AUTOMATIC DETECTION AND CLASSIFICATION OF DEFECTS IN WOVEN COMPOSITES MANUFACTURED BY RTM BASED ON X-RAY MICROTOMOGRAPHY

Anna Madra[1,2], Piotr Breitkopf[2] and François Trochu[1]
[1] Chair on Composites of High Performance (CCHP), Center of Research on Polymers and Composites (CREPEC), École Polytechnique de Montréal, Montréal, Canada
{anna.madra, francois.trochu}@polymtl.ca
[2] Laboratoire Roberval, UMR 7337 UTC-CNRS, Université de Technologie de Compiègne, Centre de Recherches de Royallieu, Compiègne, France
{anna.madra, piotr.breitkopf}@utc.fr

Keywords: Woven composites, RTM, X-ray micro-CT, Microstructure, Defects.

ABSTRACT

We present an automatized methodology for analysis of defects in Resin Transfer Molded manufactured composites. The experimental microstructures scanned with X-ray microtomography are first segmented with a k-means unsupervised clustering algorithm. The information on phase attribution is then used to extract envelopes of the woven reinforcement. The surface mesh obtained in both phase and structure segmentation steps is then used to retrieve specific geometric and spatial features. The spatio-morphological types of residual voids are finally identified in a multi-dimensional feature space.

1 INTRODUCTION

The optimization of Resin Transfer Molding (RTM) is a difficult task, especially for composites with 2D and 3D woven reinforcements. The process of injection depends on many parameters. Some are imposed by design like fiber volume fraction and type of resin. Others, such as direction and rate of resin flow can be adjusted to minimize defects in the final part.

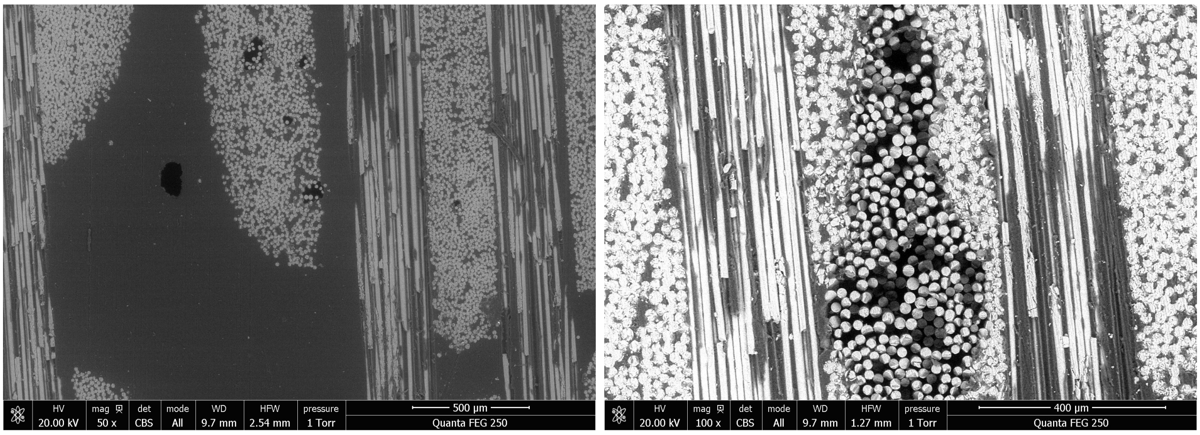
In RTM, the main observed defects are residual voids. They are primarily the result of imbalances in capillary or viscous impregnation mechanisms but can also be due to resin solidification blocking the air escape routes, gas present in the resin prior to injection or even residual humidity in the mold. Some examples, like air bubbles and resin deficiencies in the center of a fiber tow, are visible in a Scanning Electron Microscope (SEM) image in Fig. 1.

To identify the origins of a given defect a study of the microstructure relating defect characteristics to the manufacturing conditions is required. A defect can is characterized by

- the volume fraction of defect phase in the material;
- geometric properties of individual defects;
- determining classes of defect morphology;
- identification of spatial clusters of defects.

The above operations can be performed at different scales. At the macroscale, the volume fraction of residual voids is obtained according to the ASTM standard D 3171 [1]. The geometry of microvoids can be analyzed with optical or SEM microscopy. The non-destructive volume imaging techniques like X-ray microtomography provide a view of the experimental microstructure at a microscale resolution [5].

The main use of X-ray microtomography is to assess volume fractions of phases in the material. This operation is straightforward for properly segmented microtomographic scans. The characterization of morphology and spatial distribution of defects though requires the introduction of specific geometric and spatial features. In this work, we would like to propose such features and present a clustering-based approach that enables their retrieval from microtomographic scans. The structure of this paper is as



(a) air bubble (b) resin deficiency

Figure 1: SEM images of defects in a RTM manufactured composite: (a) bubble of residual air; (b) resin deficiency.

follows: we begin with tomogram segmentation ensuring proper identification of phases in reconstructed tomograms. Then we extend this approach to detection of structures like fiber tows. Section 3 introduces concepts of geometric and spatial features. The work is concluded by the outline of classification algorithms and preliminary results for RTM defects.

3 IDENTIFICATION

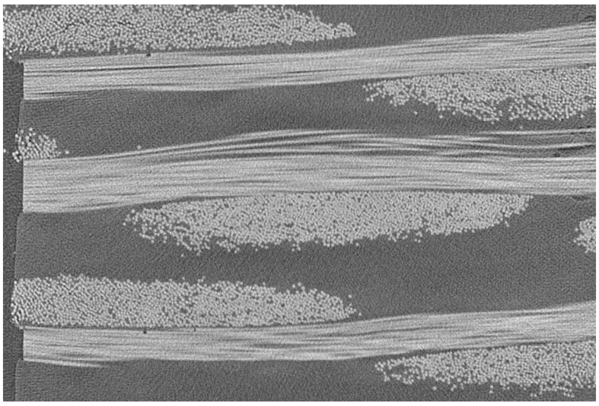
The result of a microtomographic scan is a three-dimensional table of coefficients of attenuation μ coded as 8 or 16-bit grayscale values. One two-dimensional slice of this table is called a tomogram (Fig. 2a). The μ depends on the density and the atomic number of a given phase in the material. In transmission X-ray imaging it relates the initial energy N_0 of an X-ray beam with the N_1 energy after scattering on the *path* along the x direction through the specimen. This relation is given by the Beer-Lambert law:

$$N_1 = N_0 \exp\left[-\int_{path} \mu(x,y)dx\right]. \tag{1}$$

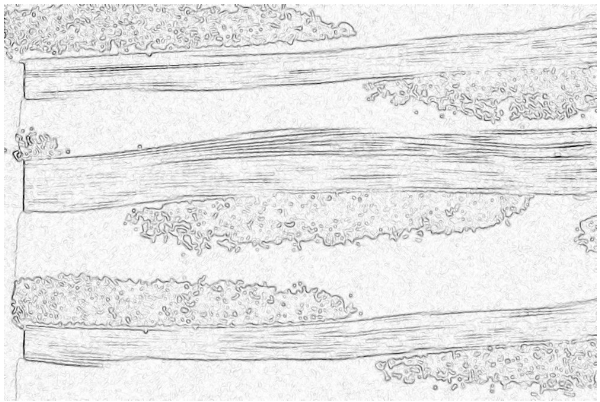
The photons with energy N_1 are captured by a CCD camera of a given resolution. The diameter of the beam, the size of the specimen and CCD resolution contribute to the final scan resolution r. The phase elements of a size smaller or equal than r cannot be identified in a tomographic scan due to the partial volume effect. This artifact plays a crucial role in a segmentation process.

During segmentation, the individual voxels, i.e., discrete volume elements in a 3D grayscale array, are attributed to phases in the material. In the case of a polymer composite with woven reinforcement, the phases observed should be fibers, a polymeric matrix, and residual air. The partial volume effect though may cause the intermediary values to appear. They are the result of the interpolation of μ inside voxels containing different phases.

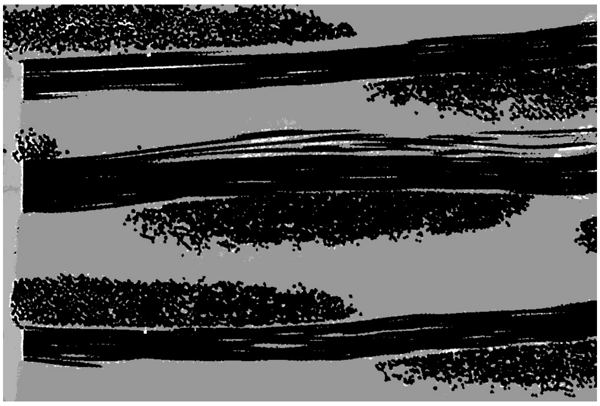
Whereas for two-phase materials, like ceramic and metallic foams, the segmentation error introduced by the partial volume effect can be controlled, this task is more difficult for the materials containing at least three phases. For this reason, the frequently used thresholding approach that sets arbitrary ranges of mu for different phases does not perform well for composites. An approach to phase and structure segmentation adapted to composites with woven reinforcement will be presented in the following subsections.



(a) untreated tomogram



(b) tomogram convolved with Sobel kernel



(c) tomogram with segmented phases

Figure 2: An X-ray tomogram: (a) untreated 16-bit grayscale; (b) convolved with Sobel kernel and inversed; (c) after k-means segmentation.

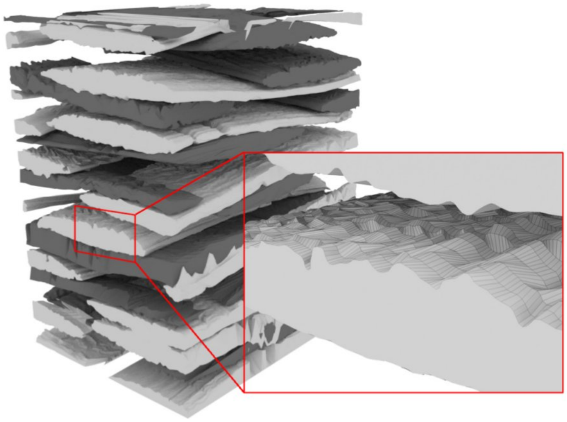
2.1 Phase identification

A segmentation attributing voxels to different phases is the most common approach in X-ray microtomography in material science. As has been mentioned above, the analysis based solely on the grayscale levels is not sufficient for multiphase materials like composites. An alternative is to explore the geometry of phase elements. In the case of fibers and fiber tows, a characteristic shape with distinct, crisp boundaries helps in the task of identification. The existence of boundaries can be retrieved by convolving the grayscale data with a Sobel kernel

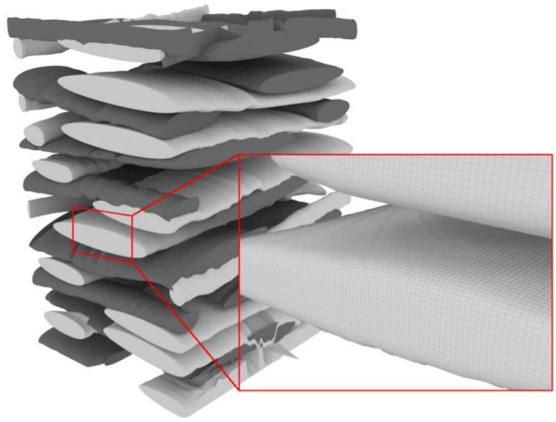
$$S_x = \begin{bmatrix} 1 & 0 & -1 \\ 2 & 0 & -2 \\ 1 & 0 & -1 \end{bmatrix} \tag{2}$$

and $S_y = S_x^T$. The result of this operation is shown in Fig. 2b. The voxel data is thus enriched with an additional parameter: the existence of an edge. Other kernels that can be employed include Gaussian or median blurs that homogenize local grayscale values and help in the elimination of intermediary phases from artifacts. A Laplacian kernel approximates directional gradient helping to determine local orientation.

The three-dimensional table of voxels with a list of grayscale mu values and their k convolutions can be used to construct a partition into phases. A k-means clustering algorithm looks for voxels that are close in the $k+1$ dimensional feature space. It begins by randomly selecting seeds – initial voxels, and proceeds by looking for other voxels closest to them. The centers of such formed clusters are then calculated and



(a) detailed reconstruction



(b) smooth reconstruction

Figure 3: Different reconstructions of fiber tow envelopes modeled with dual kriging: (a) detailed; (b) smooth. The insets show reconstructed 3D surface mesh.

taken as new seeds. The algorithm stops when the set inter- and intra-cluster variability conditions are met. The main drawback of this approach lies in its randomness, thus implying inconsistent results even for the same data. For this reason, we propose a hybrid method where the seeds are sampled from a database of manually calibrated seeds from scans of similar materials. The resulting phase segmentation is shown in Fig. 2c.

2.2 Structure identification

While phase segmentation is sufficient to measure characteristics of particular phases, it is limited when compound structures like fiber tows are sought for. The latter are of interest for example for modeling of textile compression and deformation during placement in the mold. In these cases, the models of fiber tow envelopes are required to estimate changes in geometric properties. The envelopes can also be used to determine the location of defects, e.g., inside or outside of a fiber tow.

In our previous work [4], we have proposed a method based on dual kriging to model fiber tow envelopes. The model used the results of k-means segmentation and their convolutions with blurring and Laplacian kernels to extract an approximation $\hat{\Gamma}$ of a contour of a transversal cross-section of a fiber tow. The contour was modeled with a discrete parameter t as a sum of the mean function $A(t)$ and its fluctuation $B(t)$

$$\hat{\Gamma}(t) = A(t) + B(t) \tag{3}$$

where

$$\hat{\Gamma}(t) = \sum_{l=1}^{L} a_l p_l(t) + \sum_{j=1}^{N} b_j K(|t - t_j|) \tag{4}$$

$A(t)$ is a polynomial function of degree L with weight coefficients a and fluctuation $B(t)$ is modeled with an arbitrary kernel of spatial correlation between the original and predicted locations t. The accuracy of the reconstruction is controlled by the nugget effect σ, calculated as segmentation probability. Small weight of σ results in a detailed reconstruction (Fig. 3a), bearing resemblance to the original geometry retrieved during phase segmentation. The increase in the weight of σ gives a smooth geometry (Fig. 3b) that follows a mean envelope of the fiber tow. The smoothed geometry is especially useful for determining the spatial location of defects as described in Section 3.2 on spatial features.

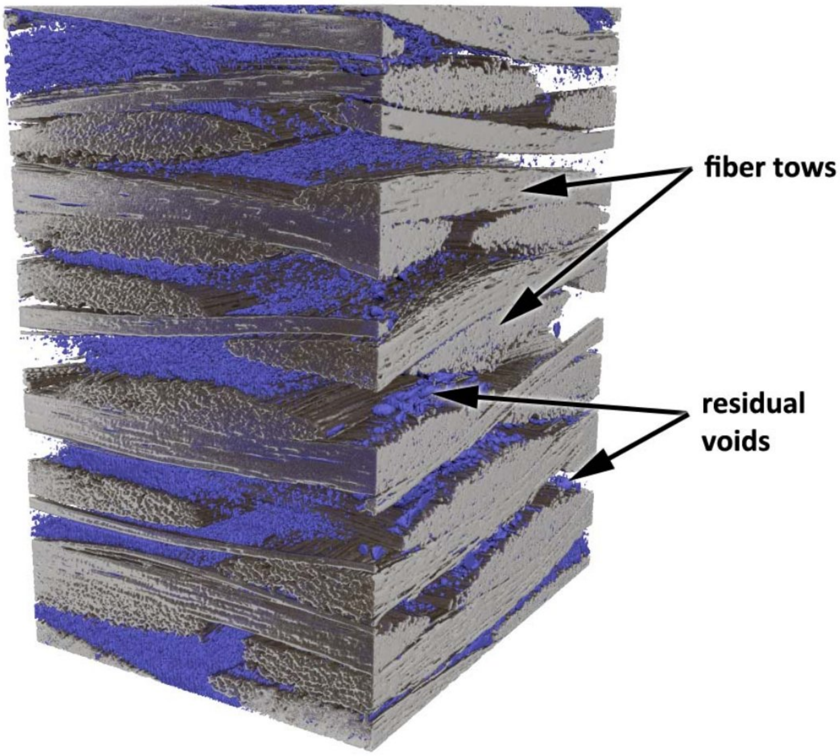


Figure 4: Reconstruction of the surface mesh of fibers and residual voids. The polymeric matrix has been removed for clarity.

3 FEATURES

The phase and structure-related information extracted during respective segmentation operations described in the preceding section can be used to characterize the microstructure in several ways. Here, we will introduce the geometric and spatial features, helpful in the task of morphology classification. At the same time, the feature definition can be extended to other properties, not necessarily limited to the X-ray tomographic scans.

3.1 Geometric features

The phase segmentation provides a 3D map of phase attributions. Their convolution with edge finding Sobel kernel can be used to extract a surface mesh of distinct phases, e.g., with a marching cubes algorithm described in [2]. The resulting triangular surface mesh for fibers and voids is shown in Fig. 4.

The analysis of angles in the mesh enables detection of its disjoint elements which is synonymous with dividing it into individual phase elements. Such elements can be further measured as has been presented in our work [3]. The properties such as volume, surface, length, aspect ratio and tortuosity are determined from the individual surface meshes. Some limitations are present in this approach. While the definition of volume and surface is straightforward for all types of geometry, the length or aspect ratio can be ambiguous. Additional, though less intuitive features need to be introduced for void geometry. One of them is the earth mover's distance (EMD), in which the ensemble of mesh nodes are treated as a result of a probability distribution. The EMD is a distance between probability distributions of different objects over a designated region. For the case of defects, the EMD can be interpreted as a measure of geometric distortion, useful for distinguishing elongated void deficiencies from air bubbles.

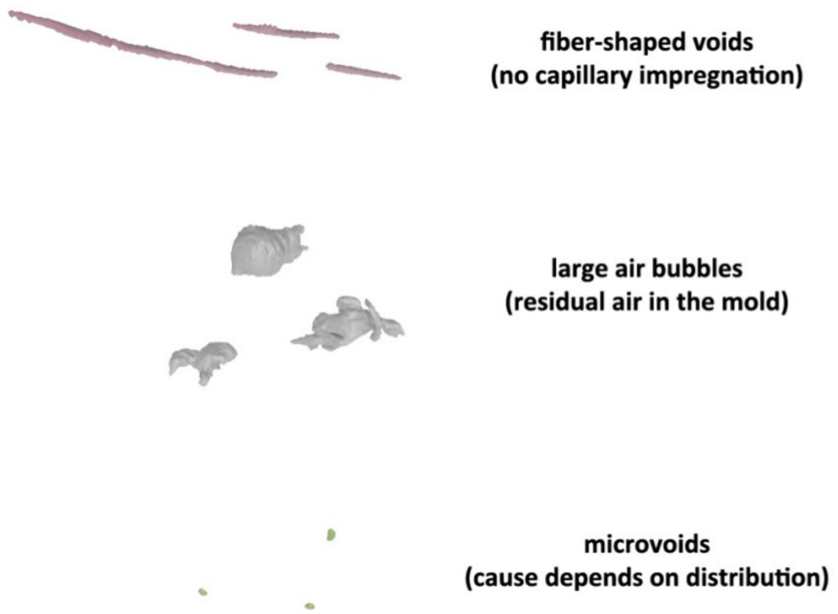


Figure 5: Different defect types identified during hierarchical clustering of spatio-geometric features.

3.2 Spatial features

The representation of phase objects as individual surface meshes enables measurement of two types of spatial features. First, the centroid and extents of a bounding box of a mesh can be retrieved in the coordinate system of the specimen. The k-means clustering on centroid locations would provide spatial clusters of voids, although calibration is necessary to determine the correct number of such clusters.

The second type of spatial features combines the phase and structure reconstructions. Hence, a simple ray-tracing operation is employed to find out if a given void is inside a fiber tow envelope. Boolean operations on 3D surface meshes further inform if a defect is contained inside a tow or spreads outside it. These compound spatial features depend strongly on the accuracy of the structure reconstruction. Thus, low values of the nugget effect σ are recommended.

4 CLASSIFICATION

The geometric and spatial features of defects are numeric or boolean in nature. In the latter case, for example for the spatial feature: void inside/partially in/outside fiber tow, it can be coded as a discrete value from the [0,0.5,1] range or as a percentage of defect volume inside a structure. The features represent each defect in a multi-dimensional feature space. If clustering is performed, distinct spatio-morphological classes are retrieved. As the k-means requires previous knowledge of the number of classes, it is not efficient for this task.

We propose a hierarchical agglomerative clustering. Instead of choosing arbitrary seeds, in this method, the linkage matrix of distances between all objects in the feature space is calculated. Then, the objects closest to each other are grouped in a cluster. The next step recalculates the linkage matrix taking into account the newly formed clusters. The algorithm stops when all objects are in the same, final cluster. This approach provides a hierarchical view of defects in the material. The final classes are determined by choosing a threshold distance to stop the clustering.

The examples of defect types identified for an RTM manufactured composite with 2D woven reinforcement are shown in Fig. 5. Inside fiber tows, long, thin voids were identified pointing towards the lack of capillary impregnation. In the areas between fiber tows, large bubbles indicated either lack of resin degassing or small gradient of pressure inside the mold. The microvoids strongly depended on the spatial distribution. In most cases, they accompanied the larger clusters of air bubbles in the vicinity of mold vent.

5 CONCLUSIONS

A methodology for automatized identification, measurement and classification of defects in composites has been presented. The approach is principally data agnostic – it can be applied to a variety of materials. For phases different than voids, the specific geometric and spatial features may be ambiguous and ill-defined and require an adaptation.

A representation of tomographic scans and phase elements as points in a multi-dimensional feature space can be used to apply various clustering algorithms to determine objects with similar morphology and/or spatial location. In the case of RTM defects, it enabled automatic identification of resin deficiencies inside fiber tows and air bubbles outside of the textile reinforcement. Such approach has the major advantage of finding groups of defects that are difficult to qualify without in-depth analysis of their frequency and thus provides an extension to the traditional visual inspection. Further studies will include verification of the presented framework in a comparative study of defects in composites manufactured under different conditions.

REFERENCES

[1] ASTM. ASTM D 3171 â 99 Standard Test Methods for Constituent Content of Composite Materials. *ASTM International*, 15(May 2009):1–6, 2010.

[2] Thomas Lewiner, Héllo Lopes, Antônio Wilson Vieira, and Geovan Tavares. Efficient Implementation of Marching Cubes' Cases with Topological Guarantees. *Journal of Graphics Tools*, 8(2):1–15, 2003.

[3] Anna Madra, Piotr Breitkopf, and Eric Maire. A clustering method for analysis of morphology of short natural fibers in composites based on X-ray microtomography. *Composites - Part A: Applied Science and Manufacturing - In Review.*

[4] Anna Madra, Piotr Breitkopf, Alain Rassineux, and François Trochu. Image-based model reconstruction and meshing of woven reinforcements in composites. *International Journal for Numerical Methods in Engineering*, may 2017.

[5] Anna Madra, Nemr El Hajj, and Malk Benzeggagh. X-ray microtomography applications for quantitative and qualitative analysis of porosity in woven glass fiber reinforced thermoplastic. *Composites Science and Technology*, 95:50–58, 2014.