Novel micro-CT based local strain mapping tool to characterize the failure modes of bone tissue engineering scaffolds

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Introduction. As proliferation and differentiation of osteogenic cells is also promoted by mechanical strains caused by the deformation of the structures to which the cells attach¹, the local strain distribution inside bone tissue engineering (TE) scaffolds on which the cells are seeded can influence cell behaviour and subsequent bone formation. In order to evaluate bone TE scaffold designs in relation to this specific requirement, two approaches can be applied: (i) modelling by using finite element analysis (FEA) to predict the local strain distribution or (ii) experimental quantification of the local strain distribution. For the first, an accurate input of the material and the geometrical models is required as well as a thorough validation of the local strain predictions. For the latter, a combined use of micro-CT and in-situ loading can be applied, including experimental local strain mapping of the micro-CT scans at different loading steps. A novel local strain mapping approach was applied in this study based on non-rigid image registration² of the micro-CT scans at different loading steps.

Figure 1. A typical (A) longitudinal 2D image of the CAD-model of design with beam length (L) 1.2 mm, (B) 3D CAD-model for the same beam length variation, (C) unit cell of the designed porous structures and (D) SLM fabricated open porous Ti6Al4V structure with designed beam length (L) 0.8 mm.

Materials, methods and results. Open porous Ti6Al4V structures produced by rapid prototyping, and more specific selective laser melting (SLM), with varying beam length (L) and constant beam thickness were used as scaffold examples (fig. 1). 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 with the local strain distribution predicted by FEA. For the latter, to obtain 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.
Figure 2 shows respectively (A) one representative centred longitudinal 2D micro-CT image of a structure with designed beam length 1.0 mm, (B) its strain distribution in y-direction at 7 % strain, (C) a magnification of (A), and (D) the corresponding, detailed image of its strain distribution. In figure 2D, it can be seen that the largest strains occurred near the nodes and that they were compressive. Away from the nodes smaller strains were noticed. In the midsection of the beams tensile strains were found, which indicated buckling of the beams. A high magnification radiographic image after failure (fig. 3A) confirms these findings.

Based on the strain mapping one would predict failure near the nodes, which was indeed substantiated by optical images after failure (fig. 3B). Furthermore, the local strain maps showed inhomogeneities with regard to the strain distribution although the design was homogeneous. These inhomogeneities resulted from the beam roughness, which is also the reason for the difference between the experimentally determined and the FEA predicted local strain distribution.

**Figure 2.** A representative centred longitudinal 2D micro-CT image of a structure with designed beam length 1.0 mm (scale bar = 2 mm), (B) its strain distribution in the y-direction at 7 % strain (scale bar = 2 mm), (C) a magnification of (A) (scale bar = 200 µm) and (D) its strain distribution (scale bar = 200 µm), showing the largest compressive strains near the nodes. Away from the nodes smaller compressive strains are found and in the midsection of the beams tensile strains are present.

**Figure 3.** (A) A high magnification of a typical radiograph after failure for a structure with designed beam length 1.0 mm showing buckling of individual beams (scale bar = 500 µm), (B) a typical optical image after failure for a structure with designed beam length 1.0 mm showing failure near the nodes (red circle) (scale bar = 200 µm).

**Conclusions.** The combination of micro-CT imaging, 3D image analysis and in-situ mechanical loading with local strain mapping showed to be a valuable tool to, both
morphologically and mechanically, characterise porous structures and to assess their failure behaviour. Moreover, it was proven to be a suitable input and validation tool for FEA.

References