POROSITY EVALUATION OF CARBON FIBER-REINFORCED POLYMERS WITH POROSITY ANALYZER

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Keywords: X-ray computed tomography, fiber-reinforced polymers, porosity, segmentation, parameter space analysis, comparative visualization

Summary: Porosity evaluation of eight carbon fiber-reinforced polymer specimens using *Porosity Analyzer*.

1. INTRODUCTION

For non-destructive inspection of fiber-reinforced polymers (FRPs), industrial X-ray computed tomography (XCT) has become an approved method for regarding the characterization of pores and determining the overall porosity. Pores show a large influence on the mechanical and physical properties of FRP structures. Therefore, it is essential for domain specialists to qualify newly developed materials and components including the specimens' porosity. In order to determine the porosity, pores must be extracted using a segmentation pipeline. A properly chosen segmentation pipeline with a suitable set of parameters increases the accuracy, robustness, and reproducibility of the porosity analysis. Choosing a pipeline with a suitable set of parameters however is a challenging task because the segmentation pipeline has to perform well on a wide range of datasets providing robust and reliable results. Additionally, different reference segmentations from different reference methods need to be considered and compared. These preconditions represent a challenging task in the evaluation of porosity including several time-consuming trial-and-error steps.

In [1] we have presented the *Porosity Analyzer* tool, which supports the user when determining the porosity in FRP specimens. *Porosity Analyzer* consists of two modules: the *computation module* and the *analysis module*. The *computation module* provides tools for a convenient setup and execution of distributed off-line-computations: segmentation pipelines are assembled from individual steps, the parameter space sampling is specified, and different XCT volume datasets are chosen for the evaluation. The computation is performed and results in input parameters in combination with resulting porosity values and derived parameters. This data is then aggregated with the corresponding reference segmentation/porosity. The aggregated data is passed to the *analysis module* which performs a drilling-down filtering and a visual analysis. The overview visualizations show the porosities of the segmentation pipelines applied to evaluated datasets and allow a quick comparison to the reference segmentations/porosities. The segmentation pipelines are then examined in more details using a scatterplot matrix which shows the high-dimensional data of individual pipeline runs and reveals correlations between the pipelines' input parameters and the output values. Selections of individual run sets are conveniently managed in a list and can be loaded at any time. These selections are visually examined and compared with 2D slices and 3D views using aggregated segmentation renderings and statistical contours.

In this work we apply several different segmentation pipelines using *Porosity Analyzer* to eight carbon fiber-reinforced polymer (CFRP) specimens and compare the results with the proposed method by Plank et. al [2] for porosity determination.

2. MATERIALS AND EXPERIMENTAL METHOD

We investigated eight carbon fiber-reinforced polymer (CFRP) specimens manufactured of cyanate ester (CNT-PT-30/carbon fiber). The specimens with a thickness of 1.78 mm and a width of 20 mm show a unidirectional fiber lay-up orientation of 0/+45/90/-45/-45/90/+45/0. Due to manufacturing imperfections each sample shows a varying degree of porosity. Samples were scanned using a GE Nanotom x|ray 180NF system. The following scanning parameters were applied: 60 kV, 260 µA, 900 ms (integration time), 1800 projections, and 12.5 µm isotropic voxel size.

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3. RESULTS

As Plank et. al [2] have shown, high resolution region of interest XCT scans can be used to determine a reference porosity value of a specified sample that is subsequently used to determine a global threshold that is used to quantitatively calculate the porosity value of the whole sample. Based on this method we estimated the reference porosity values for eight cyanate ester CFRP specimens. Using the porosity analysis module in VGStudioMax 3.0, we showed that the porosity values in our sample vary between 2.45 % and 10.09 % for the CFRP specimens [3].

Our preliminary results show that the *Porosity Analyzer* tool is able to provide a porosity range resulting from the applied segmentation pipelines for each dataset, which enables the user to estimate the uncertainty of the porosity value of a specimen. Figure 1(a) shows the porosity distribution of five exemplary datasets (D1-D5) using different threshold parameters of a histogram-based segmentation algorithm. For example, Figure 1(a) displays different porosity results (I-III) and Figure 1(c) shows the respective segmentation results (I-III, "under-segmentation", "optimal" segmentation, and "over-segmentation") of one example pore for D5. P*orosity Analyzer* also provides a boxplot view for each dataset (see Figure 1(b)). D5 has a median porosity of ~6.9% (bold black line) and a reference porosity of ~8.7% (red dashed line). Figure 1(d) depicts the aggregated segmentation masks of all the segmentations between I-III and the statistical contours, minimum (blue), median (black), and maximum (red). Figure 1(e) shows the reference segmentation mask of dataset 5.

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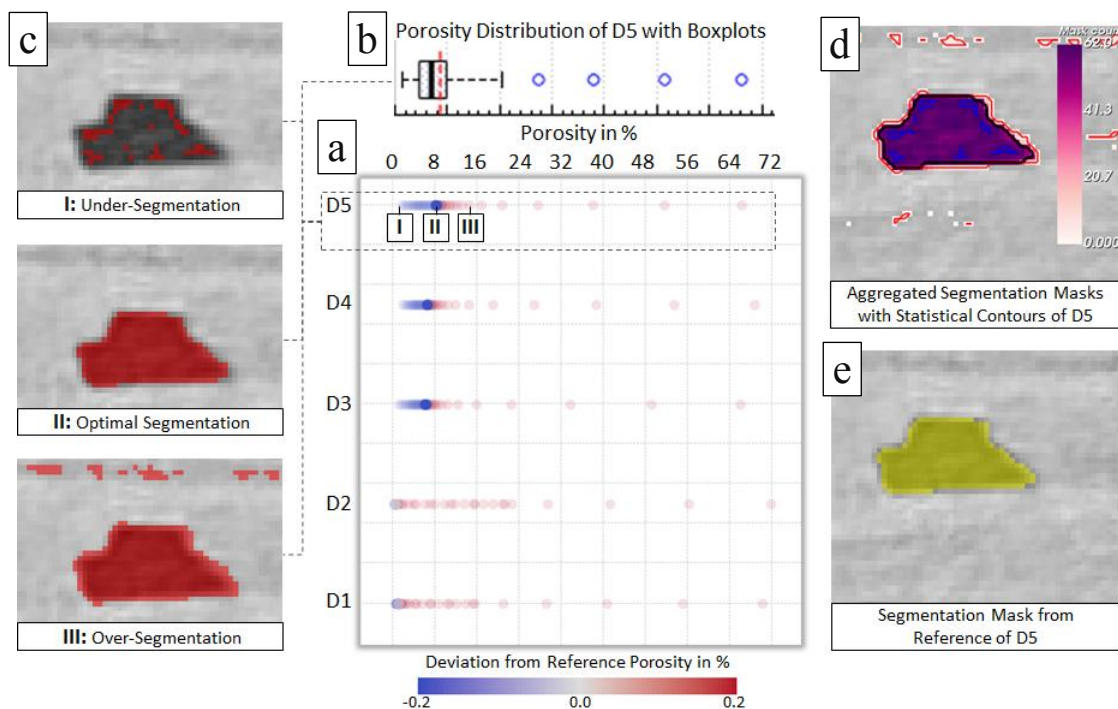
Figure 1: (a) Porosity distribution of datasets D1-D5. (b) Boxplot of D5. (c) Different segmentation results of D5. (d) Aggregated segmentation masks of all the segmentations between I and III and statistical contours of D5. (e) Reference segmentation mask of D5.