

Micro-CT Studies for Three-Dimensional Leather Structure Analysis

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Introduction

The aim of the present work was to elucidate the three-dimensional microstructure of leather more in detail by determining local structural forms and conjunctions of collagen fibres as well as corresponding structural and mechanical characteristics. Furthermore, fundamental deformation processes occurring at fibre bundles level were studied thus providing information for geometric modelling of the leather microstructure and a prospective numerical simulation of mechanical properties.

Materials and Methods

The structural analysis of leather occurred on the basis of data generated by three imaging techniques: micro-computed tomography (micro-CT), scanning electron microscopy (SEM) and optical microscopy. The main focus was on the tomographic procedure, the microscopic procedures complemented thereby the obtained information.

Three-dimensional images were produced using a high resolution X-ray micro-computed tomography equipped for weakly absorbing materials. Imaging parameters were optimised; the best resolution for analysis of the fibre bundle structure was found to be 3.6 µm.

Imaging of grain and papillary layer required higher resolution as provided by the scanning electron microscope (type of FEY XL 30 ESEM). Usually, samples were examined after Au-sputtering in low vacuum mode at 30 kV. For optical microscopy a device of the type Olympus BX61 was used.

Results and Discussion

Nine leather samples with different technological background (chrome-tanned, vegetable tanned, metal-free tanned) were imaged by micro-CT with subsequent image analysis (Figure 1). Collagen fibres provide only a weak absorption contrast resulting in low grey value dynamic in the reconstructed three-dimensional images. Traces of metal induced by the tanning process did not enhance contrast like a contrast medium (like in medical screening applications), as they are not distributed evenly. Thus just metal-free tanned samples were processed further.



Figure 1: Three-dimensional tomographic image of a bovine vegetable tanned leather.

For quantitative results, i.e. geometric characteristics of the microstructure, CT image segmentation was required. The most simple segmentation step, the so-called binarisation, assigns every pixel either to the solid component consisting of fibre bundles or to the pore space. So, after an extensive pre-processing of original grey-level images (denoising, contrast enhancement, see Figure 2) and subsequent thresholding binary images were obtained permitting the extraction of structure characteristics like surface area density, fibre lengths, etc. In this study various approaches for this separation were tested. Another task is to segment individual fibre bundles in order to study their branching and interlocking behaviour.



Figure 2: Micro-CT slice (grey-level image) of leather (left), binary images after segmentation – automated with thresholding (middle) and with ILASTIK (right).

However, automated segmentation and identification of individual fibre bundles are hindered by the complexity of the microstructure: cavities in the fibre bundle (between adjacent fibres or subunits) are often of the same order of magnitude as the interstices between fibre bundles. Grey values (levels) vary strongly within fibre bundles and differ only locally from grey levels in pore volumes. Moreover, fibre bundles split up and interlock as well. In consequence, the best available micro-CT data set (vegetable tanned leather) had to be segmented semi-manually: low level automatic segmentation using a watershed transformation approach was followed by a tedious manual post-processing uniting segments belonging to the same bundle, see Figure 5.

Due to the low contrast in micro-CT and the problems in automated image analysis the study focuses on the structure analysis of the corium layer. The aim of this manual image segmentation was to make the spatial arrangement accessible for typical bundle elements in order to deduce a statistical model for the leather structure. Here, the original grey value image was used for the manual segmentation. For each hierarchical structure level every 10th sectional plane of the available micro-CT data set of a leather volume of (4,0 x 4,0 x 4,0) mm³ was analysed. The manual segmentation can be performed due to the traceability of individual subunits and fibre bundles between the three-dimensional image sectional planes: In sequential image slices the position and relation of single elements within the volume can be detected and the associated segments can be marked. An example of the manual segmentation and the subsequent reconstruction of fibre bundle subunits are presented in Figure 3: the subunits were analysed over a sectional depth of 750 µm, in Figure 3b different subunits are marked by different colours.

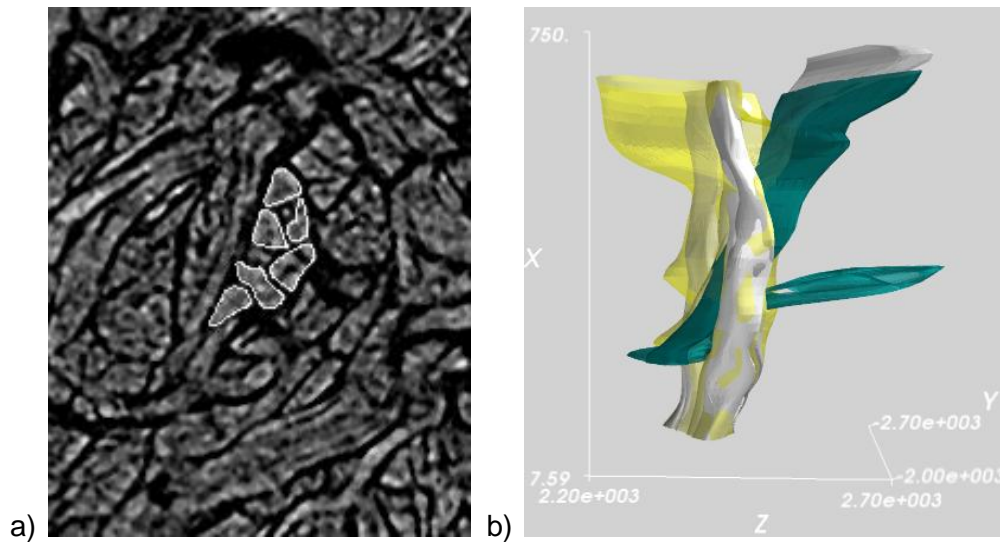


Figure 3: a) Manual segmentation example of subunits in a sectional plane of micro-CT data
b) Reconstructed subunits of a fibre bundle: Subunits in the fibre bundle (white-grey), crossing subunits (green) and envelope of the bundle (yellow).

The smallest structure units distinguishable were fibre bundle subunits. Subsequently, the traced subunits were combined to fibre bundles and used for tracing of structure units and for extraction of geometrical characteristics like the length between branches. Selected bundles were traced together with outgoing branches. The average length between branches was 236 µm. Figure 4 presents an example of fibre bundle reconstruction on the basis of the manual segmentation results.

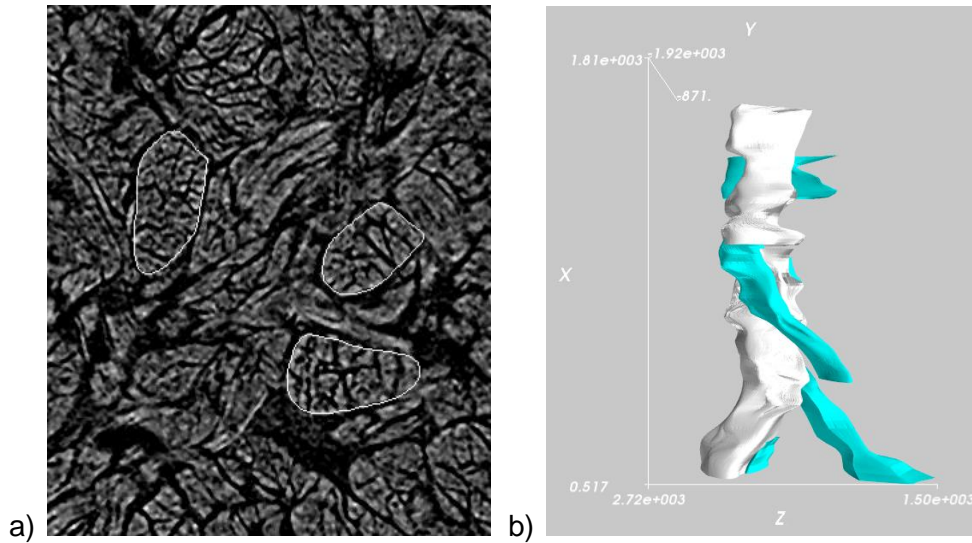


Figure 4: a) Manual segmentation example of different fibre bundles in a sectional plane of micro-CT data b) Reconstructed fibre bundle (white-grey) with branches (turquoise).

The statistical evaluation of the leather structure was based on the manual reconstruction of the fibre bundle network. Here, fibre bundles were approximated as cylinders keeping the diameter constant between two branching points. As fibre bundles are non-circular the lowest dimension was taken into account. So, the average cylinder diameter obtained by statistical evaluation amounted to 100 μm , being significantly under the values determined with optical microscopy. Consequently, a systematic underestimation of the volume of the fibre bundle network resulted.

In order to overcome this drawback the semi-automatic segmentation results mentioned above were used. Here, the detected structure units generally representing fibre bundle subunits (Figure 5a), were manually combined to fibre bundles (Figure 5b). In this way fibre bundle segments can be reconstructed with their real dimensions and relative position and the leather volume element can be generated. A draw-back of this approach is that fibre bundle branches are not detected.

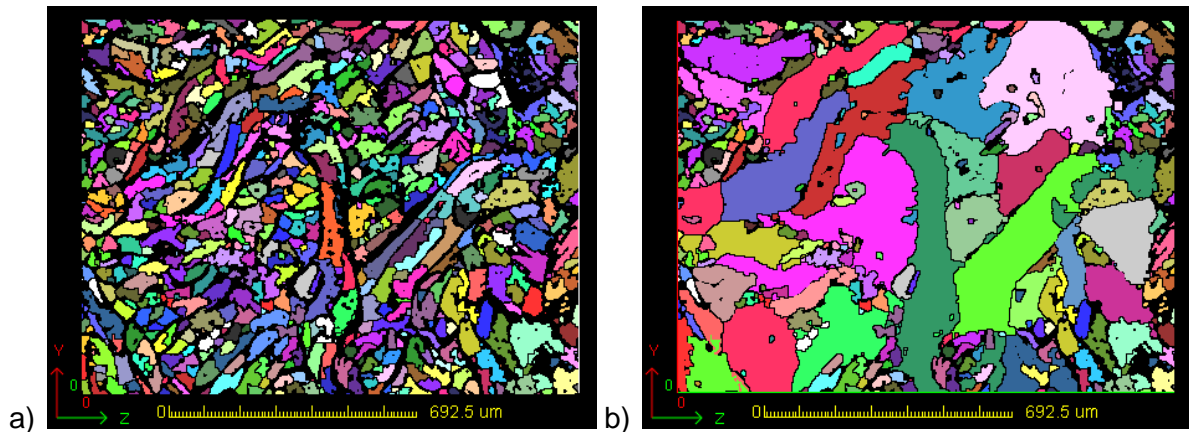


Figure 5: (a) Example of partly automated segmented micro-CT sectional plane before post-processing and (b) after subsequent manual combination of fibre bundles.

Conclusion

Micro-CT proved to be suitable for imaging the three-dimensional microstructure of the corium: layers of leather, fibre bundles with their branches and inner structure are detectable. For the fine-fibred and denser structured grain layer techniques with higher resolution such as SEM are required.

Due to the fine structure of fibre bundles and of the relatively small interstices between fibre bundles, an automated segmentation could not detect and distinguish individual fibre bundles. The alternatives are a semi-automatic or a time-consuming manual segmentation.

Difficulties in transforming image data into processable three-dimensional graphs had a negative effect on the size of the data pool obtained. As segmentation is the fundamental prerequisite in generation, adjustment and validation of a leather structure model possibilities have to be found to enable automation of this evaluation step. So, once an automatic segmentation is guaranteed, the generation of a representative data pool will be feasible.

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