NOVEL MICRO-CT BASED CHARACTERIZATION TOOL FOR SURFACE ROUGHNESS MEASUREMENTS OF POROUS STRUCTURES

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Aims

As the surface roughness determines the microscale morphology of the surface of a porous material in quantitative way [1-3], appropriate surface morphology analysis is needed. Also, a thorough analysis of the surface morphology of porous structures is important for the modeling. Indeed, when included in the FE models, a precise quantification of the surface roughness of the porous structures can improve the analysis of the local mechanical properties [4,5]. Since commercially available profile measuring systems fail when determining the surface roughness of advanced 3D porous structures, and because a high surface roughness of struts of 3D porous structures compared to their dimensions causes difficulties for quantitative determination of the surface morphology, a new protocol for quantitative analysis of the surface morphology has been developed on the basis of high resolution micro-CT images. The roughness was determined based on 2D cross-sectional micro-CT images using the profile line of the surface for the calculations. As the 2D images were taken with a high resolution SkyScan 1172 µCT system, which required no special sample preparation, the measurements could be performed in a non-destructive way.

Materials and methods

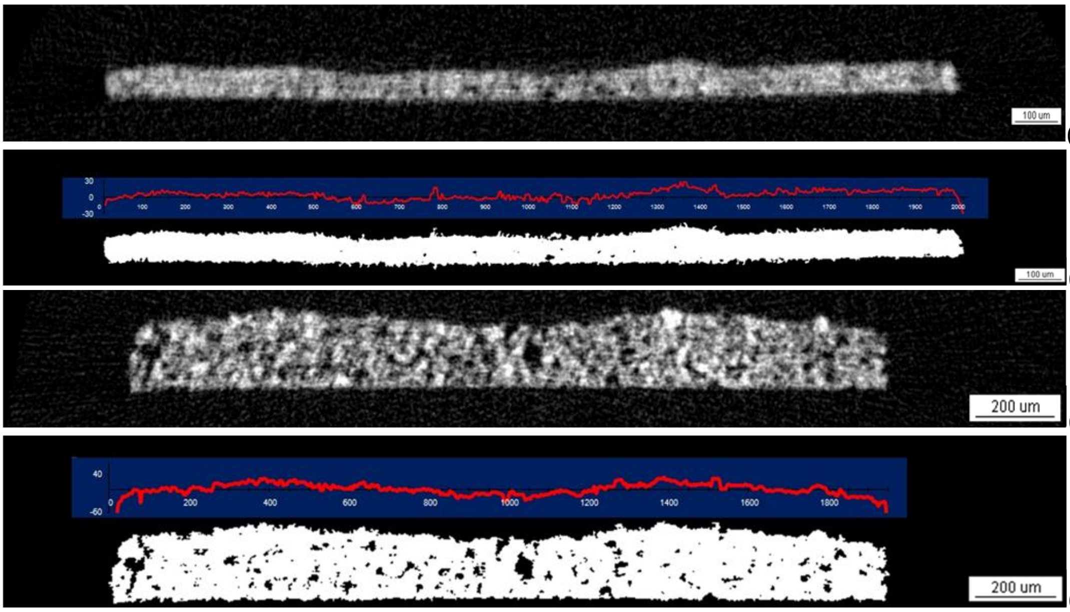
As mentioned earlier, commercially available profile measuring systems fail when determining the surface roughness of the struts of complex, 3D porous structures. As a solution, in this study a novel high resolution micro-CT based protocol for quantitative analysis of the surface morphology has been proposed. In this protocol, the roughness is calculated based on the profile line of the strut surface in the 2D micro-CT images.

- Validation of the surface roughness measurement protocol

In order to assess and validate the accuracy of the novel micro-CT based protocol for surface roughness measurement, TiH_2 coatings deposited on 2D Ti6Al4V substrates using electrophoretic deposition (EPD) of a TiH_2 powder particle suspension followed by sintering under vacuum [6] were first analyzed using a WYKO NT3300 Profiling System to get reference characteristics of the surface morphology. Then, the coatings were scanned using a high resolution SkyScan 1172 micro-CT system [SkyScan NV, Kontich, Belgium]. Two types of coatings with a different surface roughness, named EPDTi and EPDTE, were investigated (fig. 1A and 1C respectively). No special sample preparation was needed. The 2D micro-CT images of the coatings, having a voxel size of 1.5 µm, were binarized with CTAn [SkyScan NV, Kontich, Belgium] and the profile lines of the struts edges were selected as shown in fig. 1B and 1D. In the next step, the images (bitmap format) were processed with Chropek.jar software (developed by Łukasz Sznajder, Poland) which extracts the pixels distribution of the profile lines. This data was transformed to Microsoft Excel in order to calculate the following roughness parameters:

- the arithmetic average deviation:…………………………………..….. $R_a = \frac{1}{n}\sum_{i=1}^{n}|y_i|$
- the root mean square deviation of the roughness profile from the mean line: ……………………………………………………………………….... $R_q = \sqrt{\frac{1}{n}\sum_{i=1}^{n} y_i^2}$
- difference between highest peak and deepest valley:………………. $R_T = R_P - R_V$

where n = number of data points in X direction, y = the surface height relative to the mean plane, R_P = the highest point and R_V = the lowest points in the evaluation length.



(A)
(B)
(C)
(D)

Figure 1: Typical (A) cross-sectional micro-CT image of the EPDTi coating, (B) the binarized micro-CT image of the EPDTi coating with its corresponding surface profile line, (C) cross-sectional micro-CT image of the EPDTE coating and (D) the binarized micro-CT image of the EPDTi coating with its corresponding surface profile line.

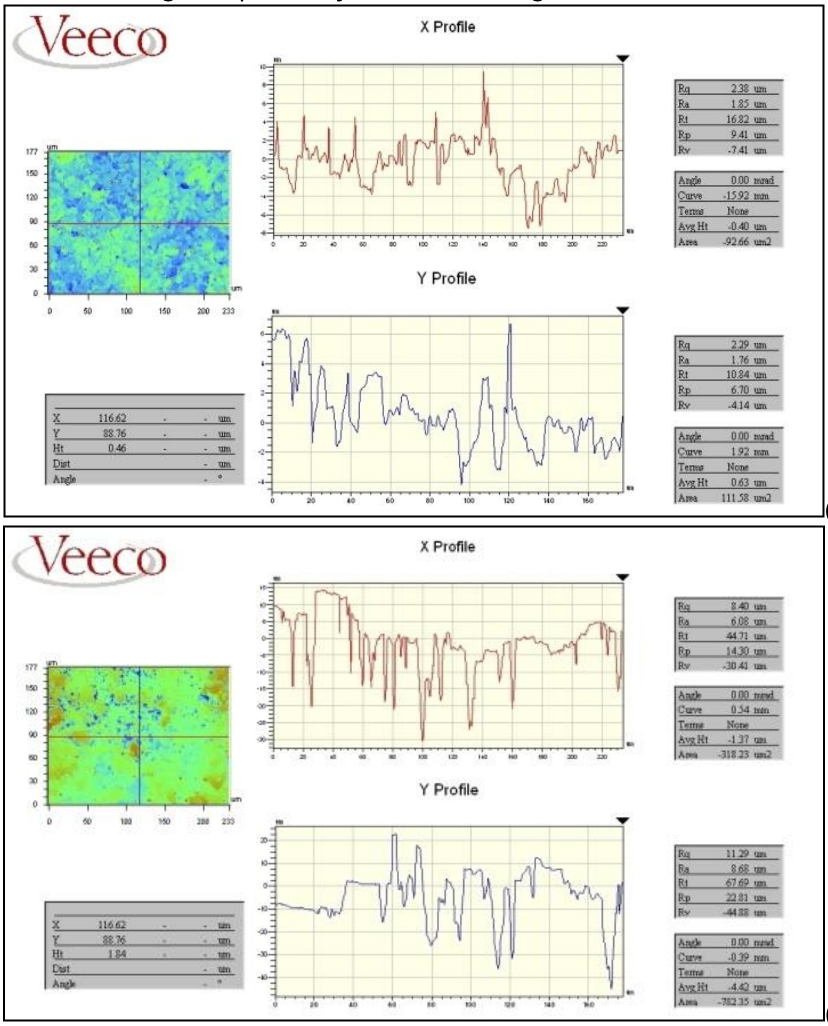
- Application of the surface roughness measurement protocol

Compared to commercially available profile measuring systems, the novel protocol for surface roughness measurement offers the possibility to quantitatively analyze the strut surface morphology of complex 3D porous scaffolds. In this study, the micro-CT based surface roughness measurement protocol has been used to investigate the strut surface roughness of porous Ti6Al4V structures produced by selective laser melting, a rapid prototyping technique, to be used as tissue engineering (TE) scaffolds [4-5, 7-8]. The local roughness has been calculated based on small sections selected from the main profile line of the strut.

Results

- Validation of the surface roughness measurement protocol

Figures 3A and B show typical images of the 2D surface morphology of the EPDTi and the EPDTE coatings respectively obtained using the WYKO interferometer.

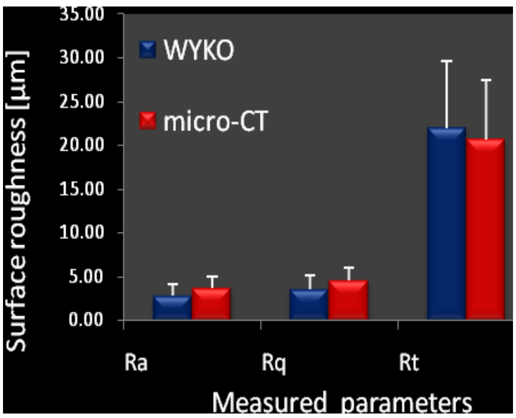


(A)

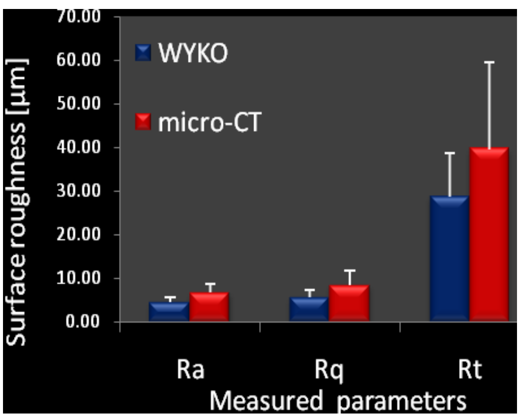
(B)

Figure 2: Images of the 2D surface morphology of (A) the EPDTi coating and (B) the EPDTE coating obtained using the WYKO interferometer.

Figures 3A and 3B show the comparison of the surface roughness parameters obtained using the WYKO interferometer and the micro-CT based surface roughness measurement protocol for both the EPDTi and the EPDTE coating respectively. It can be clearly seen that there are no significant differences in surface morphology between the measurement techniques. Thus, it was concluded that the micro-CT based protocol can be used with similar accuracy than commercially available profile measuring systems to determine the surface roughness.



(A)



(B)

Figure 3: Comparison of the surface roughness parameters obtained using the WYKO interferometer and the micro-CT based surface roughness measurement protocol for the (A) EPDTi and (B) EPDTE coating.

- Application of the surface roughness measurement protocol

Figure 4A shows a typical high resolution 2D micro-CT image (voxel size = 1.5 µm) of a single strut of a porous Ti6Al4V structure. A difference in surface roughness between the top and bottom of the strut was noticed, which is inherently related to the production technique. This difference is elaborated in figure 4B, where a selection of the binarized 2D micro-CT image (fig. 4A) is shown with the corresponding profile lines for the top and bottom surface of the strut.

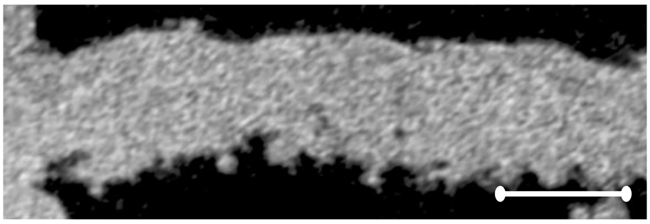
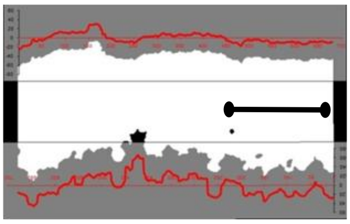

(A)

(B)

Figure 4. (A) A typical high resolution (voxel size = 1.5 µm) 2D micro-CT image of a single strut of a porous Ti6Al4V structure and (B) a binarized section of (A) with the corresponding profile lines. Scale bars = 200 µm.

The difference in surface roughness between top and bottom of the strut, observed in the micro-CT images (fig. 4A and 4B), was quantified using the novel micro-CT based surface roughness measurement protocol on a typical cross-sectional high resolution micro-CT image of a single strut of a porous Ti6Al4V structure (fig. 4A). Table 1 summarizes the strut surface roughness parameters, indicating that the roughness was about twice as large for the bottom surface of the strut than for the top strut surface.

Table 1. Strut surface roughness parameters determined for the top and bottom surface of a single strut of a porous Ti6Al4V structure using high resolution micro-CT.

Investigated strut surface	**Surface roughness**		
	R_a [µm]	R_q [µm]	R_t [µm]
Top	9.28	11.37	54.40
Bottom	19.23	22.65	107.10

Conclusion

In this study, it was shown that high resolution micro-CT can be applied accurately and in a robust manner for the quantification of the surface roughness and morphology of porous surfaces. Additionally, it is valuable tool to determine the surface roughness of complex, 3D porous structures. The non-destructive character of the micro-CT based surface roughness measurement protocol allows a thorough analysis of the influence of different surface modification procedures [9,10] on the struts and nodes surface morphology of porous materials.

Thorough analysis of the struts and nodes surface morphology is essential for the modeling as it provides indirect (the profile lines of the struts can be implemented in virtual models) or direct (using the micro-CT images) input for the FE models of the porous structures. Additionally, specifically for TE scaffolds, it is known that the primary interaction between the TE scaffolds and the surrounding biological environment depends mostly on the surface properties, i.e. surface chemistry and surface topography. For this reason, it is essential to quantify the surface roughness in order to correlate cell behavior to the surface properties. In this way, the most optimal surface properties for future designs and production of TE scaffolds can be looked for.

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