3D image processing for single fibre characterization by means of XCT

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Keywords
Computed Tomography, Short Fibre Reinforced Polymers, Fibre Length Distribution, Fibre Orientation Distribution

Introduction

X-Ray computed tomography (XCT) is nowadays widely used for scientific and industrial applications. Many laboratory XCT devices are installed for non-destructive testing (NDT) of materials and metrology. Starting with simple analysis of slice images, quantitative 3D image analysis came more and more important [1]. One of the fields where XCT delivers useful information is fibre reinforced material systems. The orientation distribution was determined for ceramics and carbon and glass fibres using visualization techniques [2,3]. Quantitative information about orientation was delivered by 3D image processing algorithms reported in [4,5]. All the published work did not show an analysis of single fibres which prevents from calculating local orientation accurately and could not deliver the information of fibre length distribution. A first approach of single fibre characterisation can be found in [6]. The accuracy of this approach suffers from the ability to segment fibres at high fibre content. Starting from 20 wt. % the accuracy drops considerably. The approach presented in this paper tries to overcome the detected problems by using a template matching approach. A comparison of both methods applied on glass fibre filled polypropylene filled with 30 wt.% glass fibres will show the advantages of the new approach.

Materials and Methods

Specimens from Polypropylene, filled with short glass fibres were manufactured by injection moulding (Fig. 1). The fibre content was 30 wt. % with a mean fibre diameter of 12.5 µm. The scan object size was 3.2 x 3.2 x 8 mm³. From this dataset a small cut-out was taken, containing less than 300 fibres. The specimen was investigated by applying 2 µm voxel edge length, which results in a representation of approx. 6 voxels per fibre diameter. The scans were performed at a Sub-µm CT device Nanotom 180NF (*GE phoenix|x-ray*). Scan parameters for tube voltage, integration time and number of projections were chosen as follows: 80kV, 750 ms and 1700.

For data analysis an in-house software pipeline was used that allows for the characterization of every single fibre. Figure 3 gives an overview of the algorithm which is applied on the XCT dataset. There are currently two different implementations available to perform the analysis task. Figure 3 shows the concept of feature detection based on the cross correlation between the XCT image and a template image (this implementation will be henceforth referred to as FCP-TM, for template matching). The older concept uses ortho-plane-analysis to define the centreline of each fibre [6] (this implementation will be referred to as FCP- MAE, for medial axis extraction). Both implementations have a preprocessing step in common including Gaussian smoothing, calculation of Gradient magnitude and the Hessian matrix followed by Otsu- segmentation.

The FCP-MAE implementation uses the segmented volume and the Hessian matrix to determine the local direction of fibres. From the eigenvalues we obtain an orthonormal coordinate system that is aligned with the second order structure of the image.

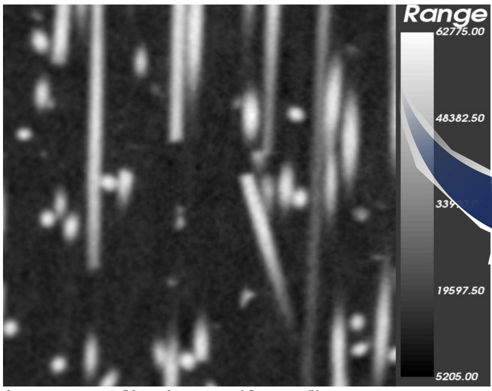

Fig. 1: XCT slice image (frontal)

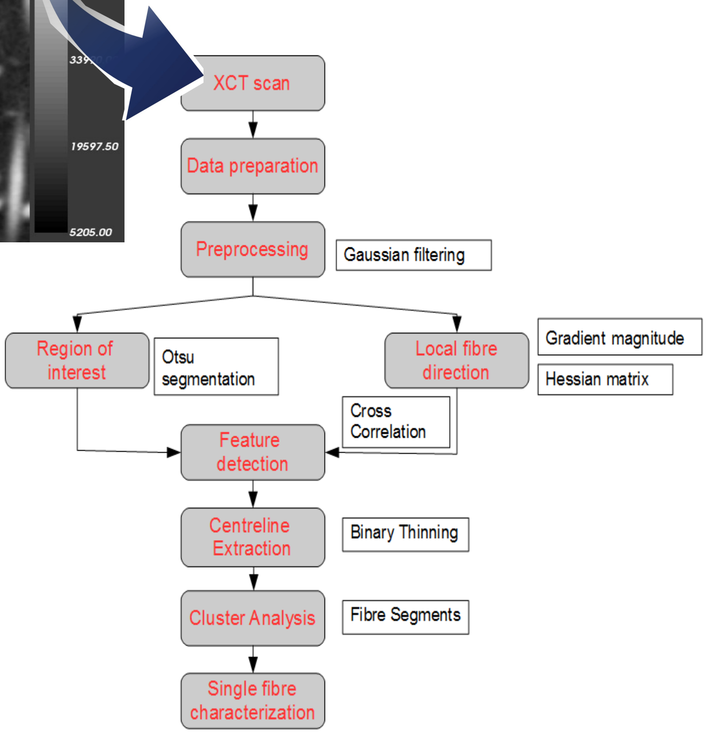

Fig. 2: Overview of the proposed pipeline

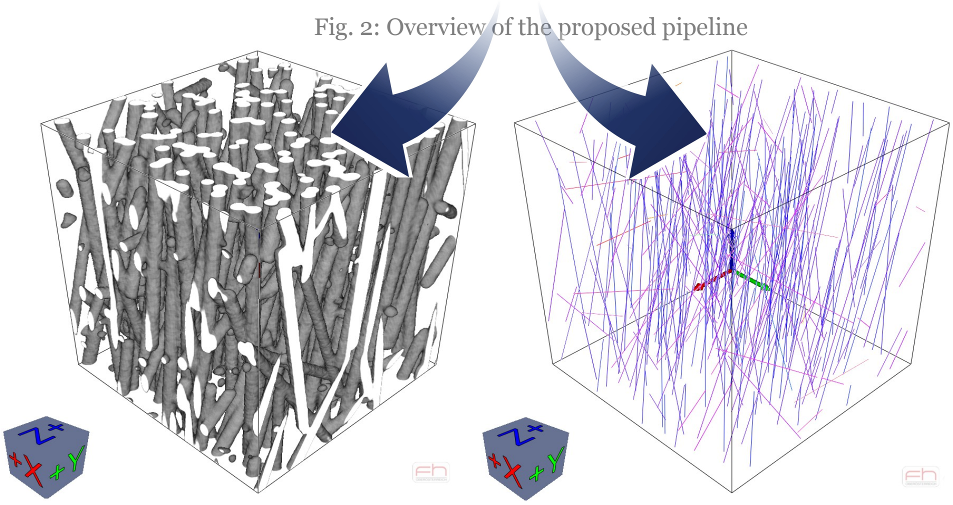

Fig. 3: Results of the proposed pipeline: Rendered fibres according to diameter (left), line representation of single fibres (right).

The eigenvectors associated with different eigenvalues provide the direction of the gradient of the fibre as well as the remaining two orthogonal axes. By iterating over the voxels within one orthogonal plane we are searching for the voxel with the maximum value. This voxel is marked as center-voxel. Post-processing includes a thinning filter to ensure a centreline of one voxel thickness. Consecutive cluster analysis includes the separation of fibres which are very close together or almost touching each other.

The main part of the new pipeline (FCP-TM) is the feature detection procedure, where the normalized correlation between the XCT dataset and a spherical template is obtained. Correlation is at its maximum if two structures are aligned in an almost perfect manner. Since the fibre diameter is expected to be approximately 12 µm, a template is chosen which has the same extent as the fibre diameter. Post-processing also includes binary thinning and cluster analysis. The result of both FCP pipelines is the characterization of every single fibre through start- and endpoint, length and diameter. Other values e.g. orientation, volume and surface can be derived from those values. The glass fibres within this specimen are assumed to be straight, therefore fibre length is defined as euclidean distance between start- and endpoint. The orientation is represented as 2nd order tensor and the 6 relevant elements for symmetric tensor are given. In order to determine the accuracy of the quantitative data analysis tool, comparisons of the results from well defined input were used. This ground truth data were generated from a high resolution XCT scan (1µm) and a semi-automated cylinder fit procedure. The fitting was done with the Software VG Studio MAX 2.2.

Results and Discussion

Figure 3 depicts the graphical representation of the results obtained by the pipeline. On the left image one can see the rendered fibres in accordance to their individual diameters. In the right image each fibre is represented as line between its corresponding start- and endpoint. The most relevant results of the data analysis are the number of fibres, their length and orientation (FLD, fibre length distribution and FOD, fibre orientation distribution). These results are serialized in a comma separated value (.csv) file. Table 1 summarizes the results of both pipelines. Input is considered as the reference result obtained by cylinder fit. The values for fibre count, length and orientation are compared with these ground truth values.

Parameter		Input	FCP- MAE	FCP-TM
Total fibre count		279	286	276
Mean length	(µm)	201,9	187,1	192,8
Weighted mean length	(µm)	273,8	264,4	267,8
Mean diameter	(µm)	12.5	12.2	12.2
Orientation tensor	axx	0,122	0,123	0,121
	ayy	0,013	0,013	0,009
	azz	0,865	0,864	0,869
	axy	0,010	-0,001	-0,001
	axz	0,195	0,190	0,188
	ayz	0,037	0,040	0,038
Execution time (Intel Xeon X5680 @3.33 GHz)			10,8 sec.	16,5 sec.

Table 1: Comparison of the numerical results obtained by the FCP-MAE and FCP-TM pipeline.

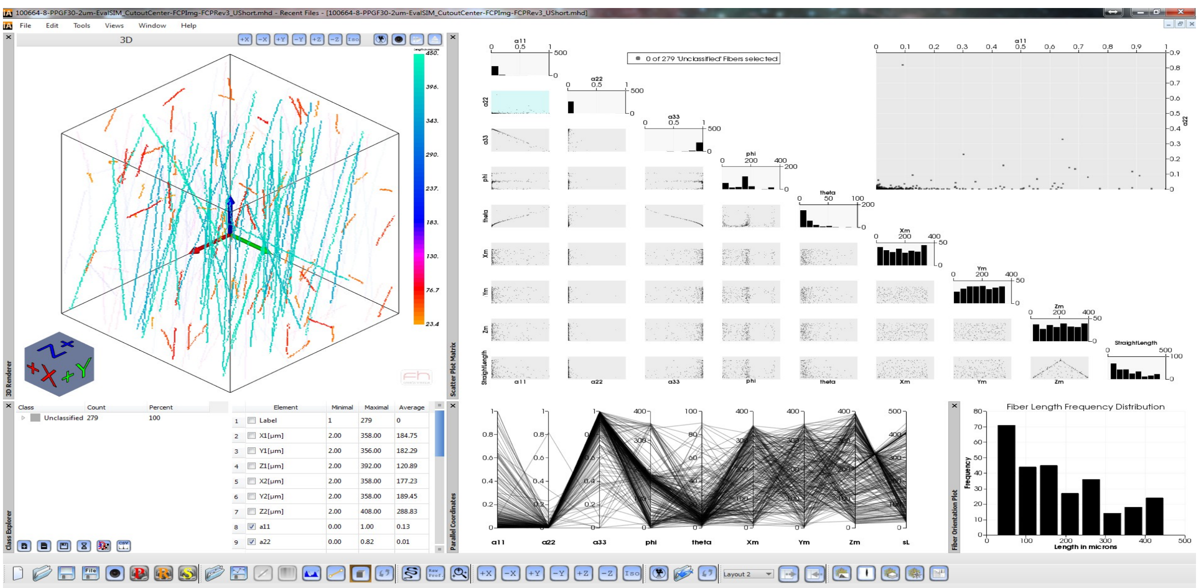

Fig. 4: Result visualized in FiberScout[7].

Based on the results of the proposed pipeline another in-house software development allows for the quantitative evaluation of the results [7]. Figure 4 depicts a screenshot from the FiberScout. On the left side one can see the individual fibres colour coded according to their individual length (orange indicates short fibres - approx. 30µm, green indicates long fibres - approx. 450 µm). On the right side one can see a Scatter Plot Matrix, the parallel coordinates as well as a FLD histogram.

Conclusion

In this paper a novel approach for the determination of fibre length and orientation distribution using XCT was presented. Problems for the algorithm arise from grey value variations due to artefacts or fibres which are very close together or variations in diameter. Using a spherical template improves the accuracy in detecting the centrelines for individual fibres without raising runtime drastically.

Both pipelines have performed very well, with the template matching approach being more precise at border regions. Slightly higher runtime is justified with better accordance of mean and weighted mean fibre length with ground truth.

Another advantage using a template is the possibility to apply the method to alternative fibre types like carbon or natural fibres.

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Acknowledments

This work is part of the K-Project "Non-Destructive Testing and Tomography Plus" supported by the COMET program of the Austrian Research Promotion Agency (FFG) and the Provinces of Upper Austria (LOÖ) and Styria (STMK).