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Surface Measurement and Characterisation of Additively Manufactured 3D Cellular Scaffold for Acetabular Implants

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Abstract
The surface topography of acetabular implants is important for cell attachment and tissue growth. The measurement and characterisation of the surface texture of the cellular scaffold layer on the acetabular cup are challenging due to the complex lattice/cellular geometry. X-ray Computed Tomography (XCT) is employed to measure the surface texture of an electron beam melting (EBM) produced Titanium acetabular cup. The surface texture of its cellular scaffold is evaluated using the newly developed 3D surface texture field parameters, which allows surface characterisation on 3D freeform surfaces. In addition, the surface pit density, a feature-based parameter, which is more related to cell communication and proliferation, is estimated based on the 3D watershed segmentation.

Additive manufacturing; cellular scaffold; surface texture; X-ray computed tomography

1. Introduction

In comparison to solid metal materials, open cellular scaffolds of the in-growth layers of joint implants produced by additive manufacturing (AM) are proved to be more effective structures to support cell attachment and proliferation, cell morphology and spreading as well as better bone-implant fixation. These metallic interconnected cellular structures have optimal combination of surface roughness, pore size and porosity. Surface topography of scaffold not only affects the bone-implant contact, but also the biomechanical interaction of that interface at early implantation periods.

An identified fatal challenge of surface measurement of scaffold implant is that it is almost impossible to define the surface roughness of the scaffold structures accurately because of their three dimensional character. Furthermore, currently only height parameters, e.g. Ra, Rq, Rp, Rk, or their areal counterpart, were adopted to quantify the surface quality. However, it was recognised that surface pits are playing a major role of cell attachment and tissue growth. In addition, another obstacle is with surface measurement techniques. Traditional optical and tactile techniques, are not able to measure internal/introverted surfaces of porous structures, whose intricate forms do not permit line-of-sight.

2. XCT scanning setup

A Nikon MCT225 device was used to scan a Titanium acetabular cup testing sample (diameter: ~60 mm) made by EBM. The key parameters for XCT scanning are listed in Table 1. The whole scanning took 104 minutes. 3141 projection images were then reconstructed into a 3D volume using Nikon's CTPro 3D software. The follow-on data analysis of the 3D volumetric data was dealt via the VGStudio Max 2.2 [1]. The advanced local iterative algorithm was used to find the material boundary based on the local surrounding voxel. A local threshold method can significantly compensate the deviation caused by the acquisition issues, such as beam hardening. Figure 1 illustrates the reconstructed surface model of the acetabular cup. The cup surface data was then exported as stereo-lithography (STL) mesh format, using the VGStudio Max 2.2 "Super Precise" setting, which provides highest available resolution. The mesh was then processed using RameshCleaner [2] to remove non-manifold edges and it was finally remeshed using the anisotropic algorithm proposed by Botsch et al. [3]. A magnified surface patch extracted from the scaffold structure of acetabular cup is illustrated in Figure 2.

Table 1 Scanning parameters of Nikon XCT 225M.

XCT Scanning Parameters	Values
Beam energy	170 kV
Beam current	118 µA
Power	20.4 W
Filter	Copper, 1 mm
Detector size	2000 x 2000 pixels
Voxel size	31.7 µm
Number of projections	3141

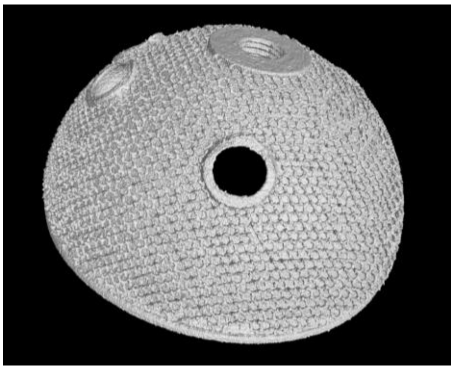


Figure 1. Reconstructed 3D surface of Titanium acetabular cap scanned by XCT.

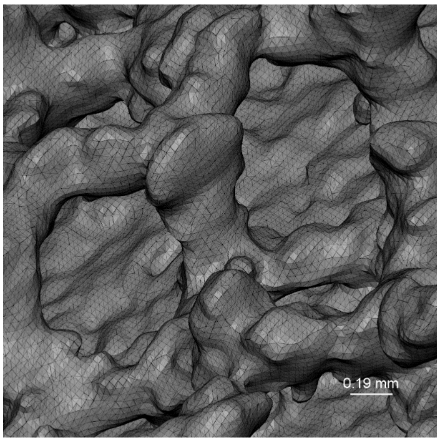


Figure 2. Extracted surface patch from the scaffold structure of acetabular cup.

3. Surface Texture evaluation

3.1. Field parameters

Due to the complexity of the 3D cellular scaffold structure on the acetabular cup, the parameters per ISO 25178-2 [4] cannot be computed. Instead, the manifold parameters defined by Pagani et al. [5] are used to evaluate the surface texture on the cellular scaffold.

The initial step of the 3D surface characterisation is the computation of a reference form surface such that surface texture can be defined. A feasible method to compute the reference form surface is using the morphological opening operator in order to enhance the peak of an additively manufactured surface [6]. In this study, the extracted surface is converted into a signed distance. The morphological opening operation is then performed on the 3D volume data. The generated mesh was then manually cut into four surface patches and each of the patches was individually analysed.

The second step of the characterisation process is the computation of the signed distance between the measured surface and the reference form surface. The distance has a positive value if the measured point is located along the direction of the outgoing normal of the reference surface, negative otherwise. A portion of the measured mesh and the computed reference form are shown in Figure 3. The morphological opening operation resulted in a smooth reference surface with the globule generated by the AM process suppressed.

To compute the manifold parameters, each measured point projected to the reference surface has the correspondent signed distance. The height manifold parameters can be therefore computed as the integral of a scalar field on a surface. The mean absolute value of the height, root mean square height, skewness and kurtosis of the heights are reported below:

$$Sa = \frac{1}{A_{form}} \iint_{\Sigma_{form}} |r_{sl}(u,v)| \, d\sigma_{form}$$

$$Sq = \sqrt{\frac{1}{A_{form}} \iint_{\Sigma_{form}} r_{sl}^2(u,v) \, d\sigma_{form}}$$

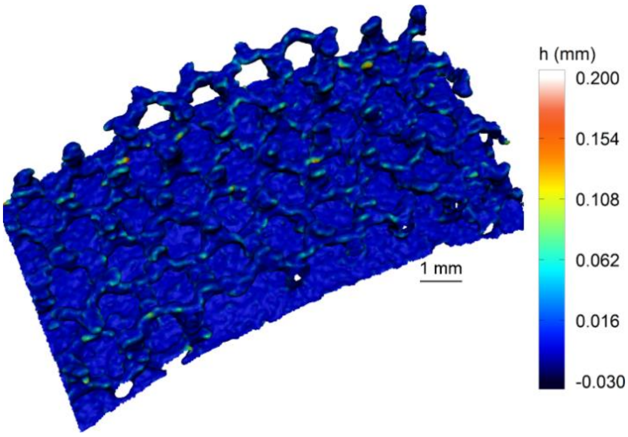
$$Ssk = \frac{1}{A_{form} \cdot Sq^3} \iint_{\Sigma_{form}} r_{sl}^3(u,v) \, d\sigma_{form}$$

$$Sku = \frac{1}{A_{form} \cdot Sq^4} \iint_{\Sigma_{form}} r_{sl}^4(u,v) \, d\sigma_{form}.$$

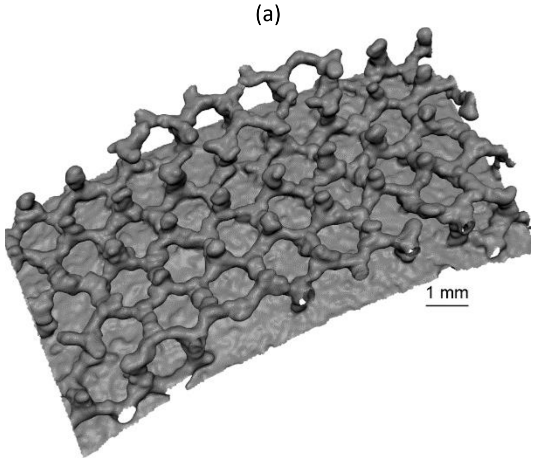
where

$$d\sigma_{form} = \left\| \boldsymbol{r}_{form,u}(u,v) \times \boldsymbol{r}_{form,v}(u,v) \right\| \, du \, dv$$

and $\boldsymbol{r}_{form,i}(u,v)$ is the partial derivative of $\boldsymbol{r}_{form}(u,v)$ in the i direction, $d\sigma_{form}$ is the infinitesimal areal element and $A_{form} = \iint_{\Sigma_{form}} d\sigma_{form}$ is the area of the form surface. The estimated surface texture parameters of the selection are listed in Table 2.



(a)



(b)

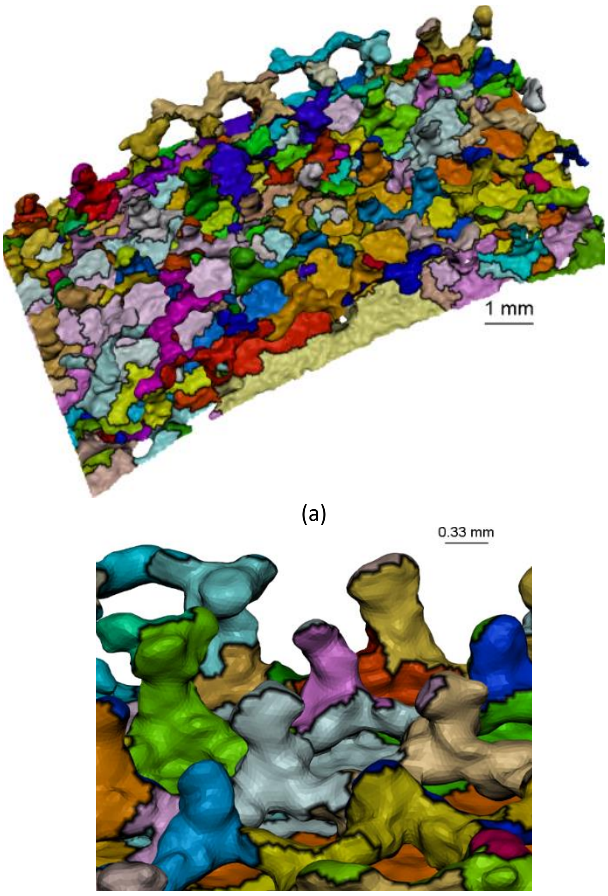
Figure 3. Extracted mesh and reference surface (the colour represents the distance between the measured and the closest point of the reference surface): (a) measured surface; (b) reference form surface.

Table 2. Estimated surface manifold parameters along with the mean and the standard deviation of the analysed surface patches.

Patch No.	**1**	**2**	**3**	**4**	**Mean**	**STD**
Sa **(µm)**	5.94	5.71	5.61	5.73	5.75	0.14
Sq **(µm)**	10.77	10.33	9.94	11.62	10.67	0.72
Ssk	4.29	4.22	3.84	6.99	4.84	1.45
Sku	32.26	31.89	24.92	94.83	45.98	32.74

3.2. Feature parameters

In addition to the height parameters listed in Table 2, another set of surface texture parameter that can be useful for the characterisation of the acetabular cup is the so-called feature parameters [7]. The surface topography is first segmented into a variety of local regions. Indexes for characterising the surface are then computed for each region. The watershed segmentation [8] is used to segment the mesh surface. Due to the local trivial surface topographical features as well as the measurement noises, the watershed segmentation tends to produce a number of tiny local segments, which is often called over-segmentation. This issue can be solved by building a change tree and applying the Wolf pruning to reduce the leaves with height differences less than a given threshold value [9]. An empirical value of 12 µm is used to reduce the number of segmented regions. The segmented regions of surface pits are shown in Figure 4.



(a)

(b)

Figure 4. Watershed segmentation of cellular scaffold surfaces with the height threshold value 12 µm: (a) pit-based watershed segmentation; (b) magnified portion of the pit-based watershed segmentation.

A straightforward parameter to characterise surface pits is the density of the pits (valleys) of the measured area

$$Svd = \frac{\#\,valleys}{A}$$

where A is the area of the analysed surface. Since each segmented region only contains a single significant pit, the number of the pits corresponds to the number of the regions for pits. The estimated pit density is listed in Table 3.

Table 3. Estimated pit density along with the mean and the standard deviation of the analysed surface patches.

Patch No.	**1**	**2**	**3**	**4**	**Mean**	**STD**
***Svd* (1/mm²)**	0.97	1.18	1.08	1.10	1.08	0.09

4. Discussion

(1) Considering the size of the acetabular cup used in this study, the X-ray source is placed close to the measured acetabular implant sample in order to obtain a maximised magnification and therefore a minimised voxel size. The experiment studies show that for a typical as-built AM surface the voxel size for full characterisation should be less than one half the surface Sa value [10]. The average value of resulted Sa of the measured acetabular cup is 5.75 µm, which is far smaller than the voxel size 31.7 µm. Even with the sub-voxel surface determination of VGStudio software, where one-tenth voxel size accuracy might be expected [11], the currently used voxel size is still far from satisfaction. To solve this issue, the acetabular cup shall be scanned by a more capable XCT system. Alternatively, the RoI scanning technique can be attempted.

(2) The 3D nature of the cellular scaffold of the acetabular implant makes surface roughness difficult to be evaluated because current areal surface texture parameters per ISO 25178-2 [4] are defined on a 2.5D basis. In terms of its applicability, two restrictions apply: measurement points should be uniformly sampled and surface texture is supposed to be measured on a planar or nearly planar basis [12]. The fatal issue of evaluating XCT measured surface texture, however, is that XCT measurement data does not conform to these two constraints as required by ISO 25718-2. The newly developed 3D manifold parameters that extended traditional areal surface texture parameters into the 3D case can provide a solution, where surface texture is evaluated on the surface form without having to be projected onto a 2D plane.

(3) The 3D height parameters, i.e. Sa, Sq, Sku, Ssk, give a quantitative evaluation of the surface quality of cellular scaffold. They can indicate the roughness and sharpness of the surface texture from a statistical point of view. The proposal of using feature-based parameters, e.g. pits density, provides a complimentary assessment of surface quality from the bio-functional aspect. The pits density parameter is implemented based on the 3D watershed segmentation of surface topography features. This parameter is more related to the cell communication and tissue growth.

5. Conclusion

Surface texture of the scaffold are critically important for cell communication and proliferation. The measurement and characterisation of the scaffold's surface texture are very challenging due to its 3D nature. XCT is employed to conduct a non-destructive measurement of the surface texture of an EBM produced Titanium acetabular cup with a cellular scaffold in-growth layer. The surface texture of 3D scaffold is evaluated using the newly developed 3D manifold parameters, which enables surface characterisation on freeform lattice/cellular surfaces. Four commonly used height parameters, i.e. Sa, Sq, Ssk, Sku, are resulted from four surface patches extracted from the XCT measured surface. In addition, the surface pit density is estimated based on the 3D watershed segmentation, which is more relevant to cell growth.

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