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Investigation of effect of voxel size choice for the measurement and analysis of porous coatings

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Abstract

This study aims to investigate the effects of voxel size change with measurement and characterisation of functional characteristics of a porous surface or coating. Prevalent across numerous fields, porous coatings and surfaces have been utilised and exploited for their unique characteristics, particularly in the biomedical field, where their osseointegrative potential is paramount. Due to the topographical nature of this surface type, the use of X-Ray Computed Tomography (XCT) is often dictated when re-entrant features are present. Voxel size is the indicative parameter in determining the resolution of the corresponding scan, with lower values resulting in increased scan times and data size implications but offer an increase in the scale of features that can be obtained. Topographical surface area information and amplitude parameters have been utilised in this comparative study to demonstrate the effects a change of voxel size has on the surfaces extracted from XCT measurements.

Titanium Alloy (Ti6Al4V) coupon samples (12.7 mm diameter, 4.73 mm avg. thickness) were used for this study. They incorporate a porous plasma sprayed top coating with machining marks present on the opposing surface with a unique engraved identification mark present. A voxel size range of 8 µm to 76 µm was used, these resulted in a topographical surface area decrease, with values of 883 mm^2 and 471 mm^2 respectively. Amplitude parameters were used on the machining marks only, with root mean square roughness changing from 0.9 µm to 3.1 µm, with large variation between the voxel size intervals. Visible differences are instantly noticeable with the identification mark being only visible at voxel sizes below 25 µm.

Keywords: Ti6Al4V, Porous, CT, X-Ray Computed Tomography (XCT), Topography, Voxel, Surface.

1. Introduction

The use of X-Ray Computed Tomography (XCT) for surface measurement and analysis has seen heightened interest, progressed further by the advent of complex additive manufactured (AM) parts, where both internal and external surfaces can be designed and manufactured [1]. Traditional measurement techniques such as optical and contact methods are unsuitable when features are present such as re-entrant features that do not fall within the scope of line-of-sight methodologies, and thus multiple *Z*-points for a given *X* coordinate are captured and non-destructive analysis is not possible. Techniques such as Focus Variation Microscopy (FVM), whilst capable of higher resolutions suffer with these constraints, although capable of being utilised for AM parts, where re-entrant or internal features are present alternative methods such as XCT are employed [2]. A major contributor to the resolution of XCT is the voxel size for a given measurement, commonly determined by geometrical constraints of the sample where CT instrumentation uses cone beam technology. A lower voxel size is associated with finer resolution and increases the opportunity to capture finer features on the surface and overall increase in the sharpness, aiding in a more precise surface determination.

Porous coatings and surfaces have been exploited across numerous industries, in particular within the biomedical field for the design of prosthetics [3, 4] and to harness their osseointegrative potential. Although coined a porous surface, the topography of the surface is that of a highly irregular, stochastic design with pores that are not contained but instead exhibit overhangs and therefore does not fall within the conventional definition of the term, porous. The porous surface used within the scope of this research, has been deployed through a plasma spraying process, identical to that of the coatings found on hip prosthesis. The use of XCT for the measurement and characterisation of porous coatings and acquisition of quantifiable data regarding topographical information is yet to be recognised. This research aims to highlight the importance of establishing a suitable voxel size for a given application.

2. Methodology and Materials

2.1. Materials

A 12.7 mm diameter, Titanium alloy (Ti6Al4V) coupon sample was used with a thickness of 4.73 mm. The sample consists of a porous plasma sprayed top coating, with conventional turned tooling marks on the underside resultant of the parting process from a lathe machine. A unique identifier is engraved across the tooling marks. A reconstructed model of the specimen can be seen in figure 1.

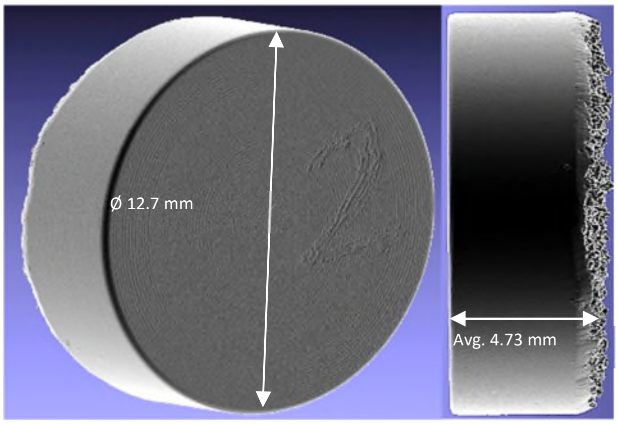


Figure 1 - Reconstructed Model of specimen captured through XCT**.**

2.2. Measurement methodology & scan parameters

As previously stated, XCT was utilised to capture both faces of the specimen, the porous coating, and the machined underside. A Nikon MCT 225 CT instrument was employed for all measurements. Alicona G5 (FVM) was utilised to measure the machined underside only. The measurement parameters for both XCT and FVM can be found in tables 1 & 2 respectively.

Table 1 - XCT Measurement Parameters

XCT (Nikon MCT 225)	
Parameter	**Value**
Filter	Cu (0.25 mm)
Voxel range	8 – 76 µm
Detector	2048 x 2048
Acceleration Voltage	195 kV
Filament Current	35 µA
No. of projections	1600

Table 2 - FVM measurement information

FVM (Alicona G5)	
Parameter	**Value**
Magnification	20x
Measurement Area	4.2 x 4.2 mm
Light Configuration	Coaxial
Brightness	31.74 ms
Contrast	1.36
Lat. Resolution	0.881 µm
Vert. Resolution	0.597 µm
Sampling Distance	0.440 µm

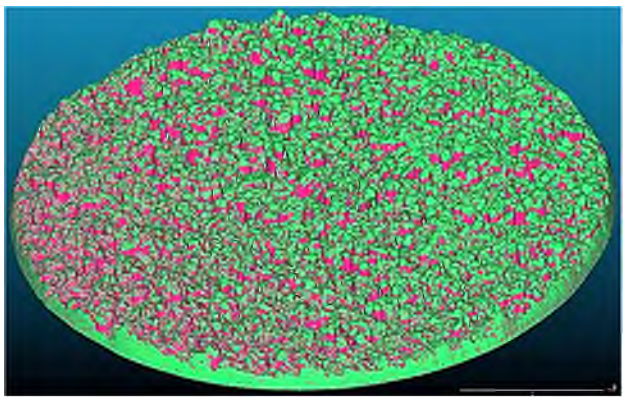
To ascertain the effects of a change of voxel size, scans were repeated within a range of voxel sizes; 8, 16, 24, 30, 36, 46, 56 and 76 µm. The lowest voxel size was chosen as this represented the minimum distance the sample can be placed to the beam aperture and still capture the entirety of the sample through a full rotation. The same sample, with identifier "2" was used for measurements and repeated at each voxel size twice. The sample was mounted vertically to a carbon fibre plate mount with the porous top face parallel to the gun. Care was taken to ensure the power remained below 10 W to remove the requirement for "auto-defocus" of the beam being activated, an automated setting within the CT software which results in an increase in voxel size through a focal spot size increase [5].

For measurements acquired with FVM, the sample was placed on a V-block. The lateral resolution refers to the determination region of the contrast of a single point, for each measured height point. The vertical resolution refers to the sampling rate of *Z* points within the vertical range [2].

2.3. Characterisation and analysis

For measurements acquired through XCT the subsequent files were first reconstructed within CT pro 3D software and transferred to VG Studio Max 3.0 software for surface determination and mesh conversion (STL). ISO 50 surface determination was used for all datasets along with identical export parameters. For measurements obtained through FVM, files were exported as Surface files (.SUR) for later analysis in MountainsMap 9. This software was additionally used for the analysis of the machined underside, captured through XCT. Although capable of handling STL file formats, MountainsMap software relies on a surface extraction process. This results in the projection of points onto a mean plane, effectively removing the re-entrant features, resulting in an areal representation of the original 3D measurement. This is not dissimilar to the results of applying ISO 25178 surface filtration for amplitude parameters, further showing the difficulties in the characterisation of complex or porous coatings. Highlighted in figure 2 below. For this reason, areal surface area information has been used to quantify the change in voxel size, with traditional surface parameter characterisation being conducted on the more traditional, machined surface present on the underside.

Figure 2 - Projected (Pink) surface Vs Real surface (Green). Image obtained through Meshlab software.



2.3.1 Topographical surface area information

The topographical surface area is defined within this research as the total surface area, not based on the form of the sample and includes all re-entrant features. In order to obtain this information, the mesh was first cleaned, to remove any isolated areas with a diameter less than a specific constant. This value was applied consistently through this study. Assuming a cylinder representing the overall form of the sample, with dimensions of 12.7 mm diameter with a thickness of 4.73 mm, the resultant surface area can be compared to the surface areas calculated through the voxel intervals. This gives an indication of the volume of surface area contained within the surface texture/ coating.

2.3.2 Surface characterisation

Traditional surface characterisation was conducted on the machined underside. This was completed on measurements taken on both XCT and FVM. For measurements utilising FVM, the analysis consisted of 3 measurements of 4x4 mm extracted randomly across the surface with an average taken. Measurements were exported and analysed within MountainsMap 9. A 0.5% threshold was applied to the dataset to remove any “spikes” common with optical measurements prior to ISO 25178-3 [6] surface filtration. In line with this standard, a λ_s Gaussian 2.5 µm and λ_c Gaussian 0.8mm filter was applied.

Parameters were generated in accordance with ISO 25178-2 [7], within this report, three parameters have been included: Sq, Ssk and Sku.

3. Comparison of Scans

In order to obtain a visual representation of the changes through voxel sizes, each surface was cropped to an 8 x 8 mm square and aligned to a master within CloudCompare software to allow for a profile to be extracted in the same location for all voxel intervals. Figure 3 below represents a selection of the profiles extracted at the same location.

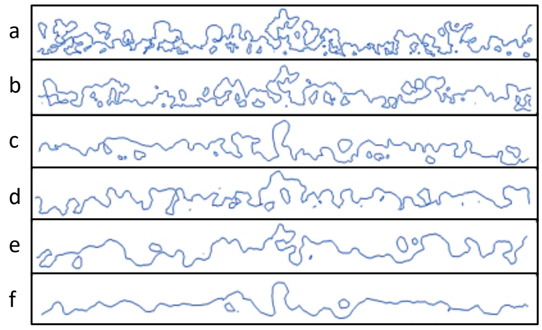


Figure 3 - Extracted profiles for a selection of intervals. (a) 8 µm, (b) 24 µm, (c) 30 µm, (d) 36 µm, (e) 46 µm & (f) 76 µm

4. Results and Discussion

The measured topographical surface for each voxel interval can be seen in table 3 below. Significant differences are apparent with the lowest and largest voxel size, 8 and 76 µm respectively. At the largest voxel size, the measured area is approximately half of that measured at the smallest. The measurement of 471 mm^2 is more similar to the one represented by form only, 442 mm^2. This relays the lack of the detail captured within the topography at a larger voxel size.

Table 3 - Measured topographical surface area for all voxel size intervals

Voxel Interval (µm)	Surface area (mm^2)	Difference to form only (%)
8	883.33	99.64
16	774.17	74.97
24	729.08	64.78
30	627.17	41.75
36	599.05	35.39
46	526.87	19.08
56	494.65	11.80
76	471.11	6.48
Form only	*442.46*	

Figure 4 shows the relationship between voxel size and measured topographical surface area. This shows a significant decrease in the measured area across the interval range.

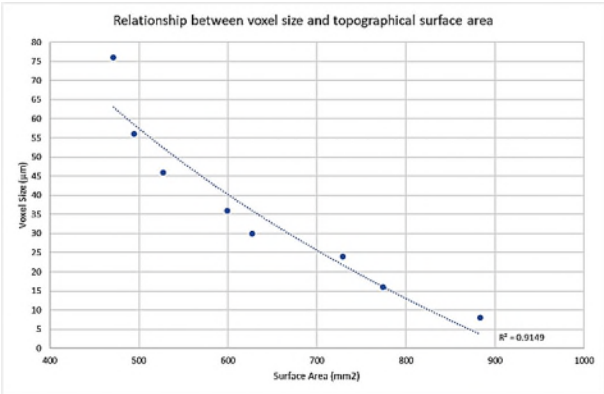


Figure 4 - Relationship between voxel size and topographical surface area

Table 4 details tabulated average data for amplitude parameters calculated on the machined underside only. A large variation is apparent between the voxel intervals. Included within, are values calculated through FVM on the machined underside. Although an identical process was followed for all datasets, even the lowest voxel size differs to the parameters calculated from FVM. While it would seem intuitive to assume this interval would produce values consistent with optical approaches due to the scale of interest (figure 3, a) and whilst closer in comparison to other intervals, a difference still remains. Interestingly, the Skewness (Ssk) measured for all datasets regarding XCT shows that for intervals after 16 µm the values become negative, showing that the surface has become more valley dominant. Together with the similar decrease apparent with kurtosis, a ‘smoothing’ effect of the surface could be assumed. This is again, shown in the level of detail captured within figure 3.

The identification mark present on the underside of the sample, was only identifiable at 30 µm and below, with the machining marks following a similar trend. Visual differences between the intervals became apparent, with triangulation artefacts becoming visible at greater voxel sizes. A selection of the reconstructed scans are shown in figure 5 below.

Table 4 - Surface amplitude parameters calculated for all XCT and FVM measurements on machined underside.

Sample Type	Sq (µm)	Ssk	Sku
8	1.249	0.3328	4.626
16	3.145	0.02613	8.159
24	1.362	-0.04874	3.384
30	0.9446	-0.01722	3.201
36	1.209	-0.261	3.730
46	1.096	-0.0478	3.275
56	0.9074	-0.1336	3.190
76	1.392	-0.1759	3.153
FVM – 20x	1.035	0.1873	2.952

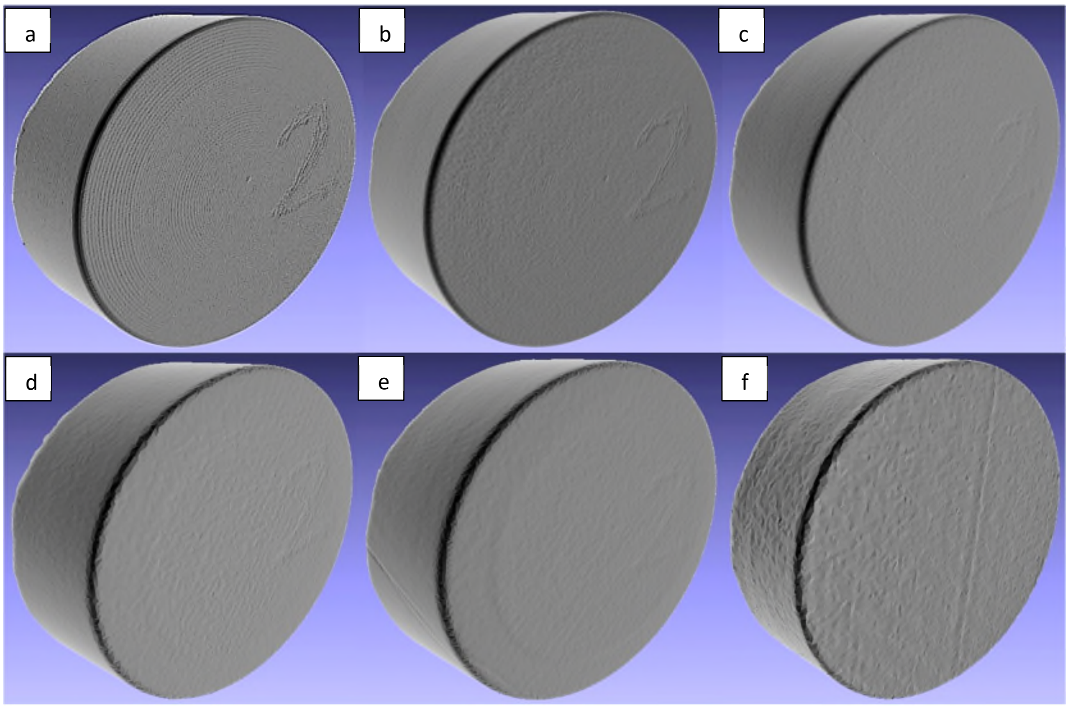


Figure 5 - Reconstructed surfaces showing machined underside and identification mark. (a) 8 µm, (b) 24 µm, (c) 30 µm, (d) 36 µm, (e) 56 µm & (f) 76 µm.

5. Summary, Conclusion and Future Work

The aim of this research was to highlight the impact voxel size has on functional information gained through XCT. The topographical surface area, containing all features, were calculated for scans captured at different voxel sizes. This ranged from 883 mm^2 to 471 mm^2 for voxel sizes 8 and 76 µm respectively. The available voxel size is directly related to the distance of the sample to the beam aperture, therefore larger samples or workpieces are limited, geometrically. This sample/ aperture distance is of paramount importance in determining the smallest possible feature and is highlighted in the magnification value [8]. With greater magnification values the penumbral blur of the image increases, resulting in a reduction of the sharpness of that image and consequently a reduction in the accuracy of the surface determination.

Surface characterisation was undertaken in accordance with ISO 25178-2/3 to characterise the machined underside of the sample, containing a more traditional surface texture. Variation was apparent across the voxel sizes, and this was compared to a measurement captured through FVM. At the lowest voxel size (XCT), the surface parameters matched more closely to those calculated from FVM. Parameters concerning the nature of the surface such as Ssk were highly affected by an increase in voxel size and began to show opposing values at later intervals.

The quality of the scans, including the sharpness of the surface determination deteriorated rapidly at larger voxel sizes, and whilst still able to maintain some dimensional accuracy, any discernible level of detail was lost. Surface characterisation through XCT whilst still in its infancy is often the only solution for measurement and characterisation of surfaces and geometries such as the one contained within this research, where re-entrant features play a vital role in the application of the surface. Functional information such as surface area, is of a high importance, especially with the rapid increase in the propensity of parts being manufactured through additive means. For post processing and information for biological applications, accurate determination of a parts surface area is highly desirable. This level of detail, whilst achievable through XCT it is highly dependent on geometrical constraints of the workpiece.

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