

Advanced Visualization and Exploration Techniques for Fiber Reinforced Polymers

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Abstract

For the development of fiber reinforced polymers (FRPs) properties such as fiber content, fiber length, fiber orientation or weaving patterns play a crucial role. To non-destructively analyze these material characteristics 3D X-Ray Computed Tomography (XCT) is currently the method of choice to provide high detailed data of the internal structures. In [1] we have introduced the FiberScout system, a novel tool for interactive exploration and visual analysis of fiber characteristics in XCT data. In this work we present the newly added FiberScout functionalities to support the materials experts in their work and to provide them with new insights into the material systems. The new functionalities include the extension of the selection and classification process to voids based on their specific characteristics as well as the calculation and visualization of a void/fiber mean object. In addition, histograms show the distribution of all fiber characteristics. Furthermore, the illustration of fiber cluster points in the dataset by the previous calculation of the metadata and the possibility to inspect the slicer data with the Meta Lens was developed. The results were evaluated by applying our visualization techniques to three different material systems.

Keywords: Industrial 3D Computed Tomography, fiber reinforced polymers, visual analysis, interaction techniques, visualization

1. Introduction

Lightweight materials, more precisely fiber reinforced composites have been picked up increasingly in the last years by the transportation industry [5] as they are lightweight while keeping high mechanical loads. The industry branches of aerospace, automotive and wind energy have recognized the advantages of fiber reinforced polymers (FRPs) and will rely on these material systems in the upcoming years. As described in [6] the annual global demand for carbon FRPs will increase from 37,000 tons in 2011 to about 130,000 tons in 2020. This tendency is already visible in the new generation of wide-body aircrafts, which consist of more than 50 % of fiber reinforced materials [7]. As the aerospace industry has high quality demands on FRP components, material research and inspection are challenged to continuously improve. For this purpose the use of industrial 3D X-Ray Computed Tomography (XCT) as a non-destructive testing (NDT) method has significantly increased over the recent years. Currently available XCT systems are capable to resolve structures of less than one micron [4]. These high-resolution measurements make it possible to resolve individual fibers and to determine their orientation and length, as these characteristics strongly influence the material properties in terms of stiffness, strength and ductility. A major challenge in this case is the constantly increasing data size which requires suitable software and image processing algorithms to extract the individual fibers and their properties. Another challenging task is to visualize the data to improve the working process of the material scientists.

In [1] we have presented a tool called FiberScout which meets these challenges. The system was developed in collaboration with domain experts to assist them in their work. It allows the interactive exploration and analysis of high resolution XCT data of FRPs. We use parallel coordinates to define initial fiber classes and a scatter plot matrix to refine the initial classification. The Class Explorer, the 3D rendering view and the slice view (slicer) show the

resulting fiber classifications. The Polar Plot view is used to provide an overview of the fiber orientation distribution in the data. We also provide visualizations for the fiber orientation distribution and the fiber length distribution. Furthermore, two abstract visualization methods, the Blob and Metadata visualizations describe fiber regions with similar fiber characteristics.

In this work we present further significant extensions to the FiberScout system (see Figure 1) which improve the analysis of high resolution XCT scans of FRPs. The system is now able to analyze and classify fibers and voids in FRPs. Furthermore, we have added a Mean Object view, which calculates and visualizes the void/fiber mean object of user-defined classes. The calculation of the mean object is based on [2]. The Metadata visualization is extended to calculate the Number of Fibers in a Cell to show cluster points in the dataset. In case of the Metadata visualization we now also provide a so-called Meta Lens to display the meta- and original data simultaneously. Another new contribution of this work includes the illustration of the void/fiber characteristics and their histogram distributions. Finally, an export function allows the storage of all user-defined void/fiber classes with the corresponding fibers/voids properties in XML format.

In summary, the following features have been added to the FiberScout system and stand out from the previous work [1]:

- Classification of voids
- Calculation and visualization of Mean Objects (voids and fibers)
- Calculation and visualization of fiber cluster points within the Metadata visualization and the use of the Meta Lens
- Histogram distributions for void/fiber characteristics
- XML export function for user-defined classes

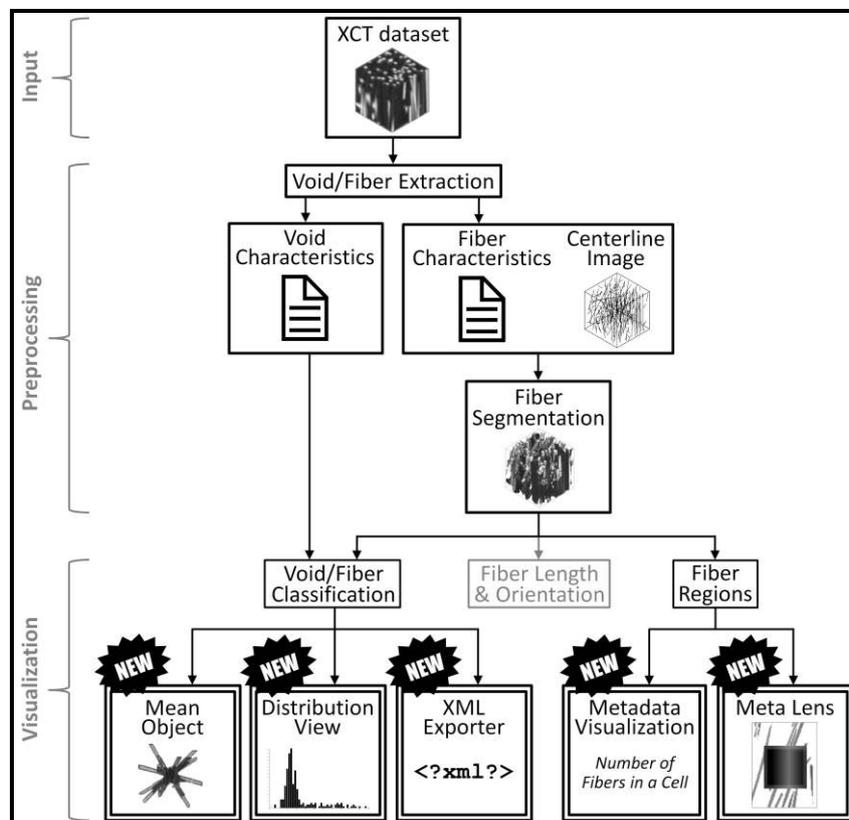


Figure 1: Workflow of the FiberScout system and the newly added functionalities.

2. Dataset Description

The new functionalities of the FiberScout system are demonstrated in this work based on three selected datasets, which are made of different materials. The first dataset is an injection-molded short glass fiber tensile test specimen (see Figure 2a) with a polypropylene matrix (PP-SGF30). This dataset has already been presented in [1]. The second data set is an injection-molded long glass fiber tensile test specimen (see Figure 2b) with a polypropylene matrix (PP-LGF20). As a third dataset a carbon fiber reinforced polymer laminate (CFRP laminate) containing voids which originate during the manufacturing process (see Figure 2c). The XCT scans were performed on a GE phoenix | x-ray Nanotom 180 NF. **Table 1** summarizes the main data of the investigated specimens and the XCT measurement parameters.

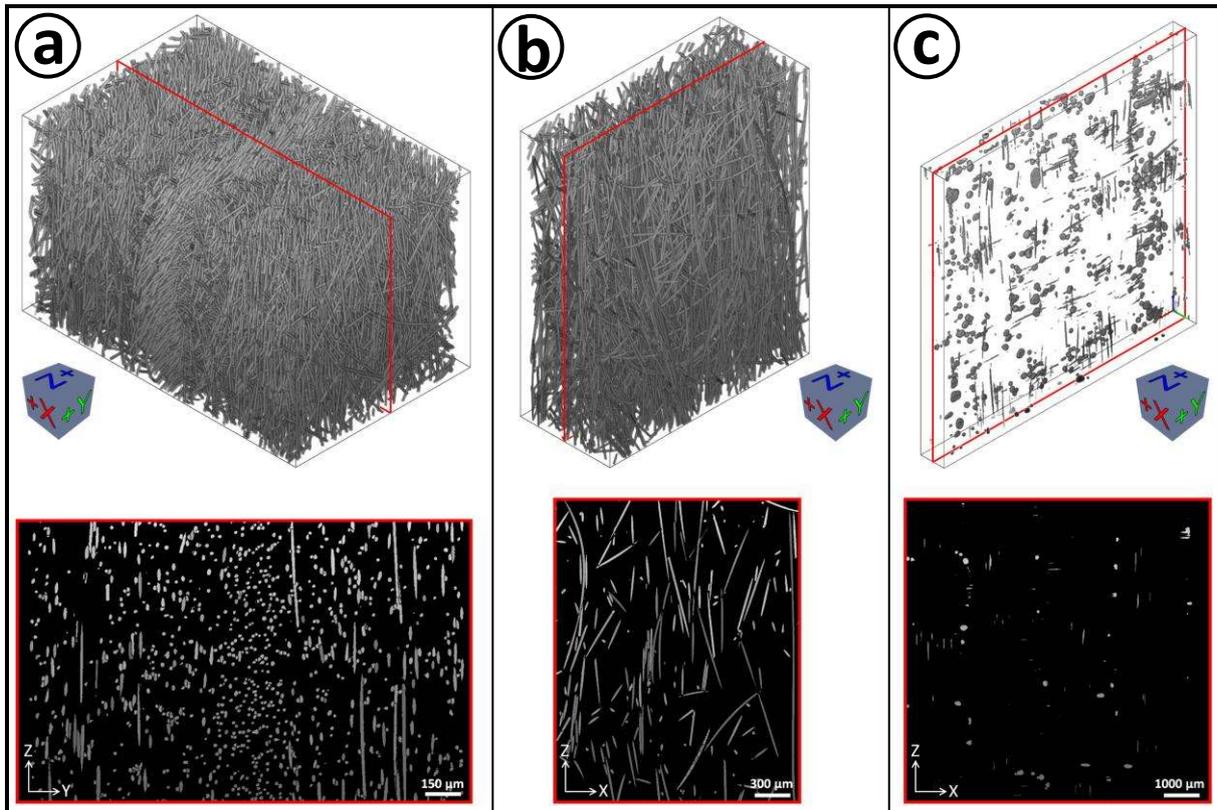


Figure 2: 3D and slice view of the segmented datasets. (a) Short glass fiber specimen with segmented fibers, PP-SGF30. (b) Long glass fiber specimen with segmented fibers, PP-LGF20. (c) Carbon fiber reinforced polymer specimen with segmented voids, CFRP laminate.

Table 1: Overview of the scan parameters and most important properties of the datasets.

Specimen	Fiber weight content	Fiber diameter (μm)	Number of fibers/voids	Dataset size X Y Z (μm)	U (kV)	I (μA)	T _{int} (ms)	Images	Scan time (min)	Voxel size (μm)	Averaging	ZD (mm)
PP-SGF30	30%	ca. 13	15916	614 961 600	80	120	750	1900	300	2	5	300
PP-LGF20	20%	ca.16	3653	1000 500 1250	80	120	750	1900	300	2	5	300
CFRP laminate	--	--	1721	800 75 800	60	320	500	1800	117	10.5	5	220

3. Newly Added FiberScout Functionalities

3.1 Classification of Voids in FRPs

As described in [1] the simple rendering of XCT is insufficient when analyzing FRPs because of the high number of micro-structures, e.g., fibers, which lead to occlusions in the visualizations. Therefore, the FiberScout system has been developed to overcome this problem by selecting the individual fibers according to their characteristics with different interactive exploration techniques (Parallel Coordinates and Scatterplot Matrix). The selected fibers can then be grouped into classes and are listed in the Class Explorer.

FRPs not only consist of fibers, but also contain defects such as voids. These voids are of great interest for the domain experts as they strongly influence the material properties in terms of stiffness and strength.

In this work we adapted the fiber classification concept to voids. To accomplish this, the voids in the XCT data are extracted by suitable segmentation algorithms [3]. Each void receives a unique label. Subsequently, the characteristics of each single void are calculated and stored. This adaptation now allows individually selecting and analyzing these defects according to their specific characteristics (see **Table 2**). The results of the void classifications are shown in Section 4.1.

Table 2: Characteristics calculated for each void.

Void Characteristic	Description	Unit
ID	The corresponding unique label of a void	--
Volume	The volume of a void	μm^3
DimX, DimY, DimZ	The extents of the void in the X, Y and Z direction	μm
PosX, PosY, PosZ	The XYZ coordinates of the void center	μm
Shape Factor	The shape factor of a void is defined as the ratio between the surface and the volume	--

3.2 Void/Fiber Mean Objects in FRPs

As described in [2], the high-resolution XCT datasets of FRPs contain a high number of voids/fibers, which overlap each other. Therefore, the analysis in terms of shape, size, and orientation of each void/fiber turns out to be very difficult. To cope with this problem Reh et al. describe the so-called MObjects (mean object).

In our work we have taken up the concept of MObjects and apply it not only to voids but also to fibers. For this purpose, a mean object is calculated for each defined class. The voxel data of every void are superimposed in their centers. The number of voxel overlays are summed up and normalized to one. The normalized frequencies result in a blue colored core of the mean object (high frequency) and yellow colored edge regions (low frequency). The colors, opacity and the threshold of the mean object regions can be changed by setting the transfer functions. The resulting mean object quickly gives an insight of how the voids/fibers in the defined class are aligned on average and how the average shape and proportions look like. The results of the void/fiber mean objects are shown in Section 4.2.

3.3 Metadata Fiber Cluster Points and the Meta Lens

Due to the high number of fibers in an FRP specimen, locating regions of interest in the original XCT volume data is a difficult task for the domain experts. As described in [1] the

Metadata visualization helps the experts to quickly find these interesting regions. For this purpose, the original volume data is divided by a user-defined voxel factor. From all the fibers which are within a cell the average fiber characteristics are calculated. The resulting meta-volume is then visualized as a context of the original volume data in the 3D view and the slicer.

In this work we calculate a new metadata characteristic, called Number of Fibers in a Cell, which shows fiber cluster points in the FRP specimen. Depending on the number of fibers, the cells can be colored by setting the transfer functions. The results of the new metadata characteristic Number of Fibers in a Cell are shown in Figure 7a. In addition, the original XCT volume data can be investigated with the so-called Meta Lens. When moving the Meta Lens in the slicer over the original XCT volume data, the corresponding metadata are displayed. The concept of the Meta Lens makes it possible to simultaneously show the original volume data and the metadata of the fibers without losing the context. In contrast to blend the original data over the metadata the Meta Lens allows to display both with full contrast. The results of the Meta Lens are shown in Figure 7b.

3.4 Distribution View for Void/Fiber Characteristics

In the Distribution view all the selected void/fiber characteristics, e.g., fiber length, fiber diameter, void volume, void shape factor, etc. are calculated and displayed as histogram distributions. The lower and upper class limits as well as the class frequencies of the individual distributions can be saved to a file. The results of the Distribution view for the datasets are shown in Section 4.4.

3.5 XML Export Function

The XML export function is an interface to third party applications, such as simulation or modelling tools and provides relevant information. The fiber classes defined by the domain experts may be saved as a file including all internal objects and characteristics. Figure 3 exemplarily shows the XML structure for voids and fibers.

<pre> <FiberClasses> <FiberClass-1> <CColor>0x00C0C0C0</CColor> <NFibers>123456</NFibers> <Fibers> <Fiber-1> <X1>482</X1> <Y1>46.0168</Y1> <Z1>7.02143</Z1> <X2>480.745</X2> <Y2>45.9512</Y2> <Z2>299.052</Z2> <Phi>182.992</Phi> <Theta>0.240775</Theta> <Dia>11.5256</Dia> <sL>299.055</sL> <cL>301.505</cL> <Surf>11037</Surf> <Vol>31200.7</Vol> </Fiber-1> <Fiber-2> ... </Fiber-2> </Fibers> </FiberClass-1> <FiberClass-2> ... </FiberClass-2> ... </FiberClasses> </pre>	<pre> <VoidClasses> <VoidClass-1> <CColor>0x00C0C0C0</CColor> <NVoids>123456</NVoids> <Voids> <Void-1> <Volume>1.0</Volume> <dimX>1.0</dimX> <dimY>1.0</dimY> <dimZ>1.0</dimZ> <posX>1.0</posX> <posY>1.0</posY> <posZ>1.0</posZ> <ShapeFactor>1.0</ShapeFactor> </Void-1> <Void-2> ... </Void-2> </Voids> </VoidClass-1> <VoidClass-2> ... </VoidClass-2> </VoidClasses> </pre>
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Figure 3: XML export structure for defined fiber and void classes.

4. Results

4.1 Void Classification Results

The selection and the subsequent classification of the voids in the CFRP laminate dataset were separately performed using the void characteristics volume and shape factor. Figure 4a shows all the voids in the dataset with a volume between 0.003 and $0.012 \mu\text{m}^3$. This selection of “large” void volumes mainly shows circular voids. Figure 4b shows all the voids in the dataset with a volume of less than or equal to $0.0003 \mu\text{m}^3$. This selection of “small” void volumes mainly shows needle-shaped voids. The void selection in Figure 4c is done based on the shape factor of 0.3 - 0.5 which shows the circular voids in the dataset, while a shape factor of 0.9 - 1.0 shows the needle-shaped voids in the dataset (see Figure 4d).

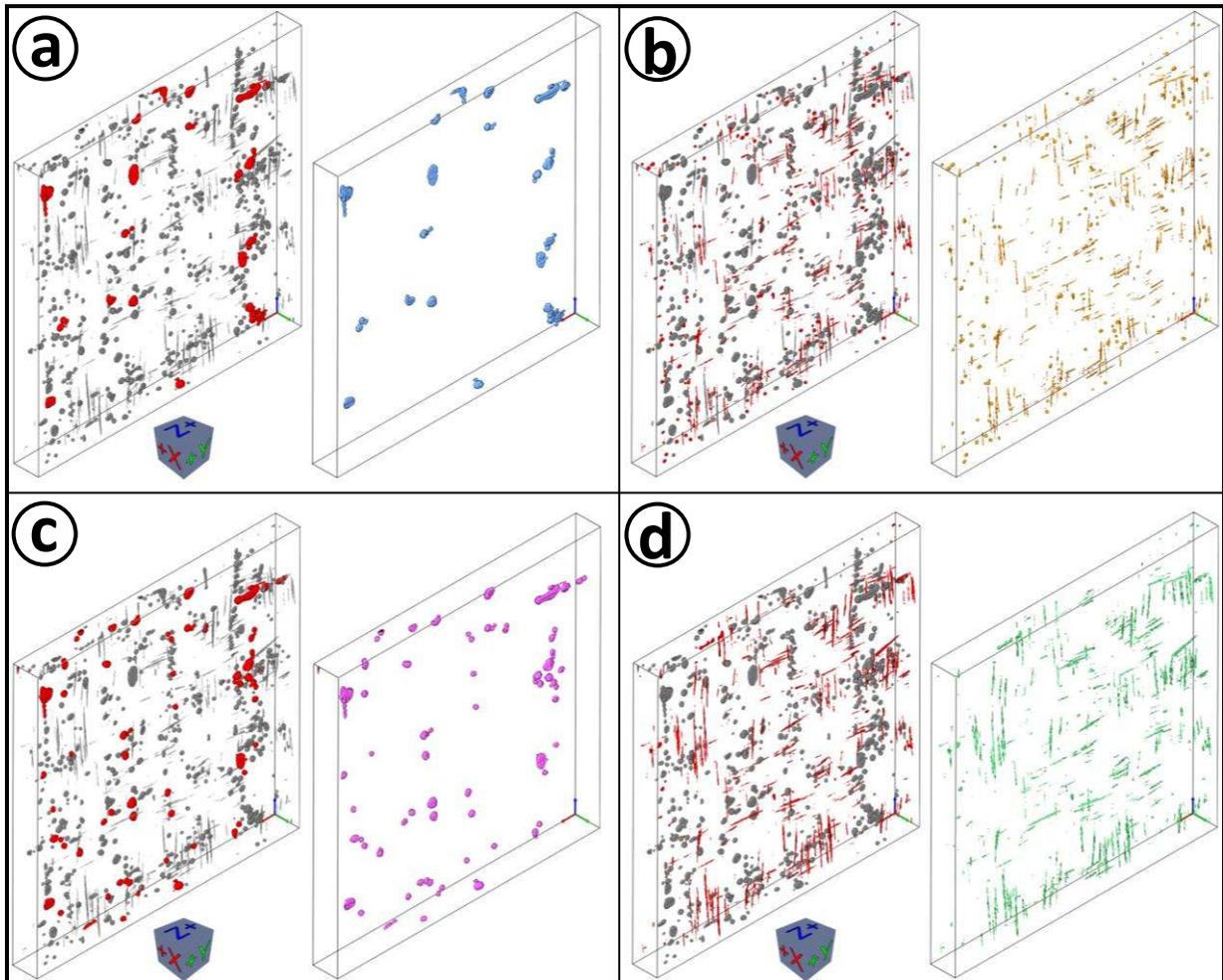


Figure 4: Void selection (red) and classification (blue, orange, magenta, green) based on the characteristic (a) Volume (0.003 - $0.012 \mu\text{m}^3$), (b) Volume (0 - $0.0003 \mu\text{m}^3$), (c) ShapeFactor (0.3 - 0.5) and (d) ShapeFactor (0.9 - 1).

4.2 Void/Fiber Mean Objects Results

The void mean objects shown in Figure 5a and b are calculated based on the defined void classes shown in Figure 4a (blue class) and b (orange class), which are based on the volume of the voids. The blue class contains “large” circular voids, the orange class “small” needle-shaped voids. This fact is getting immediately apparent in Figure 5a and b.

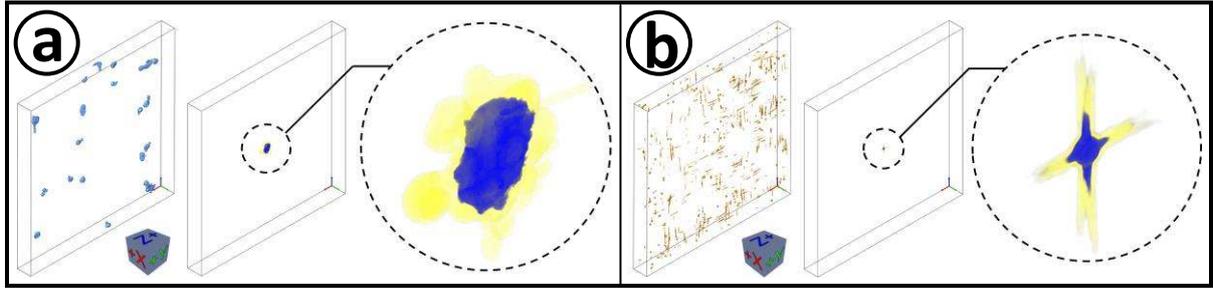


Figure 5: (a) Blue colored class of mainly circular voids and the resulting void mean object. (b) Orange colored class of needle-shaped voids and the resulting void mean object.

Figure 6a and b show the resulting fiber mean objects of the PP-SGF30 and the PP-LGF20 dataset. In case of the PP-SGF30 dataset (see Figure 6a) the blue core of the fiber mean object shows fibers which are mainly oriented in Z-direction and some fibers in the middle of the dataset (depicted in red) which are oriented along the X-axis. In the case of the PP-LGF20 dataset (see Figure 6b) the blue core of the fiber mean object indicates that the fibers are mainly oriented along the Z axis.

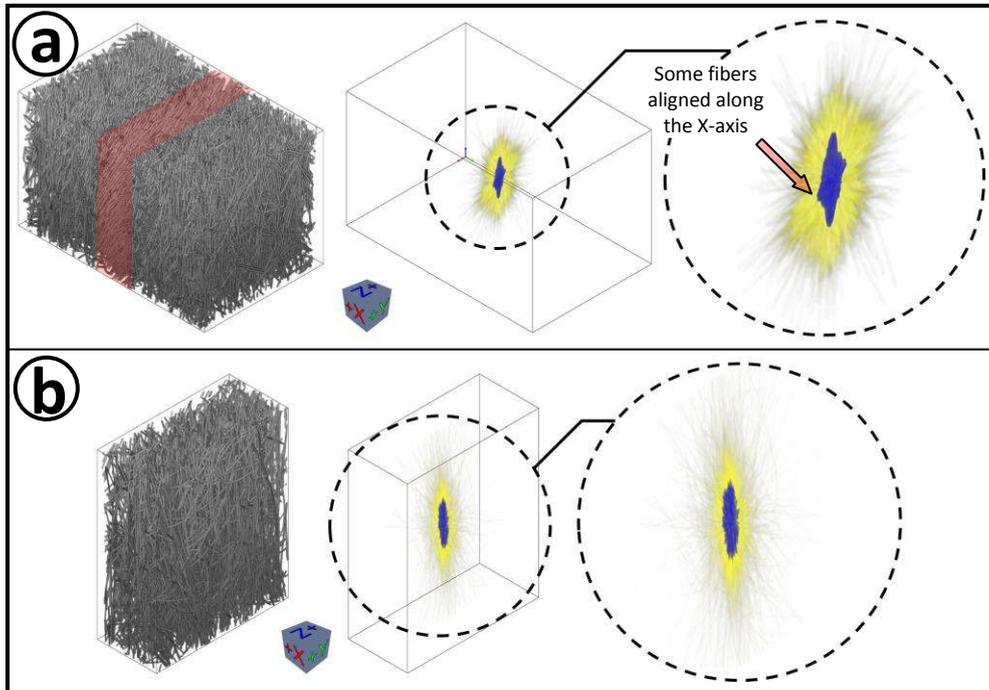


Figure 6: Detailed view of the resulting fiber mean objects (on the right) of the (a) PP-SGF30 dataset and (b) the PP-LGF20 dataset.

4.3 Results of the Metadata Fiber Cluster Points and the Meta Lens

Figure 7a shows a cut-through the PP-LGF20 dataset with a visualization of the metadata characteristic Number of Fibers in a Cell. The original XCT volume data were subsampled with a voxel factor of 50. The transfer functions were set in the way that the cluster points with approximately 10-16 fibers per cell are colored in magenta whereas cluster points with approximately 8-10 fibers per cell are colored in light-pink. Cells containing less than 8 fibers are not colored. Position 1 indicates an area with a high fiber concentration; Position 2 indicates an area with a low fiber concentration.

Figure 7b shows the Meta Lens at Position 1 and Position 2 in the slicer. The positions correspond with the positions in Figure 7a. The slicer contains the volume data of the segmented fibers. The overlaid Meta Lens (yellowish square) shows the corresponding area of the calculated metadata volume. Position 1 indicates an area with a high fiber concentration (magenta: approximately 10-16 fiber per cell, light pink: approximately 8-10 fiber per cell); Position 2 indicates an area with a low fiber concentration (black: less than 8 fibers per cell).

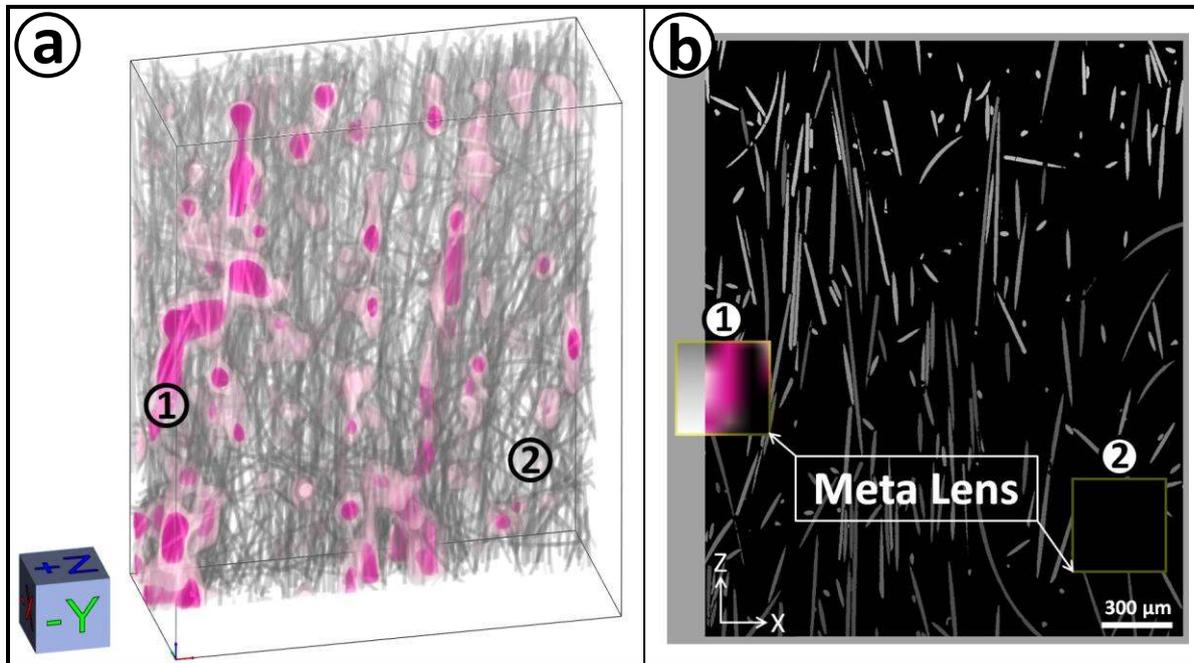


Figure 7: (a) The Metadata visualization based on the metadata characteristic Number of Fibers in a Cell. (b) The Meta Lens with the corresponding metadata overlaid onto the XZ-slicer.

4.4 Distribution View Results

The Distribution view of the short glass fiber dataset (PP-SGF30), the long glass fiber dataset (PP-LGF20) and the carbon fiber dataset (CFRP laminate) is shown in Figure 8.

In the case of the glass fiber datasets the distributions are exemplarily calculated for the fiber characteristics theta, Diameter and Length. The characteristic theta (measured in degrees) is defined as the angle between the fiber central axis and the coordinate systems' Z-axis, where an angle of 0° means a parallel orientation of the fiber to the Z-axis. The fiber diameter is specified in microns. In the case of the void dataset the distributions are exemplarily calculated for the void characteristics volume and shape factor. The void volume is specified in cubic micrometers.

The distributions of the fiber characteristic theta for the short glass fiber and long glass fiber dataset look similar and have many fibers which are oriented along the Z-axis (10° - 20°). However, they differ. The short glass fiber dataset has a peak at 85° (and at 90°), which is due to the horizontal fiber layer. This fact is shown in Figure 8a and b (left histograms). Regarding the fiber diameter distributions (see Figure 8a and b, middle histograms), the short glass fiber dataset has one fiber diameter peak which gives an average fiber diameter of about 13 microns. The long glass fiber data however has four fiber diameter peaks at approximately 10, 14, 16 and 20 micrometers. Since the dimensions of the analyzed volumes are small, the determined fiber length distribution is not representative for the material system. The fiber length distribution of the short glass fiber dataset (PP-SGF30) mainly shows short fibers (see Figure 8a, right histogram). The fiber length distribution of the long glass fiber dataset (PP-

LGF20) mainly shows long fibers (see Figure 8b, right histogram). The high bin at the beginning of the histogram shows a large number of short fibers. These short fibers (fiber particles) are caused by fiber fractures during the manufacturing process. From the void volume histogram a large number of small voids can be deduced (see Figure 8c, left histogram). In the case of the void shape factor distribution a high number of needle-shaped voids (ShapeFactor = 1) can be concluded from the histogram (see Figure 8c, right histogram).

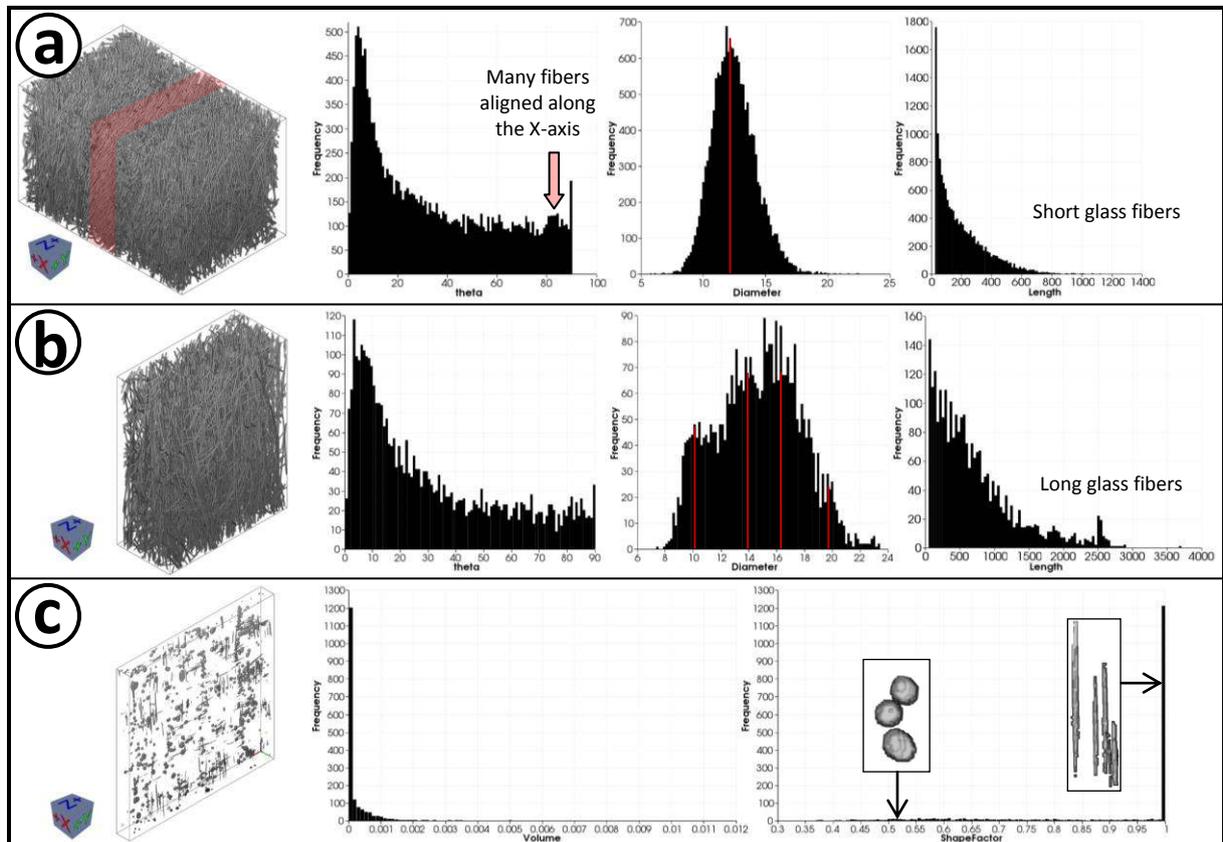


Figure 8: Distribution view of the (a) short fiber dataset (PP-SGF30), (b) long fiber dataset (PP-LGF20) and (c) void dataset (CFRP laminate).

5. Conclusion

In this work we presented the FiberScout extended functionalities to support the domain experts when analyzing FRP specimens in detail. It has been shown that not only fibers but also voids of an XCT scanned FRP specimen can be examined based on their specific characteristics and grouped into classes. An export function allows storing these classes and their characteristics as a file. The concept of MObjects was applied to fibers and voids which gives an impression of the average void/fiber shape. The extension of the Metadata visualization to Number of Fibers in a Cell makes areas with a high fiber concentration within the volume dataset clearly visible. We have presented the Meta Lens, which makes it possible to show the fiber and metadata simultaneously without losing the context. Furthermore, we have shown histogram distributions that can be created for all of the calculated void and fiber properties to enable the quantitative evaluation of the data. The introduced visualization concepts present the data in a concise and meaningful way. One application area may be the parameter optimization in the manufacturing process.

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