# Application of iterative reconstruction algorithms in Fiber Reinforced porosity determination

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## Introduction

In general, Fiber Reinforced materials are being used in case of challenging mechanical requirements, yet exhibit an amount of porosity. Since this porosity may influence the strength negatively, the actual porosity value needs to be known in order to calculate the mechanical properties. In principle, a CT scan can provide the means to determine the amount, size, and shape of the voids in an X-ray transparent material. The difficulty, which arises in fully organic based composites, is the small difference between absorption of X-rays in fibers versus the surrounding matrix. At certain conditions, when single fibers need to be resolved and voids surrounding the fibers may exist, the errors introduced by the standard FDK algorithm are visible as “virtual” voids in large quantity. Determination of the actual porosity is then not feasible. The application of iterative techniques (validated by Optical Microscopy and Laser Profilometry) however, enable accurate determination of the porosity.

The work presented here shows the application of several iterative techniques (SIRT, Gradient descend, Krylov Subspace and adaptive weighted Total Variation) versus FDK and the effect on the porosity determination.

## Method

A fiber reinforced sample of roughly 15x10x2 mm is scanned using a 1272 11Mp scanner. Scans have been made using 1k (4x4 binning), 2k (2x2 binning) and 4k (no binning).

The reconstruction is done using NRecon (FDK: weighted backprojection) and both CGLS (conjugate gradient least squares from the Krylov subspace family: Tigre toolbox, ref 1) and SIRT (Simultaneous Iterative Reconstruction Technique: Tigre toolbox, ref 1). Details on the used iterative algorithms can be found in reference 1 and the references therein. The influence of number of iterations has been studied as well as the influence of resolution. The transmission data is loaded into a custom build Matlab graphical user interface capable of addressing the TIGRE toolbox algorithms and geometry functions. The CGLS reconstruction took 46 min while the SIRT reconstruction lasted 3.5 hours.

The reconstructed volume consists of 650 slices, each 2 µm in height. To compare the visual quality, one slice is shown from the middle of the sample. The reconstructed slice is also compared to the optical microscopy and laser profilometry images. The latter comparison shows that both CGLS and SIRT closely resemble the images taken with both comparing techniques.

For comparison, the sample has been embedded in resin and sectioned at mid position. Ultra-microtomy is used to create a surface as flat as possible to be imaged with optical microscopy and laser profilometry.

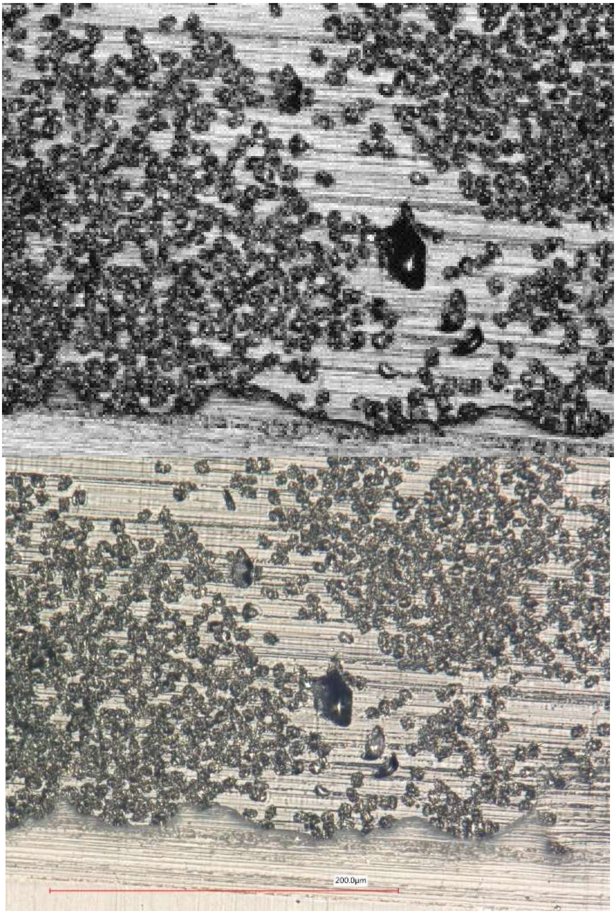


Figure 27: Left hand side: laser-profilometer measurement and right-hand side: optical microscopy measurement.

The results presented here are taken at 1k setting and 2 µm/pixel. No filter is used and 3x averaging to reduce noise. Only the case of 10 iterations for CGLS and 50 iterations for SIRT are shown.

## Results

In the images below, the bright spots are the fibers whereas the darker matter is the polymer matrix. The samples are chosen such that voids and cracks are present to be able to compare the results on porosity values.

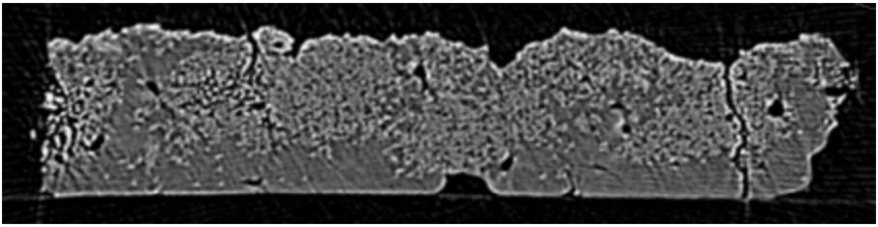

Figure 28: Reconstructed slice at position 300 of 650 slices using FDK (NRecon).

Although at first glance the FDK slice looks OK, many voids can be seen surrounding the fibers. This would suggest very loosely bound fibers. However, both validating techniques show that this is not the case. Most of the fibers are tightly packed in polymer matrix and only minor number of voids are visible.

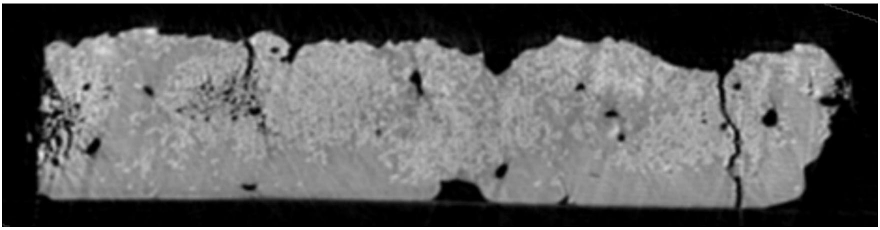

Figure 29: Reconstructed slice at position 300 of 650 slices using CGLS with 10 iterations.

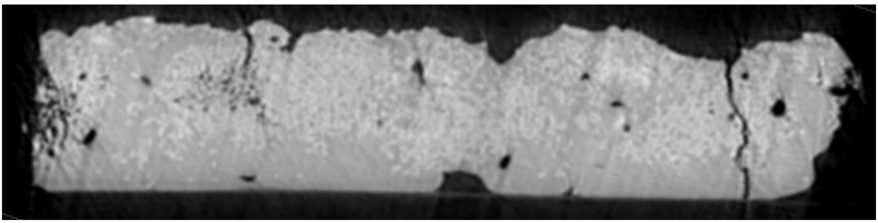

Figure 30: Reconstructed slice at position 300 of 650 slices using SIRT with 50 iterations.

Both CGLS and SIRT show close resemblance to the images obtained with the validating techniques.

Next step is to isolate the voids and determine size and shape. The results are shown in several distribution functions (kernel, bi-modal log-normal and volume weighted kernel) and the overall porosity is determined. The reconstructed volume data is loaded into AVIZO and a threshold setting is used suggested by the grey level histogram. For both CGLS and SIRT this is straightforward due to a clear separation of background level and sample grey levels. In case of FDK, the grey level histogram shows a minimum at a level which corresponds to the separation between air and sample.

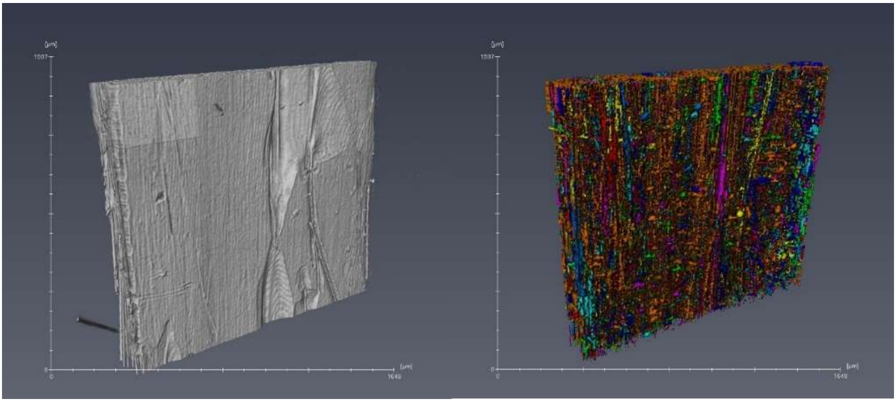

Figure 31: FDK: at left hand side, reconstructed volume and at right hand side, segmented, counted and labelled voids.

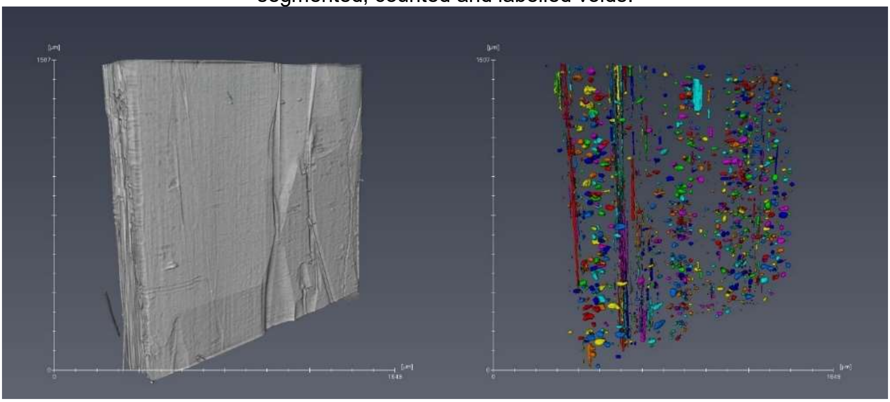

Figure 32: CGLS: at left hand side, reconstructed volume and at right hand side, segmented, counted and labelled voids.

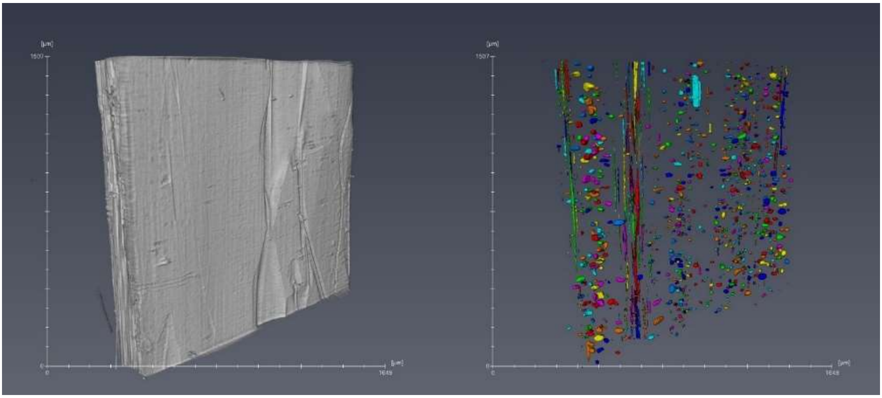

Figure 33: SIRT, at left hand side, reconstructed volume and at right hand side, segmented, counted and labelled voids.

The counted void sizes can be shown in void size distributions where the equivalent circular diameter is taken as a measure. More properties are available from the analysis, like shape and location. These are not shown here.

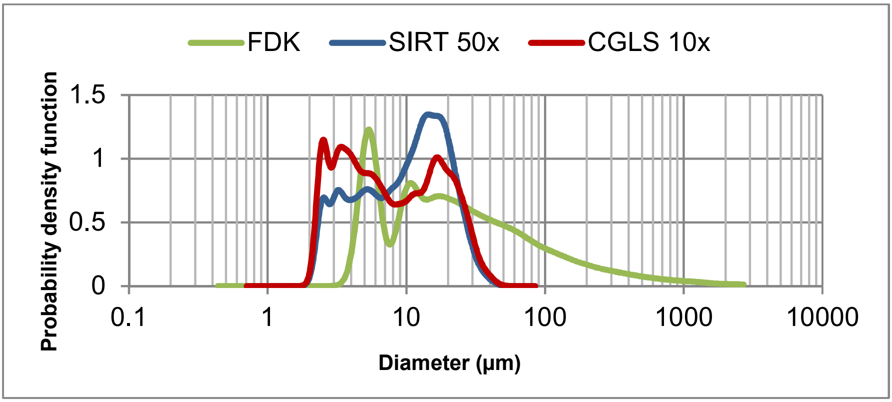


Figure 34: Kernel distributions (non-parametric distribution) of the void sizes.

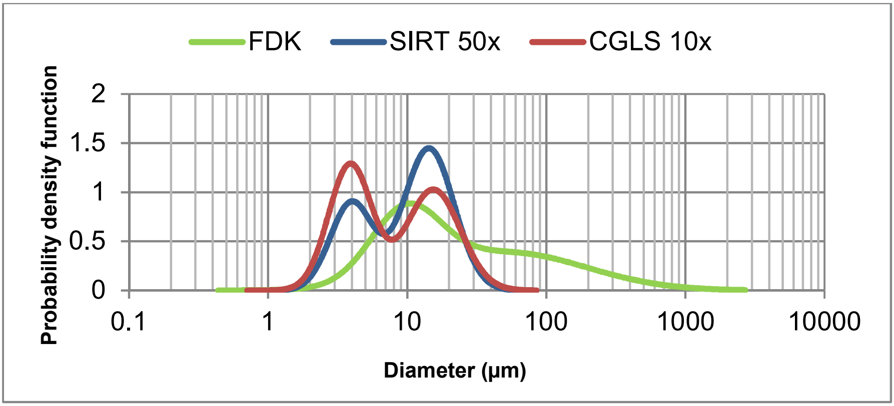


Figure 35: Bi-modal log-normal fitted distributions of the void sizes.

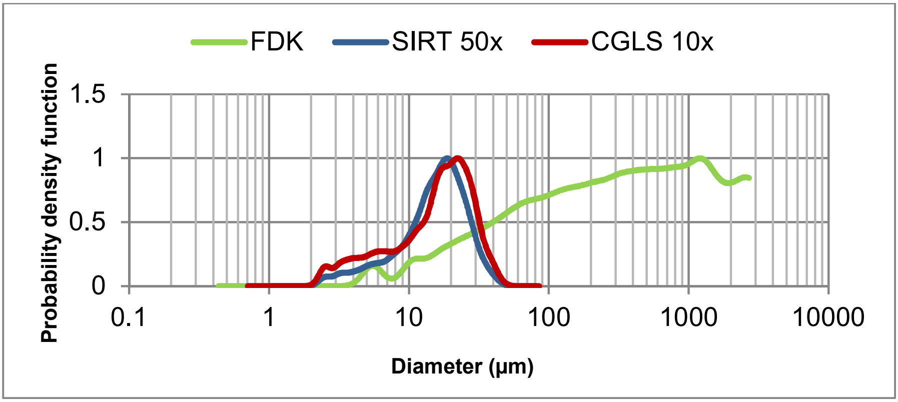


Figure 36: Volume weighted distributions of the void sizes.

The distribution functions shown above are a kernel distribution (non-parametric distribution), a bi-modal log-normal fitted distribution and a volume weighted kernel distribution. Both CGLS and SIRT distributions are very similar showing two peaks at identical locations.
Only the amplitude of both peaks differs. The FDK result is very different showing much larger voids. The overall porosity is for the FDK reconstruction 16.5% while for CGLS (1.1%) and SIRT (0.7%) the overall porosity is in the order of 1%.

## References:

[1] Ander Biguri, Manjit Dosanjh, Steven Hancock and Manuchehr Soleimani, “TIGRE: a MATLAB-GPU toolbox for CBCT image reconstruction”, Biomedical Physics & Engineering 2 (2016) 055010.