Visual analysis of void and reinforcement characteristics in X-ray computed tomography dataset series of fiber-reinforced polymers

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Abstract. Fiber-reinforced polymers (FRPs) are of great importance in various industries because of their superior properties as compared to conventional materials, their versatile processing, and their wide application possibilities. To fulfil the high-quality standards in its respective applications, industrial 3D X-ray computed tomography (XCT) is increasingly used. It enables an accurate, non-destructive characterization of material features such as inclusions, voids, fibers, or other reinforcements, which is of core importance for material and component design. In this work we present FeatureAnalyzer, a generalization of the previously introduced PorosityAnalyzer tool, which allows to analyze dataset series as generated for exploring the parameter space of image processing workflows (including pre-filtering, segmentation, post-processing or quantification) applied to XCT datasets of fiber-reinforced polymers. With a scatter plot matrix (SPLOM), the characteristics of the features of interest may be examined in more detail regarding the used input and output parameters. Individual results may be selected in the SPLOM and analyzed using 2D slice views and 3D renderings. For this work, three different samples (sample #1 - #3) were scanned by means of XCT and were evaluated by using FeatureAnalyzer. The samples #1 and #2 have a porosity value of approximately 1.7 vol. %. By using the FeatureAnalyzer in combination with SPLOM, the threshold parameters could be analyzed before the over-segmentation of voids occurs. Additional evaluations by parallel coordinates clearly show, that sample #2 has a higher number of spherical voids in the center of the specimen compared to sample #1. By evaluating the resin content of sample #3, the individual layer thickness could be measured. The source code of the tool is available on Github: https://github.com/3dct/open_iA/

1. Introduction and Motivation

Fiber-reinforced polymers (FRPs) are currently widely used because of properties like light weight and increased stiffness. With respect to these properties, FRPs have a broad range of application in common industry fields like aeronautics, sports, and increasingly in the automotive sector [1], [2]. Because of their superior properties, FRP composites can replace materials like aluminum and steel. For the design and analysis of new textile materials based on FRP composites, domain experts are interested in features like voids, inclusions, fibers, and epoxy resins to predict the behavior of materials. Especially the porosity is critical because the interlaminar shear strength of FRP composites is decreased by 7 % per 1 vol. % of porosity [2], [3]. The acceptance rate of porosity in aerospace is lower than 2 vol. % [2].
By analyzing identified epoxy rich areas in the FRP sample, domain experts can draw conclusions about the amount of layers of the surrounding fiber bundles, as well as about the properties of these fiber bundles. In order to get insights into the micro-structure, non-destructive testing (NDT) methods for materials characterization have been developed [4]. XCT is a NDT method, which provides high resolution 3D scans of the materials. Applied industrial 3D-X-ray computed tomography (XCT) gives insights into the micro-structure of FRP composites. XCT scans provide resolutions below 1 micron. The extraction or segmentation of interesting features such as voids and fibers in 3D volume datasets is performed using 3D image processing techniques. Typically, the following general characteristics of features like voids or fibers are of interest for domain experts: average feature volume, dimensions, feature count, and feature orientation. The main contribution of this work is to link the visual analysis of the 3D image segmentation process of extracted features to an interactive tool for visual analysis of feature characteristics. Moreover, FeatureAnalyzer supports the user in the visualization of specified feature regions. In the domain of FRP analysis, numerous tools for the extraction of e.g., fibers are available. For example, Salaberger et al. [5], [6], [7] developed an algorithm for extracting and quantifying fibers in FRPs. Plank et al. provide a review of porosity extraction algorithms in the field of carbon fiber-reinforced polymers [8]. However, to find a suitable feature extraction result, the domain experts need to compare segmentation algorithms with respect to the specified parameterization of the used algorithm. Aside other issues, the result of image segmentation strongly depends on the used pre-processing filters. Unfortunately, the evaluation of segmentation algorithms for feature extraction of XCT scans by analyzing parameters of applied filters with respect to the segmentation results is a time consuming process. The PorosityAnalyzer [9] supports domain experts in visual analysis of the 3D-image processing result in porosity analysis of XCT-data. Interactive parameter space analysis of segmented fibers and voids is provided by the FeatureScout [10].

Domain experts are also interested in features and reinforcements of FRP composites like inclusions, epoxy resins and fiber bundles. However, so far no software tool exists, which helps to visually analyze the parameter space of the image segmentation process for such features and their characteristics [11]. To address this research gap, we propose the FeatureAnalyzer tool as an enhancement and generalization to the PorosityAnalyzer. It assists domain experts in the evaluation of segmentation results for features. Mainly, the FeatureAnalyzer combines the aspects of the analysis of feature characteristics of interests to domain experts like volume, orientation, length, etc. with the interactive visualization of extracted feature regions in 2D and 3D by a link to the FeatureScout.

2. FeatureAnalyzer and FeatureScout

We present FeatureAnalyzer, a novel tool for the visual analysis of features from XCT scans of FRP samples. The aim of the FeatureAnalyzer is to provide support to domain experts in the evaluation of a 3D image segmentation workflow for the extraction of features like voids, inclusions epoxy rich areas as well as matrix reinforcements. As input data for the FeatureAnalyzer, a general dataset of originating from XCT scans of an FRP specimen, further a text file generated by other software tools can be applied: The FeatureAnalyzer is not constrained to a dataset containing voids only. This means that with the help of our tool, the domain experts can now analyze the 3D image segmentation process for any FRP feature. The workflow of the FeatureAnalyzer as illustrated in Figure 1 is described as follows: Building on the PorosityAnalyzer our tool consists of a computation module and an analysis module. The computation module allows to setup and run the offline computation of a user specified image processing pipeline. For each XCT dataset the image processing pipeline can be set up by combining various smoothing filters and segmentation filters. Furthermore, the computation module allows the user to sample the complete parameter space of all input parameters of the assembled image processing pipeline.
Figure 1. Analysis workflow of the FeatureAnalyzer. 3D volumetric data obtained by an XCT scan of an arbitrary FRP specimen serves as input for setup and analysis of the segmentation process in the FeatureAnalyzer. Detailed analysis of the computed feature characteristics for a specific segmentation is provided by the FeatureScout [10].

We call the segmentations from all computed runs ensemble members. Each ensemble member consists of a segmentation mask, a table of its feature characteristics, metrics like computation time and error metrics, as well as statistical properties like average volume and average length of the segmented features. The ensemble members serve as input for the analysis module. The analysis module provides visual support to domain experts in evaluating the 3D-image segmentation process with respect to the sampled input parameter range. Moreover, the analysis module allows domain experts a general analysis of the characteristics of a 3D-image segmentation result for features such as fibers, voids, etc., as mentioned before. The parameter space of related input parameters and computed output characteristics like feature count, volume and length as well as the metrics can be visually analyzed through the scatter plot matrix (SPLOM). The SPLOM consists of scatter plots visualizing the relation between every input
and output parameter for a specified segmentation algorithm. Each scatter plot visualizes the relation between two parameters. Each point contained in a scatter plot represents a segmentation result with a certain parameter combination. The scatter plots are linked, which means that a selection made in one plot is also transferred to the other plots. In addition to the data previously available in the PorosityAnalyzer, domain experts can now analyze general statistical characteristics such as volume, orientation and the feature count of features to be extracted in the SPLOM. Figure 2 depicts the analysis module of the FeatureAnalyzer. As described by Weissenböck et al. [9] individual results of the segmentation process can be selected and visually compared to a reference segmentation provided by domain experts. Further metrics such as calculation time, error metrics and dice coefficients can be analyzed by means of the SPLOM. A segmentation selected in the SPLOM is visualized in 2D-slice views [9].

![Figure 2](image)

**Figure 2.** The analysis module of the FeatureAnalyzer for visual evaluation of the 3D-image segmentation workflow. Visual analysis of the parameter space of the segmentation results is presented by a scatter plot matrix (SPLOM) (A). The segmentation results selected in the SPLOM are visually compared to a user specified segmentation in 2D-slice views (B).

The FeatureAnalyzer provides a link to the FeatureScout: Domain experts specify a single segmentation result of a general FRP feature provided by an XCT scan, such as voids and epoxy rich areas or other FRP features. The specified segmentation result, which is based on a specific input and output parameter combination, is then passed to the FeatureScout. There, domain experts can visually analyze the parameter space, e.g., the characteristics such as volume, shape and position of extracted features by means of a scatter plot matrix (SPLOM) and parallel coordinates (PC). The SPLOM and the PC visualize relations between the feature characteristics. The SPLOM and PC are linked to the 3D viewer, which provides an interactive visualization of user specified feature regions. According to the requirements of the domain experts the FeatureScout also allows a color-coded classification of regions of interests as described by Weissenböck et al. [10].

3. Experimental setup and data parametrization

3.1. Sample description and XCT parameters

In this study, three different CFRP samples, manufactured by prepreg technology in plain weave style, were investigated. Sample type #1 and #2 are made of CYCOM® 977-2 [12] and contain porosity and some additional glass fiber rovings as shown in Figure 3 (A) and (B). The samples were cut out from a
real world part. For this XCT investigation the sample size was 10 x 10 x 3.5 mm³. The sample of type #3 was made of 5 plies of PRG09229 - CC 120 ER450 43% as shown in Figure 3 (C). For this XCT investigations a sample size of 10 x 10 x 0.69 mm³ was cut out of a test plate. The ply thickness is about 0.138 mm.

XCT scans were performed on a Nanotom 180 NF device manufactured by GE phoenix|x-ray. The device uses a 180 keV nano-focus tube and a full digital 2304² pixel flat panel detector from Hamamatsu. As target material molybdenum was used. No pre- or post-filters were used for the scans. The exact measurement parameters are listed in Table 1:

| Sample Name | Voxel size [µm] | Tube voltage [kV] | Tube current [µA] | Integration time [ms] | Projections | Average | Measurement time [min] |
|-------------|-----------------|-------------------|-------------------|-----------------------|-------------|---------|------------------------|
| Sample #1 & #2 | 10              | 60                | 290               | 500                   | 2400        | 1 (continuous) | 20         |
| Sample #3   | 6               | 50                | 220               | 600                   | 1700        | 5       | 105                    |

The data specification and parametrization for the samples #1 - #3 are listed in Table 2. The data encoding represents the range of the color intensities for gray values of a dataset.

| Sample Name | Dimension [Voxels] | Components | Segmentation Threshold | Reference Porosity [vol. %] | Volume [µm³] | Voxel size [µm] | Data encoding (Color range) |
|-------------|--------------------|------------|------------------------|-----------------------------|--------------|---------------|---------------------------|
| Sample #1   | 853 x 243 x 858    | Voids      | 15846                  | 1.74                        |              | 10            | 16 Bits: 0..65355          |
| Sample #2   | 915 x 202 x 846    | Voids      | 15846                  | 1.70                        |              | 10            | 16 Bits: 0..65355          |
| Sample #3   | 699 x 99 x 699     | Epoxy resins | 42300                  | 9.57                        |              | 6             | 16 Bits: 0..65355          |

**Figure 3**: 3D visualization and 2D-slice views of volumetric datasets of FRP-samples obtained by XCT: (A) sample #1, (B) sample #2, (C) sample #3.

3.2. Parametrization of data and applied segmentation

For the void segmentation we analyzed the samples #1 and #2. To define the reference porosity value for further segmentation, we apply the segmentation of porosity through the ISO 50 method. As shown in Plank et al. [13], with high resolution scans the threshold for segmentation has quite a low impact on the evaluated porosity. For the used material system, a high resolution reference scan with 5 µm voxel size was performed and evaluated by applying the ISO50 threshold. These results were applied for the
further samples, which were scanned at 10 µm voxel size, as already introduced by Senck et al. [14]. The thresholds of the porosity segmentation of sample #1 and sample #2 were determined by ISO 50. The resulting porosity and the specified thresholds are also listed in Table 2 of section 3.1. As a starting segmentation, a general binary threshold filter from the image segmentation and registration toolkit (ITK) was applied [15], [9]. For the comparison of the segmentation results with respect to the statistical output parameter results of both datasets, the upper gray value threshold range was sampled between 12000 and 17500 with a step size of 100 gray values.

To illustrate the analysis of the extraction of epoxy rich areas, our domain experts provide an XCT dataset consisting of plain weave fiber bundles. For the dataset sample #3 a reference segmentation does not exist. Thus, the upper comparison threshold was specified to an estimated intensity value of 42300 with an obtained volume of epoxy rich areas of 9.57 vol. %. The image processing pipeline is set up as follows: For the preprocessing of the XCT data, the Gradient Anisotropic Diffusion filter is applied for edge-preserving noise removal [15]. To analyze the segmentation results, a general threshold filter was applied within a specified threshold range of gray value intensities. For the parametrization of the segmentation setup for epoxy rich areas, the lower threshold is set to 0 and the upper range of the threshold to be sampled is estimated between the range of 41000 and 44000 with a step size of 10.

4. Results and Discussion
In this section we discuss our findings on the application of the FeatureAnalyzer for porosity segmentation (see section 4.1) and the segmentation of epoxy rich areas, see section 4.2).

4.1. Analysis of void sample datasets
The relation of the gray value intensities to the parameters porosity as well as the feature count is shown in the scatter plots of Fig. 4. A clear over-segmentation of sample #1 with respect to the analysis of the feature characteristics was considered. To analyze this aspect, the threshold value parameter was sampled in a range between 6000 and 34000 gray values in steps of 250, as this gray value range includes air and materials content. Furthermore, the segmentation masks are compared at different threshold values. The color bar indicates the deviation of the segmentation result to the reference porosity where a deviation greater than or equal to 0.2 % is specified as over-segmentation, color coded in dark red, and a deviation of smaller or equal to -0.2 % is specified as under-segmentation, color coded in dark blue. It can be seen that the porosity is constantly increasing with the binary threshold. From a threshold value of 18000 with a porosity of 2.24 vol. %, the feature count (FeatureCnt) is significantly increasing with an increasing binary threshold, which is also shown by the color bar. From that point, the feature volume is slightly decreasing. This shows that additionally a large number of small elements are classified, which explains the high feature count. The property feature count reaches its highest value at a threshold of 19750, the segmented porosity is of 7.72 vol. % for this threshold. From that point on, the feature count is strongly decreasing with increasing binary threshold, as the segmentation starts classifying the matrix as void, thus connecting objects of larger volume. Starting with a threshold of 22000, the average feature volume is significantly increasing with an increasing binary threshold. Further, the feature count is slightly decreasing, and approaching a nearly constant level at a comparatively small number. The obtained porosity is at 71.54 vol. %, and the feature count is approximately 11000. Thus we identify a single major region of a large, connected volume, which represents the FRP matrix, and further regions of several small elements are identified as seen in Figure 4 (2). At a threshold of 25250 the porosity reaches 90.33 vol. %. This means, that approximately 90 percent of the sample volume of the FRP dataset is classified. This is in good agreement with the illustration shown in Figure 4 (3), which shows that the entire FRP matrix is nearly classified as void at this threshold.
Figure 4: Figure: (A) scatter plots of sample #1 visualizing the relation of the binary threshold (BinaryThr) to the feature count (FeatureCnt), porosity (Por.) and the average feature volume (AvgFeatureVol). (B) Comparison of the unsegmented data (0) to (1-3) the segmentation masks obtained at different thresholds (Thr) and their respective porosity (Por.).

For a detailed investigation of the segmentation results close to the reference porosity value in Fig. 5, the gray value intensities were sampled in the range between 12000 and 175000 in steps of 100. By means of the SPLOM, the relation of the binary threshold value with respect to properties such as the porosity, feature count (FeatureCnt) and the average feature volume (AvgFeatureVol) is visually analyzed. The SPLOM shows that the porosity is increasing along with the binary threshold. The feature count (FeatureCnt) is slightly decreasing when increasing the binary threshold to a certain point, and then starts increasing. At the same point the average feature volume reaches its maximum value. We can conclude that by increasing the binary threshold, an increasing number of voxels are classified as connected regions of voids, leading to an increase of the volume porosity, which we identified as over-segmentation. In Figure 5, we exemplarily show an over-segmentation of the porosity volume at a gray value of 17500. An under-segmentation of porosity is illustrated at the gray value intensity of 12000. The reference porosity is specified to the gray value intensity of 15900. The segmentation result of the reference porosity is shown by the yellow segmentation mask. The blue color indicates a decreased void size in comparison to the reference segmentation, whereas the red color indicates an increase of the segmented voids, as can be seen in Figure 5 (2) and Figure 5 (3), respectively.
Figure 5: (A) The SPLOM illustrates obtained segmentations for the sample #1 at different binary thresholds (Thr) of 12000 (1), 15900 (2) and 17500 (3). (B) The 2D-slice previews of the segmentation masks of (1-3) are compared to the unsegmented XCT volume.

For sample #2 the same reference threshold leads to a slightly different reference porosity, as discussed in section 4.2. The general trend of the threshold variations leads to similar results as depicted in Fig. 5. Thus, we scope our discussion to the analysis of the detailed feature characteristics of the resulting porosity extraction for both datasets. Therefore, the obtained segmentations at the reference gray value intensity of 15846 for sample #1 and sample #2 are sent to the FeatureScout. The feature characteristics for sample #1 and sample #2 were obtained by means of the Volume Graphics\(^1\) defect detection tool in order to get additional calculated properties such as the sphericity. The segmented objects of a size smaller than 27 voxels are considered to be noise and are thus removed from further analysis. The feature characteristics of both datasets are compared by means of the parallel coordinates (PC), which are linked to the 3D view as illustrated in Figure 6. In the PC every axis represents a single characteristic of the segmentation result. Every segmented object is represented by a polyline connecting every property axis [10]. In our application case each connected polyline represents a single extracted void. The PC show equally distributed voids in X and Z directions. The position with respect to the thickness of the pore specimen of the located voids in the dataset is represented by the property Pos.Y. The sphericity represents the shape of the voids. A sphericity value of 1 indicates round voids with the shape of a sphere, whereas a sphericity value close to 0 indicates voids of flat shape. The selection in red represents

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\(^1\) Volume Graphics is a software for the analysis and visualization of industrial 3D computed tomography data. https://www.volumegraphics.com/
voids at the center of the specimen thickness. There, the voids are equally distributed with respect to the x- and z-directions. Analyzing the PC view in combination with the 3D viewer, the sample #2 shows a higher number of defects with a higher sphericity between 0.5 and 0.7 located in the center of the sample compared to the sample #1. The 3D visualizations of the selected voids located in the center of the specimen confirm these findings.

Figure 6: Comparison of the feature characteristics of extracted voids for sample #1 and sample #2 through Parallel Coordinates and 3D visualization at a reference threshold of 15846. The red lines represent a selection of voids located in the center of both datasets.

4.2. Analysis of the segmentation of epoxy rich areas
In this section, we demonstrate the analysis of the segmentation result of epoxy rich areas for the specified segmentation pipeline of the dataset sample #3. The result of the reference segmentation is determined empirically with the help of FeatureAnalyzer with respect to the specified parametrization as mentioned in section 3.2. The feature characteristics obtained for the reference segmentation at the threshold of 42300 are visually analyzed in the FeatureScout. The scatter plot illustrates the correlation between feature volume (Volume) and major length (MajorLength), where the major length represents the longest extent of a segmented object along a main axis. The feature volume with respect to the major length of the segmentation results are visually analyzed in the FeatureScout at the gray value intensities of 42300 as visualized in Figure 7. The segmentation results show a large count of unconnected regions of small volumes. These regions are probably resulting from voxels misclassified by the binary threshold algorithm. The most likely reason for those misclassifications of voxels are a high level of noise in the XCT dataset as well as additional measurement artifacts due to the low difference of absorption contrast between carbon fibers and epoxy resins. The reference segmentation depicts four connected regions of
large volumes, which are classified by different colors. The connected regions are visually identified as layers of epoxy rich areas.

![Figure 7: 3D-Visualisation of identified epoxy rich areas (marked with red) of sample #3 comparing the reference segmentation at a threshold (Thr) of 42300. The scatter plot visualizes the respective feature characteristics.](image)

The volume property with respect to the sample center positions and sample dimensions of dataset sample #3 is visualized in Figure 8. The figure illustrates four layers, equally spaced within the thickness of the sample, as can be seen through the property Ym. Here a mean layer thickness of 0.131 mm can be extracted, which fits well to the theoretical value of 0.138 mm as described in chapter 3.1. Small regions of misclassified voxels are equally spread in the center of the sample. The scatter plot (Xm versus Ym) in Figure 8 on the right, depicts that the layers range along the complete specimen length Xm from zero to four millimeters.

![Figure 8: Scatter plots of the reference segmentation for the sample #3 obtained at a threshold of 42300.](image)

5. Conclusion and future work
In this work we introduced FeatureAnalyzer, a novel tool to support domain experts in the field of 3D image processing of XCT data for identifying general features in FRPs like voids and other matrix components. FeatureAnalyzer allows the user to do a visual parameter analysis of the segmentation results through a scatter plot matrix. Further the segmentation results can be quantified by analyzing relation of input parameters with respect to calculated statistical output parameters such as average feature volume and feature counts of a segmentation result. Analyzing those parameters linked to the
2D slice view of a selection, helps domain experts to visually identify a certain gray value range of a suitable segmentation and to predict the behavior of the corresponding segmentations. The parameter studies, as shown in this work on sample #1, help to optimize the segmentation results, which can then be used as a basis for future feature extraction of internal microstructures such as pores. In a further step and for error estimations, results from FeatureAnalyzer in combination with FeatureScout should be considered for developing material models used for microstructure simulations in future tasks. We demonstrated the applicability of our tool on two application cases. The analysis of detailed feature characteristics of a single segmentation result from extracted features is done by means of the link of the FeatureAnalyzer to the FeatureScout. Visual parameter space analysis with FeatureScout by means of the SPLOM and the PC allows a color coded classification and 3D-visualisation of extracted feature regions with respect to characteristics such as volume, orientation and localization of each extracted feature. In the future we plan to added quantities like different shape factors to further characterize the segmented features. Additionally, we plan to modify our tool to be able to analyze extractions of fiber bundles.

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