each mesh was cut into four sub-samples, each with a dimension of approximately 3 mm x 3 mm. A uniform re-sampling with a nominal resolution of 1.5 µm was performed. The samples were levelled and Gaussian filtering was applied. The L-filter nesting index and the S-filter nesting index were set, respectively, to 2 mm and 0.005 mm. With a confidence level of 95% the null hypothesis of equality of the means cannot be rejected for all the roughness parameters analysed. Figure 6(a) shows the bar plot of the percentage differences between the internal and external surface XCT measurements for parameters *Sq*, *Sz*, *Sal* and *Sa*, displaying the 95% confidence interval. Figure 6(b) shows the absolute values and 95% confidence interval of *Ssk*, *Sku*, *Sdr* and *Smr2*. These results show there was insignificant difference between the same surface as internal and as an external surface.



(a)

(b)

Figure 6. Areal parameters. Showing difference between internal and external measurements.

5. Conclusions

The effects of three XCT measurement and reconstruction factors on the surface texture data extracted from XCT scans have been investigated. The analysis of scanned Rubert comparator plates has shown that using local iterative surface determination during XCT reconstruction will provide the most accurate results for surface texture parameter generation. Changing the XCT filament had a statistically significant effect on the *Sa* values extracted from a Ti6Al4V SLM component. A comparison of areal parameters computed on the same surface section of a Ti6Al4V SLM part as an internal and external feature has been performed. The measurements will be expanded to include other materials and wall thicknesses, but these initial results indicate no significant difference between the mean values of the generated parameters for the internal and external measurements. These results will provide valuable information to aid in the optimisation of the XCT surface texture measurement and extraction process for research and industrial applications.

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