High-resolution X-ray computed tomography simulations of synthetically-generated volume porosity in continuous carbon fibre reinforced polymer samples

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Introduction
Due to their excellent mechanical properties, carbon fibre reinforced polymers (CFRP) have a high relevance in industries especially for highly stressed structural components. A main manufacturing problem for CFRPs are a large number of bubbles filled with gas or air entrapped in the polymer matrix, called porosity. Porosity can critically weaken the material strength and should be determined as accurate as possible. However, the standard measurement methods used, such as standardized thermo-chemical analysis (DIN EN 2564:1998), provide relatively poor accuracy of about ± 1.0 vol. %. Therefore, investigations with X-ray computed tomography (CT) can show relevant information of the inner microstructures of products with high accuracy compared to the standard methods for porosity determination of CFRPs. This high accuracy of CT faces one disadvantage in practice: It is almost impossible to proof this, because the production of CFRP reference components with a high number of well-defined micro- pores below 10 µm is impossible. Therefore, CT simulations were performed to generate well described 3D data with well-known internal structures. For a more realistic and complex grey value distribution in the CT simulation data, typical different polymer matrix systems.

Materials & Methods
For the high-resolution CT simulations, a house software tool called SimCT was used in this study. As numerical input * geo text-files were semi-automatically generated, containing all relevant information of the used artificial porosity specimens. Altogether the used CFRP models in this study were mathematically described by 1,988 different elements from whom an exact porosity value was calculated. For pores segmentation, a threshold method called ISOxx was applied in this study. The ISOxx method is usually very fast, even with large data sets, and can be easily calculated, adapted and applied with most available software tools. As software for evaluation of the relevant region of interests, VG Studio Max 3.4 (Volumegraphics GmbH., Heidelberg, Germany) was used.

Results
Figure 1 shows 3D visualization of the modelled micro-structures (a) as well as the binary input (b) and simulation results without (c) and with enabled physical artefacts (d-f) of different polymer matrix materials as well resulting grey value histograms (g) of (c) and (f).

In Figure 2 CT simulation results with (2.5 µm)³, (5 µm)³, (10 µm)³, (20 µm)³ and (40 µm)³ voxel size are shown respectively for the epoxy resin matrix model. In the bottom row the void segmentation was done by using an ISO50 threshold for all different resolutions, showing that the segmentation results, especially for the micro-voids looks good for (a) and (d), and significantly reduces in (c) to (d) at lower resolutions. In Figure 3 (a) the simulation results of all matrix material combinations are depicted. In (b) the corresponding grey value histograms of the different matrix materials combinations, including individual carbon fibres, are shown at a resolution of (2.5 µm)³ voxel size. It is shown that the different material peaks vary significantly.

Summary & Discussions
In this CT simulation study micro structures such as individual carbon fibres, micro voids as well the polymer matrix including macro- and meso- scaled voids were taken into account to generate synthetically CT data with well-known porosity. It was found out that the ratio of total surface area (SA) of the voids divided to the total volume (V) of the voids is suitable to describe and differentiate individual porosity samples. The ratio SA/V is capable to estimate a minimal necessary voxel size for a proper porosity segmentation by a simple ISO50 threshold. Under certain condition, using an adapted ISOxx threshold value at a resolution of (10 µm)³ voxel size, the pores volume can be determined with an average measurement error below 10 %. As long the CT resolution is not high enough to completely resolve all void structures, using a global threshold segmentation is always a compromise of over-segmentation of the macro- and meso- pores in combination with under-segmentation of micro voids. New materials combinations, such as different matrix materials need an separate ISOxx calibration for proper quantitative porosity results, because the position and shape of the material peak can vary significantly.

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