1.9.26. THE COMBINED USE OF MICRO-CT IMAGING, IN-SITU LOADING AND NON-RIGID IMAGE REGISTRATION FOR 3D EXPERIMENTAL LOCAL STRAIN MAPPING ON POROUS BONE TISSUE ENGINEERING SCAFFOLDS UNDER COMPRESSIVE LOADING

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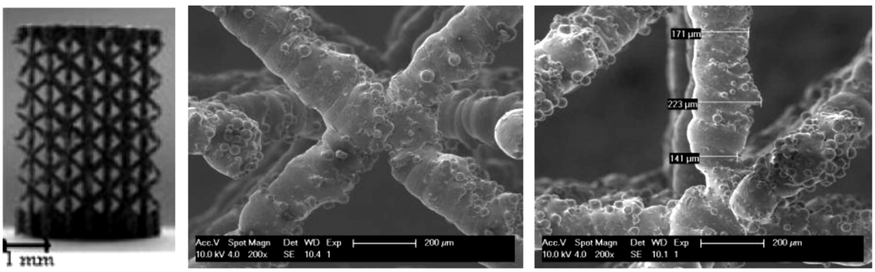
Introduction. Instead of standard treatments for large bone traumas, which focus on bone reconstruction, bone tissue engineering (TE) emphasizes on tissue regeneration. TE applies a combination of an open porous structure, also called bone TE scaffold, with osteogenic cells that, after a process of cell seeding and bioreactor culture, can be implanted in the large bone defect [1 – 3]. Since the local strain distribution of cell-seeded bone TE scaffolds can influence cell behaviour and subsequent bone formation [4], characterization of these strains is crucial for systematic scaffold design. This study used micro-CT and 3D image analysis in combination with in-situ mechanical loading to (i) provide input and validation for finite element analysis (FEA) to predict the local strain distribution, and (ii) quantify experimentally the local strains. Concerning the latter, a novel approach based on non-rigid image registration by maximization of mutual information (MMI) [5] of the micro-CT datasets at different loading steps was able to quantify the local strains and to predict material failure modes at macro- and meso-scale. Also, comparison was made with the FEA-predicted local strain distribution.

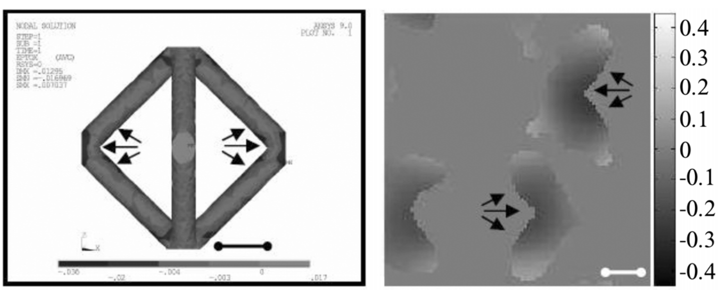
Materials, methods, results and discussion. Open porous Ti6Al4V structures produced by rapid prototyping, and more specific selective laser melting (SLM), were used as scaffold examples (fig. 1a). The purpose of the local strain mapping was two-fold: (i) experimental quantification of the local strain distribution and failure modes in the selected scaffolds and (ii) comparison to the local strain distribution predicted by FEA. For the latter, as input for the material model, bulk Ti6Al4V was produced by SLM and tested in compression. To optimize the geometrical model, the morphology of the produced structures was quantified via micro-CT imaging and 3D image analysis.

Based on the strain mapping (fig. 2b) one would predict failure near the nodes, which was indeed substantiated by optical images after failure. Furthermore, the local strain maps showed inhomogeneities with regard to the strain distribution although the design was homogeneous. These inhomogeneities result from the strut surface roughness, and a significant variability in strut thickness as can be seen in fig. 1B and 1C.



(a) (b) (c)

Fig. 1: (a) An SLM produced open porous Ti6Al4V structure and typical SEM images near the nodes of an open porous Ti6Al4V structure indicating (b) a significant surface roughness and struts forming bends near the node and (c) a significant thinning of the strut close to the node and a large variability in strut thickness



(a) (b)

Fig. 2: (a) The FE-predicted local strain distribution in the y-direction at 1.7% strain on a typical unit cell and (b) the micro-CT based strain distribution in the y-direction at 1.7% strain for a open porous Ti6Al4V (scale bar = 200 µm). Both show that the largest strains were compressive and occurred at the 90° angled connections near the nodes. Away from the nodes smaller strains were noticed

Figure 2 shows (a) the FE-predicted local strain distribution in the y-direction at 1.7% strain on an idealized unit cell and (b) the micro-CT based strain distribution in the y-direction at 1.7% strain for an open porous Ti6Al4V structure. Both show similar characteristics, as the largest strains were compressive and occurred at the 90° angled connections near the nodes. Furthermore, away from the nodes smaller strains were noticed. Since the local strain mapping tool, based on MMI, has been validated, a quantitative comparison could be made with the FE-predicted local strain distribution. The difference between the experimentally determined local strain distribution and the ones predicted by FEA mostly result from the strut surface roughness, and thus the strut surface roughness should be included in the geometrical model or should be reduced to obtain a cell-friendly and smooth surface approaching the surface characteristics of the FE model. Some preliminary experiments have been performed to evaluate the influence of a strut surface reduction protocol by using chemical and electrochemical etching on the local strains and the agreement with the FEA results.

Conclusion. The combination of micro-CT imaging, 3D image analysis and in-situ mechanical loading with local strain mapping appeared to be a valuable tool for a thorough characterization of porous structures, not only morphologically, but also mechanically and to assess their failure behaviour and local strain distribution. Moreover, it was proven to be a highly suitable as input and validation tool for FEA. In conclusion, combined experimental and mathematical non-destructive characterization tools assist to thoroughly understand the mechanical behaviour and the local strain distribution in bone TE scaffolds.

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