SPATIAL FIBER ORIENTATION ANALYSIS

[1]Aneta Gądek-MOSZCZAK, [1]Mariusz TWORZYDŁO, [2]Paulina ROMAŃSKA

[1]*Cracow University of Technology, Faculty of Mechanical Engineering, Al. Jana Pawla II 37, 31-864 Cracow, Poland, EU, aneta.gadek-moszczak@pk.edu.pl*

[2]*Cracow University of Technology, Faculty of Material Science and Physics, Al. Jana Pawła II 37, 31-864 Cracow, Poland, EU, paulina.romanska@pk.edu.pl*

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Abstract

Paper presents an analysis of 3D images of the composite with a polyamide (PA) matrix reinforced by short glass fibres. The aim of the study was the assessment of the orientation of the fibres. The algorithm used for analysis is based on describing ellipsoids on the detected objects for its orientation assessment. Three subsamples of 3D images were cropped from three different part of the original sample. Each subsample shows the visible difference in the fibre orientation. The detection of the fibres and the analysis of the direction were performed using open source software *ImageJ*. Analysis of obtained results shown that the ellipsoid method is sensitive to the differences in the fibre orientation and may deliver valuable information for structure description.

Keywords: Composite, 3D structure, fibre's orientation

1. INTRODUCTION

Spatial orientation of the fibres in composite affects the properties of the designed materials. Quantitative assessment of its orientation allows us to adjust the parameters of the production's process to manufacture elements with predictable properties. Analysis of the 3D images acquired in the computed nanotomography study delivers information on the quantity and orientation of the fibres. Application the proper measurement algorithms and analysis provide sufficient tool to give reliable and accurate information about the material's spatial structure. There are many methods for determining the orientation of objects in 3D images, like the classical stereological method of Rose od Directions [1], through methods based on the analysis of entire objects, to methods analyzing individual voxels [2,3]. The 3D imaging techniques allow analyzing the whole objects not only its intersections, in contrary to the classical stereology approach.

This kind of analysis may be of great interest for other materials science branches where the spatial orientation of a microstructure significantly influences mechanical properties (e.g. light alloys [4-6]) and a rate of wear (e.g. [7]) or corrosion (e.g. [8]). In the industry, the stretch films generate similar analytical problems related to spatial orientation (e.g. [9-11]).

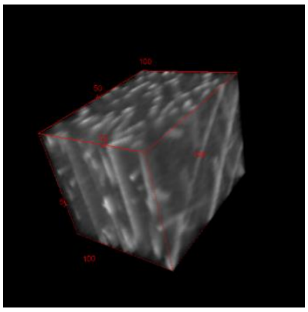
2. MATERIALS AND METHOD

As research material, a nanotomography scan of a composite with a polyamide matrix reinforced with glass fibres constituting a 15 % mass share of the sample was used. The images were made in a GE nanotom X-ray computer tomography. During the acquisition, the following exposure parameters were used for all samples: 80 kV, 145 μA, voxel size: 3.0 μm / vox, exposure time: 500 ms. The images were saved as a series of sectional images in JPEG format. The resulting image has a resolution of 662 x 368 x 1843 pixels. Visualisation and analysis were performed using open-source ImageJ software.

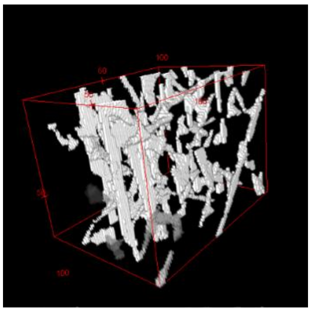
Three subsamples of the images were probed from the original image. They represent three different zones of the analysed probe, significantly differ in the spatial orientation of the fibres.

The coordinates of the subsample location in the original images are as follows:

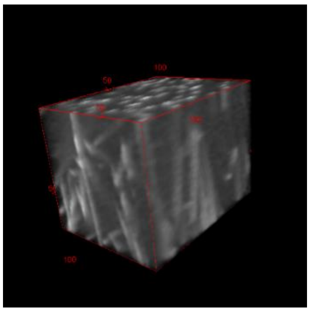
- Sample 1: x: 70-144 y: 70-144 z: 101-200 (**Figure 1a**),
- Sample 2: x: 280-354 y: 140-214 z: 900-999 (**Figure 1c**),
- Sample 3: x: 520-594 y: 230-304 z: 1650-1749 (**Figure 1e**).



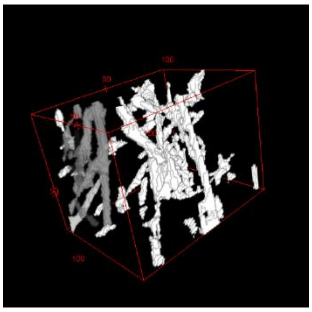
a) Subsample 1 before object detection



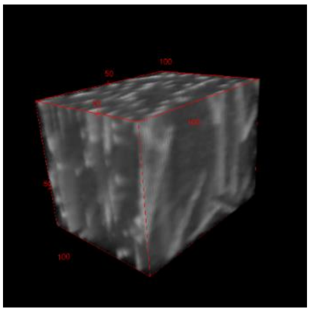
b) Subsample 1 after binarization



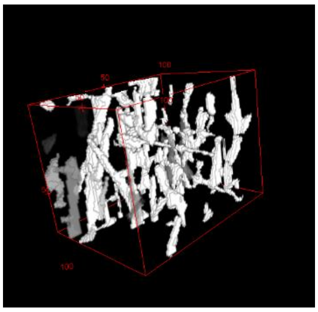
c) Subsample 2 before object detection



d) Subsample 2 after binarization



e) Subsample 3 before object detection

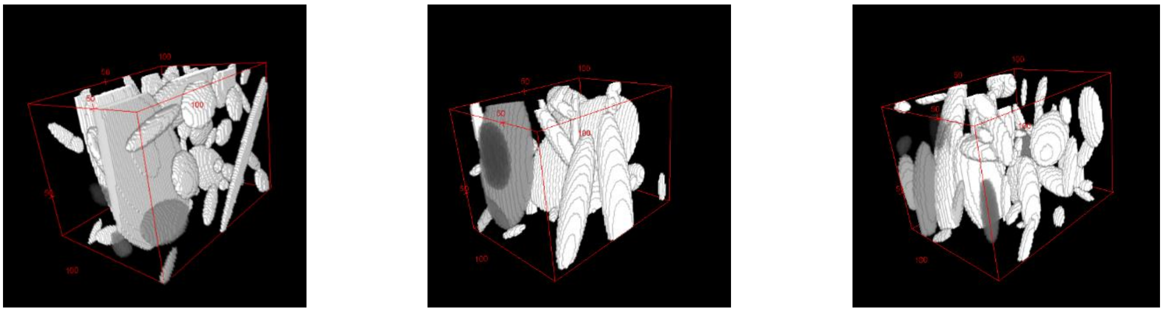


f) Subsample 3 after binarization

Figure 1 Three-dimensional reconstruction of the subsamples and the results of its detection

The quality of tested subsamples due to the noise and low contrast had to be enhanced. The median filtration and contrast adjustment were performed. Detection of the fibres was performed by binarization transformation which transformed the grey level images into the binary ones, where the fibres were mapped by voxels with the value 1. The background of the images was mapped by voxels with the value 0. The next transformation of the images that prepared them to the analysis was removing the objects smaller than 50 voxels. This operation prevents the influence of the noise effect or fibres, which was cut by the crop frame on the obtained results. Analyzed fibres located close to each other, created the clusters of the objects, what significantly affect the analysis. So due to obtained reliable results of the analysis, it was necessary to separate connected fibres from each other. It is needed to be stressed up that this operation had an impact on the volume of the fibres. Since the aim of the analysis is the orientation of the fibres, it is acceptable. The formal compliance of the edges of individual detected fibres is not crucial for determining their directivity. The result of this operation is the detection and marking of objects – in visualization through various shades of grey, which is a requirement to use the next and last algorithm (**Figures 1b, d, f**).

The critical element of the developed method of determining the 3D orientation of fibres is the use of an algorithm describing ellipsoids on the detected objects (**Figure 2**) and prints a table containing many data describing these ellipsoids [12].



a) Subsample 1 b) Subsample 2 c) Subsample 3

Figure 2 Fitting ellipsoids on the fibers on tested images

To calculate the radii and axes of an ellipsoid, the algorithm uses the equations:

$$sx^2 = \sum(x-Cx)^2/Vobj \quad (1)$$

$$sy^2 = \sum(y-Cy)^2/Vobj \quad (2)$$

$$sz^2 = \sum(z-Cz)^2/Vobj \quad (3)$$

$$sxy = \sum(x-Cx)(y-Cy)/Vobj \quad (4)$$

$$sxz = \sum(x-Cx)(z-Cz)/Vobj \quad (5)$$

$$syz= \sum(y-Cy)(z-Cz)/Vobj \quad (6)$$

where: x, y, z – coordinates of the point belonging to the object, Cx, Cy, Cz – coordinates of the center point of the object, Vobj – t he volume of the object.

It then uses the following matrix to calculate the vectors and eigenvalues of the ellipsoid.

$$\begin{pmatrix} sx^2 & sxy & sxz \\ sxy & sy^2 & syz \\ sxz & syz & sz^2 \end{pmatrix} \quad (7)$$

The three radii are then: √(5*eigen value).

Finally, the algorithm calculates the ellipsoid rays using determined eigenvalues. The result of the algorithm is a spreadsheet with data related to each object in the image. Data such as the centre point of the object, coordinates of the central elongation axis, radii, volume, coordinates of the voxels of the object used to calculate the longest diameter (Feret diameter) and angles between the central axis of the ellipsoid and the three planes are available. The angles between the central ellipsoid axis and the three planes of the coordinate system XY, XZ, YZ are critical to the developed method. It was assumed that for fibres which are the most elongated objects, applying a vector which is the central axis of elongation of the ellipsoid described on the fibre is a good indicator of the spatial orientation of the fibre itself and is sufficient to determine the directional distribution of objects.

3. RESULTS

Obtained data were used for further analysis. All fibres were identified according to their orientation concerning vertical direction. To obtained this information, the angle between the fibre and the XZ plane was analyzed. A larger value of angle means a more vertical fibre orientation, while the smaller value of the angle inform how close to the horizontal fiber orientation is. The values of the angles were divided into six classes, every fifteen degrees, which in the case of testing the method was considered sufficient accuracy of division. Then the percentage fraction of each of the bands in the entire fibre set in a given segment was calculated. The operation was repeated for all three slices. The division results are presented in **Figure 3**, **Figure 4**, **Figure 5**. For the record, the closer the angle to ninety degrees, the more oriented the object is vertically and vice versa.

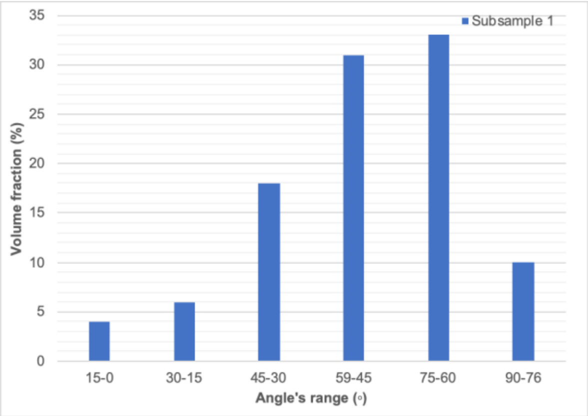


Figure 3 Distribution of fibres orientation for subsample 1

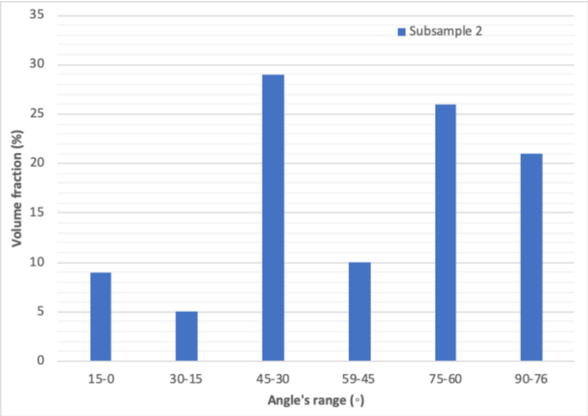


Figure 4 Distribution of the fibres orientation for subsample 2

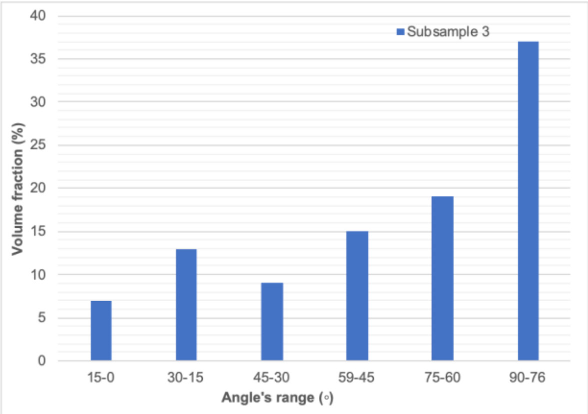


Figure 5 Distribution of the fibres orientation for subsample 3

The analysis of the results for subsample 1 showed that the majority of the fibres were directed close to vertical orientation. Percentage fraction of fibres with an orientation angle from the XZ plane greater than 45 degrees was over 73%. There were also many fibres with the value of the orientation angle in the range of 30-45 degrees, and only 10% of the fibres were in the range below 30 degrees.

The analysis of the fibre distribution for subsample 2, it is not easy to find clear trends on the chart. The values of the fraction of the fibres in each class of the angle's range differ. The highest fraction of the fibres are oriented in the range of angles between 30-45°, for more than 25 % of the fibres the orientation angle value was between 60 and 75°, what strongly suggests a more chaotic spatial arrangement of fibres. Here, the number of fibres with an angle from the XZ plane greater than 45 degrees is only 57 %. The results of fibres orientation in subsample 3 show similar trends to subsample 1, although here the most significant fraction of the fibres were strongly vertical fibres with the value of orientation angle between the 75-90°.

The total fraction of fibres with an angle to the XZ plane higher than 45° was 70 %. Quantitative analysis confirmed the visual assessment of the original image 3D. The sample of the composite which 3d reconstruction was analyzed, was produced by injection moulding, what effects in the orientation of the fibres located close to the surface of the sample along the injection direction, and more chaotic in the centre of the sample.

4. CONCLUSIONS

Quantitative analysis of the spatial orientation of the fibres delivers valuable information about the spatial arrangement of the fibres and may be applied for the analysis of its influence on the mechanical properties of the composite. The quantitative analysis of the fibre orientation may be used to the proper calibration of the injection moulding adjustments. Open-source software *ImageJ* used in this analysis with additional plugins for 3D orientation analysis allow obtained reliable results. The disadvantage of the analysis of 3D images is limited resolution to 0.8 μm, and the limited size of the sample that may be tested.

Research results and datasets obtained appear to be very inspiring for the development of new and improving known methods of data analysis, both image analysis [13-15] and estimation of results uncertainty [16-18] as well as supporting analytical databases [19,20].

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