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COMPARISON OF FIBRE ORIENTATION USING SIMULATION SOFTWARE AND MATERIALOGRAPHY

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Abstract: The models are validated by finite element simulation of the performed characterization tests. Finally, the methodology is applied to an injection moulded component with complex geometry. Fiber orientation data predicted with Moldflow software has been used to determine the local effective elastic stiffness and strength coefficients. A FE simulation of the functional behaviour of the component has been carried out. Results indicate that the degree of orientation in real samples approximately equals to degree of orientation in simulation software.

Keywords: Fibre orientation, Composites, Numeric simulation, Finite element analysis, Stereology

INTRODUCTION

This paper deals with the numerical modelling of the fiber orientation of reinforced thermoplastics. These materials show non-homogeneous orientation of the reinforcement, hence developing a local anisotropic behavior. This is the case, for instance, of short fiber reinforced thermoplastics (SFRT) in which, unlike laminated composites, the orientation of the reinforcement is not predefined, but it is the uncontrolled result of the manufacturing process: the fiber orientation varies in an injected part because of the flow pattern inside the mould, the processing conditions and the rheological properties of the material itself.

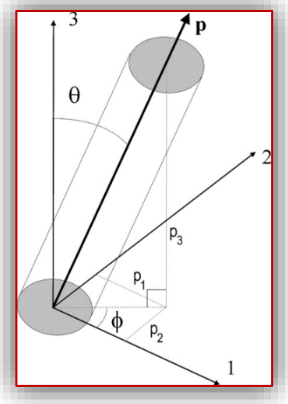

Figure 1. The orientation of a single fibre can be expressed in polar coordinates by the two angles (θ,Φ) and in Cartesian coordinates by the components of a vector p, (p_1, p_2, p_3).

The orientation of simple fiber may be defined by the two angles θ and Φ illustrated in Figure 1. In a SFRT component there are frequently millions of fibers, therefore determine the orientation of each fiber is very impractical [1]. The fibers orientation in space can be described by the probability distribution function (PDF), Ψ(θ, Φ) [2].

Orientation of a single fiber may be defined by the Cartesian components of a vector p, also. The components of p_i are described with the angles θ and Φ, as follows:

$$p_1=\sin\theta.\ \cos\Phi$$
$$p_2=\sin\theta.\sin\Phi \qquad (1)$$
$$p_3=\cos\theta$$

ORIENTATION TENSORS

The PDF function describes the fibre orientation direction (FOD) which in complete form holds a lot of information, making any numerical calculations based on these data highly computationally intensive. In some applications where there exists a simplified FOD distribution, the density function, Ψ(p) may in turn be simplified. But in many applications, it is not possible to make such a simplification [3].

The tensor description of FOD has become the most used system of characterization [4]. This tensor gets a concise description of the FOD, without the need for any a priori assumption of a simplified orientation. For the second-order tensor, it has nine components but only six of these are independent because of the symmetry condition. The components of the second-order tensor for a group of n fibres are calculated as follows:

$$a_{ij} = \frac{1}{n}\left(\sum_{k=1}^{n} p_i^k p_j^k\right) = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix}$$

$$i,j = 1,2,3 \qquad (2)$$

Six independent components for an individual fibre are as follows:

$$\begin{aligned} a_{11} &= sin^2\theta . cos^2\Phi \\ a_{22} &= cos^2\theta . cos^2\Phi \\ a_{33} &= cos^2\theta \\ a_{12} = a_{21} &= sin^2\theta . cos^2\Phi . \sin\Phi \\ a_{13} = a_{31} &= \sin\theta . \cos\theta . \cos\Phi \\ a_{23} = a_{32} &= \sin\theta . \cos\theta . \sin\Phi \end{aligned} \qquad (3)$$

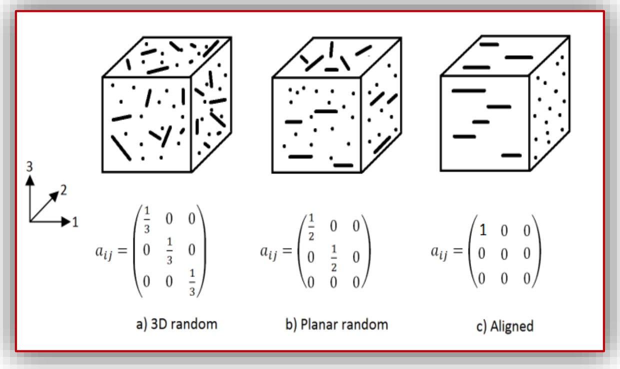

Figure 2. Example of different orientation states and corresponding orientation tensors.

Orientation tensor components have a physical interpretation. Figure 2(a) shows isotropic state, with equal orientation distribution in all directions. If all the fibres lie in the 1-2 plane (see Figure 2(b)), it corresponds to 2D isotropic (planar random) orientation state. Perfectly aligned orientation in 1 direction is shown in Figure 2(c).

EXPERIMENTAL MATERIAL AND MEASUREMENT

Good simulation software, for example Moldflow in this case, allows to view results of fibre orientation as an orientation of the X direction, Y direction, Z direction, the total orientation and orientation at surface. These first three orientations are relevant for the establishment of second-order orientation tensor. They belong to tensor´s values a_{11}, a_{22} and a_{33}, which are shown in Figures 3, 4 and 5.

Degree of orientation, which can be compared to orientation evaluated using stereological metallography, can be calculated as:

$$O = \frac{a_{ii} - a_{jj}}{a_{ii} + a_{jj}} \qquad (5)$$

QUANTITATIVE ANALYSIS OF COMPOSITE STRUCTURES

Only total examination of the structure and properties of materials carried out in the production and processing conditions should be related with macroscopic properties of the material. In the isometric structures microparticles are randomly oriented in all directions. In oriented structures, microparticles have a preferential orientation.

In the case of short glass fibres reinforced thermoplastics it's structure consist of thermoplastic matrix and reinforcing fibres, which has some preferred orientation in most of cases – the structure is anisotropy. The way of scalar measurement of structure anisotropy is determination of degree of orientation. The anisotropic microstructure is decomposed into isotropic, planar or linear oriented components using stereology methods.

Length of oriented fibres can be divided to isometric and oriented parts and degree of orientation is ratio of oriented part of length to total length. Oriented test plane method can be used. Test planes are placed perpendicular and parallel to the orientation direction [5]. The equations refer to the oriented $(L_V)_{OR}$ portion of the system of lines and to the total $(L_O)_{CE}$ length per unit volume [6]. They are [7]:

$$(L_V)_{OR} = (P_A)_O - (P_A)_P \qquad (6)$$

$$(L_V)_{CE} = (P_A)_O + (P_A)_P, \qquad (7)$$

where:

$(P_A)_O$ is number of cross-sections between test perpendicular plane and fibres per unit test area,

$(P_A)_P$ is number of cross-sections between test parallel plane and fibres per unit test area.

Degree of linear orientation O is:

$$O = (L_V)_{OR} \,/\, (L_V)_{CE} \qquad (8)$$

EXPERIMENTAL MATERIAL

For an example, an analysis of injection moulding part of pendant arm used in RC car. The arm material is LUVOCOM® 1/CF/15/HS polyamide PA66 with 15% reinforcing carbon glasses.

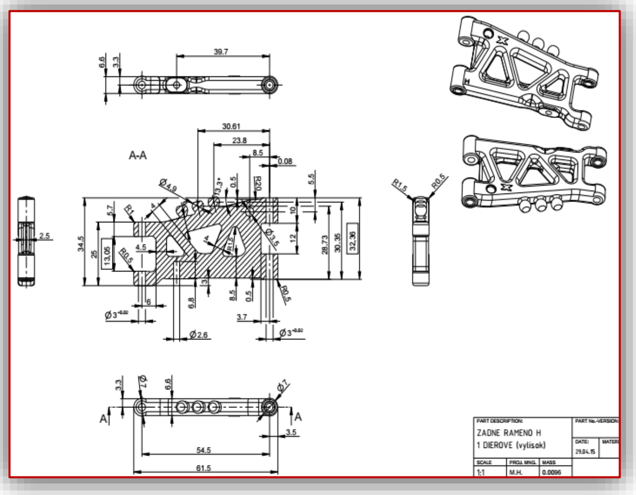

Figure 3. Design of pendant arm used in RC car (injection moulding part)

The software Moldflow Insight was used, which belongs to the top of software for injection moulding simulation. This software is supplied by Autodesk Company. Moldflow software is a simulation product which can be used for mold and plastic design. This software helps to decrease cost of physical prototypes and prevent potential manufacture defects.

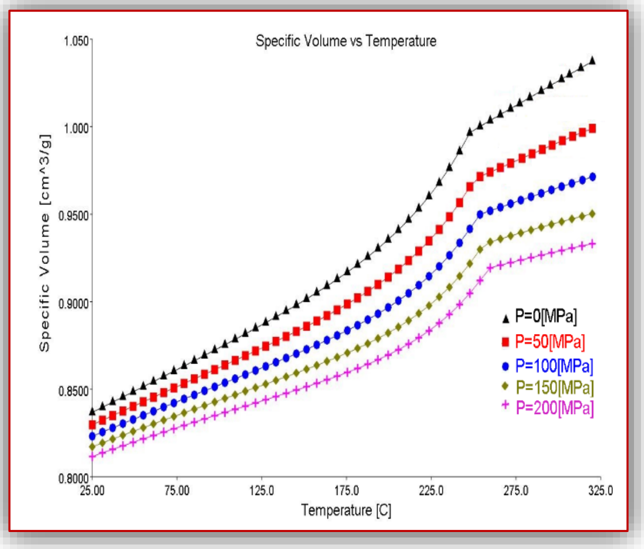

Figure 4. PVT Diagram

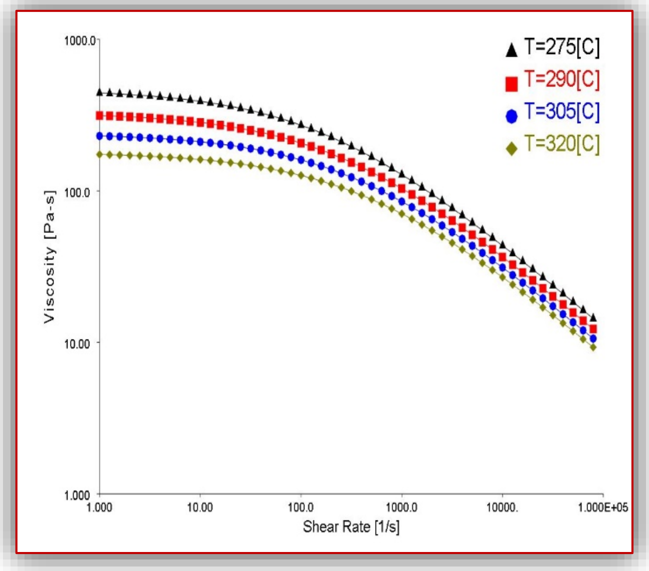

Figure 5. Rheological diagram

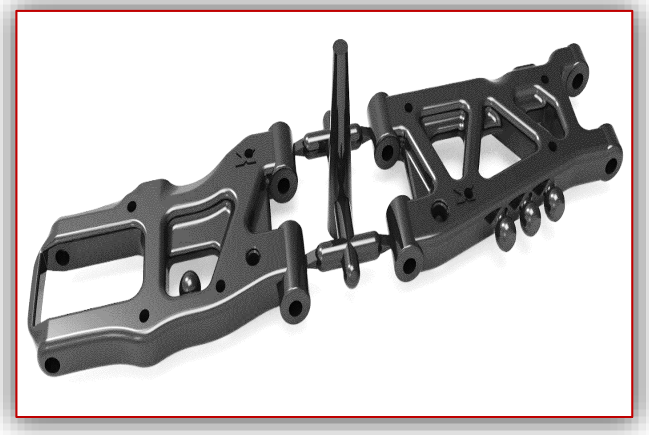

Figure 6. Injection moulding part

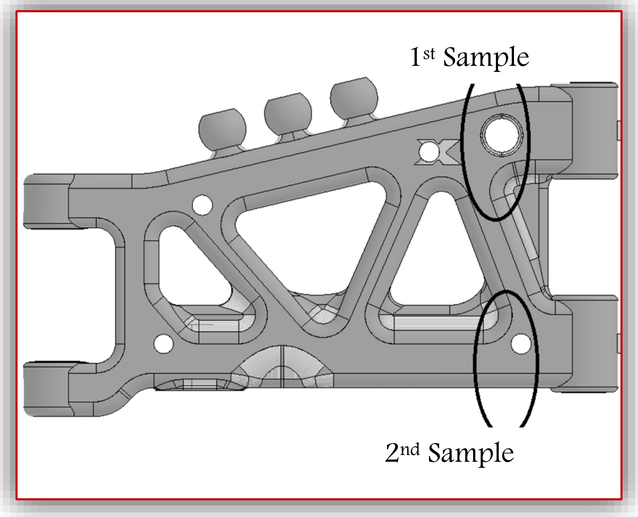

Figure 7. Samples in injection moulding part

EXPERIMENTAL RESULTS

1st sample, Parallel plane and orthogonal plane:

Parallel section at the edge in first sample is shown if Figure 8 and tangential cross-section is shown in Figure 9.

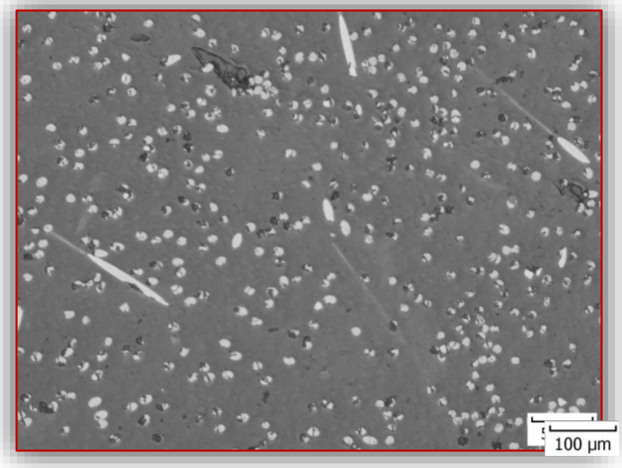

Figure 8. Cross section of fibres in 1st sample, parallel cut

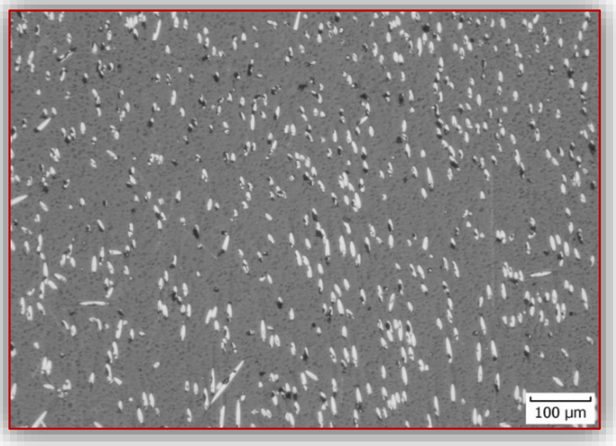

Figure 9. Cross section of fibres in 1st sample, tangential section (orthogonal direction)

In parallel direction are 490 cross-section of carbon fibers and in the tangential direction are 633 cross-section of carbon fibers. For the calculation of fiber orientation was used method for determinate the length of the elements of lines in the volume L_V.

Number of cross-sections between test parallel plane and fibers is 490.

Number of cross-sections between test orthogonal plane and fibers is 656.

Degree of orientation between parallel plane and orthogonal plane is -12.51%

Sample in the X direction is shown in Figure10 and sample in the Z direction is shown in Figure 11. Orientation of simulation is calculating by the second order tensor.

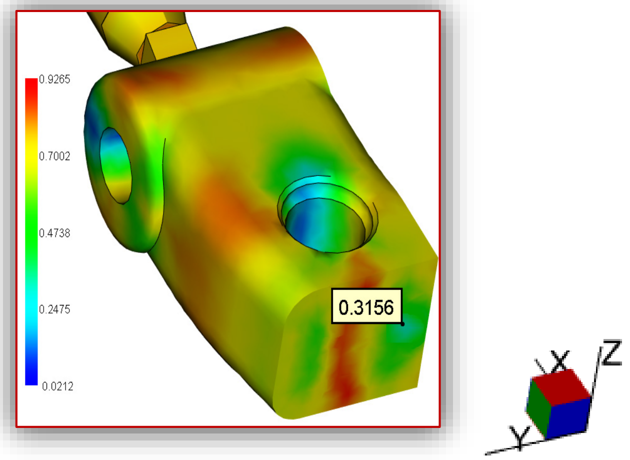

Figure 10. Fibre orientation in 1st sample, in X direction

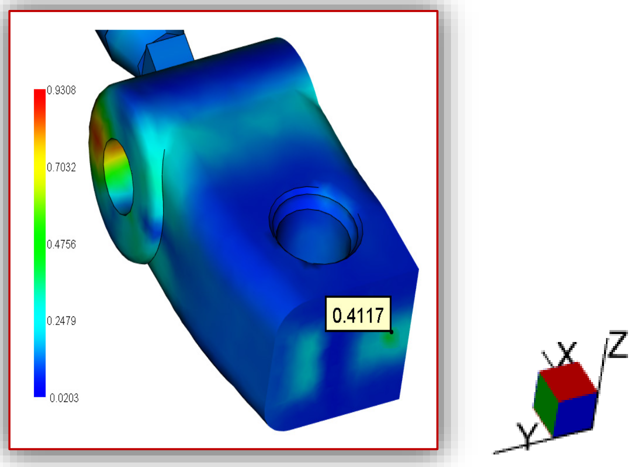

Figure 11. Fibre orientation in 1st sample, in Z direction

Degree of orientation between a_{11} and a_{33} plane is -13.21%

1st sample, Parallel plane and longitudinal plane:

Parallel section at the edge in first sample is shown if Figure 12 and longitudinal cross-section is shown in Figure 13. In parallel direction are 827 cross-section of carbon fibers and in the longitudinal direction are 633 cross-section of carbon fibers. For the calculation of fiber orientation was used method for determinate the length of the elements of lines in the volume L_V.

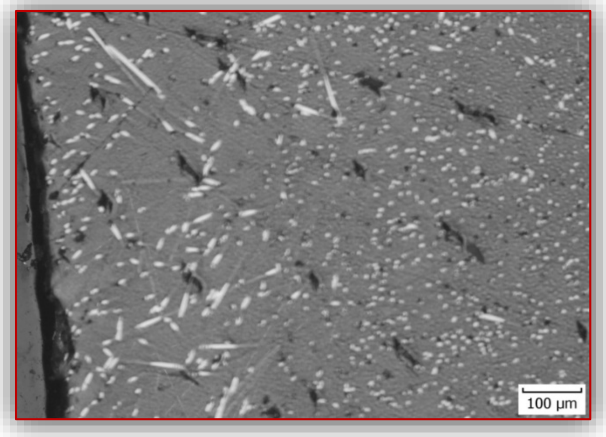

Figure 12. Cross section of fibres in 1st sample, at edge, parallel section

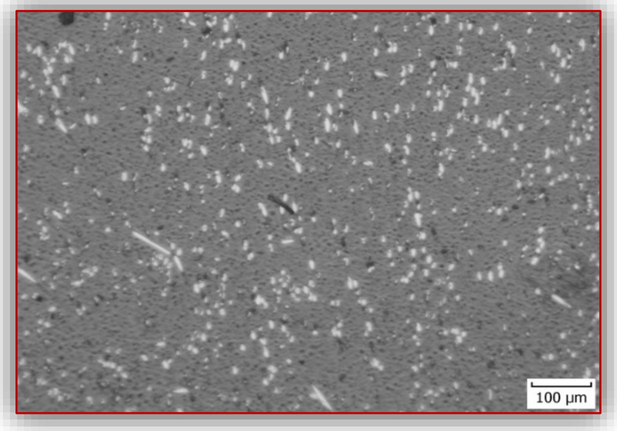

Figure 13. Cross section of fibres in 1st sample, at edge, longitudinal section (orthogonal direction)

Number of cross-sections between test parallel plane and fibers is 827.

Number of cross-sections between test longitudinal plane and fibers is 633.

Degree of orientation between parallel plane and longitudinal plane is 13.28%.

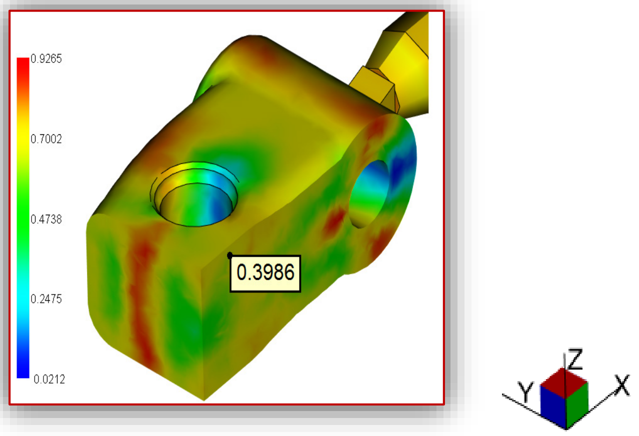

Figure 14. Fibre orientation in 1st sample in X direction

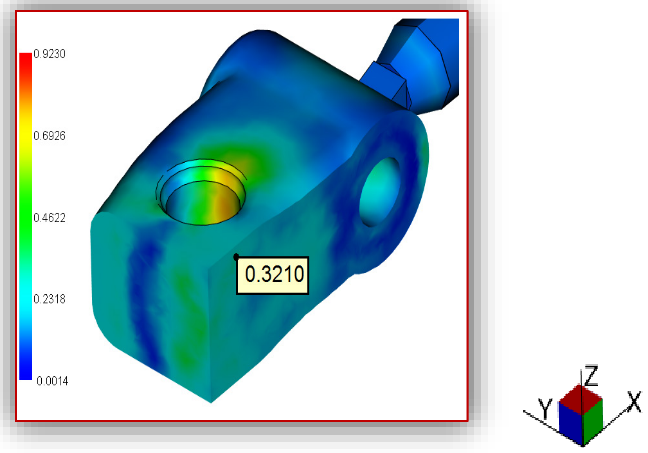

Figure 15. Fibre orientation in 1st sample in Y direction

Sample in the X direction is shown in Figure14 and sample in the Y direction is shown in Figure 15. Orientation of simulation is calculating by the second order tensor.

Degree of orientation between a_{11} and a_{22} plane is 10.78%

2nd sample, Parallel plane and longitudinal plane

Parallel section at the edge in first sample is shown if Figure 16 and tangential cross-section is shown in Figure 17.

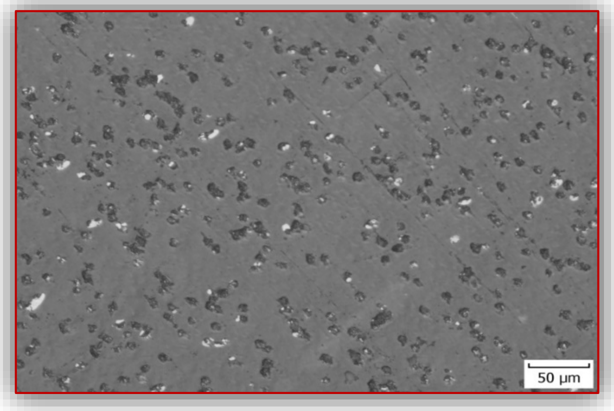

Figure 16. Cross section of fibres in 2nd sample, parallel section

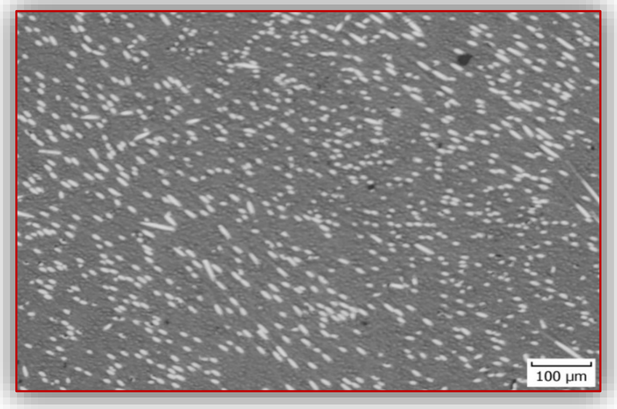

Figure 17. Cross section of fibres in 2nd sample, longitudinal section (orthogonal direction)

In parallel direction are 409 cross-section of carbon fibers and in the tangential direction are 1052 cross-section of carbon fibers. For the calculation of fiber orientation was used method for determinate the length of the elements of lines in the volume L_V.

Number of cross-sections between test parallel plane and fibers is 409.

Number of cross-sections between test longitudinal plane and fibers is 1052.

Degree of orientation between parallel plane and longitudinal plane is 21.72%

Sample in the X direction is shown in Figure 18 and sample in the Y direction is shown in Figure 19. Orientation of simulation is calculating by the second order tensor.

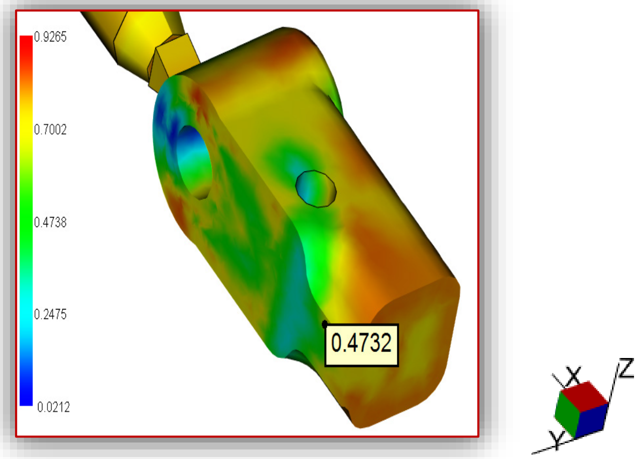

Figure 18. Fibre orientation in 2nd sample in X direction

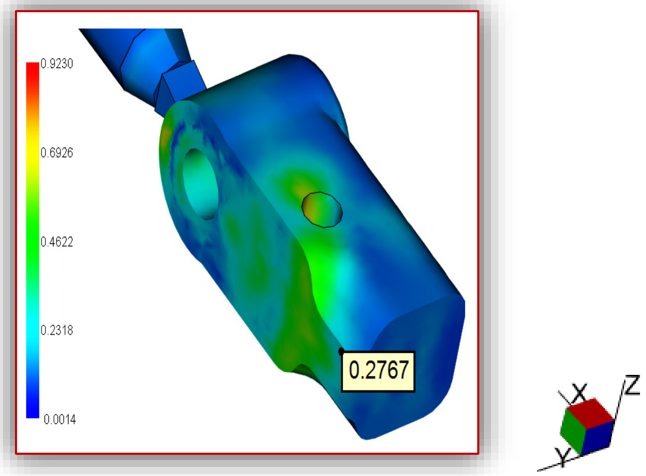

Figure 19. Fibre orientation in 2nd sample in Y direction

Degree of orientation between a_{11} and a_{22} plane is 26.19%

2nd sample, Longitudinal plane and tangential plane:

Longitudinal section at the edge in first sample is shown if Figure 20 and tangential cross-section is shown in Figure 21. In longitudinal direction are 555 cross-section of carbon fibers and in the tangential direction are 384 cross-section of carbon fibers. For the calculation of fiber orientation was used method for determinate the length of the elements of lines in the volume L_V.

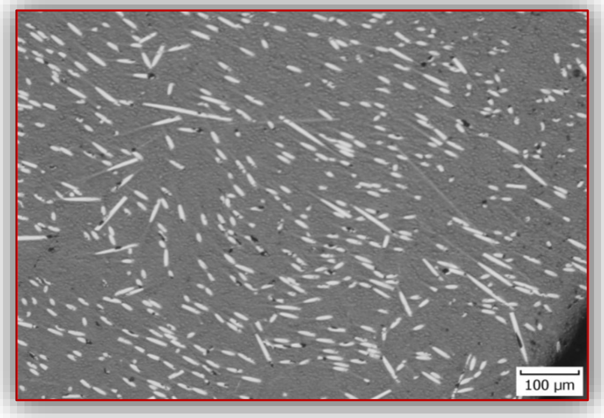

Figure 20 .Cross section of fibres in 2nd sample, at edge, longitudinal section

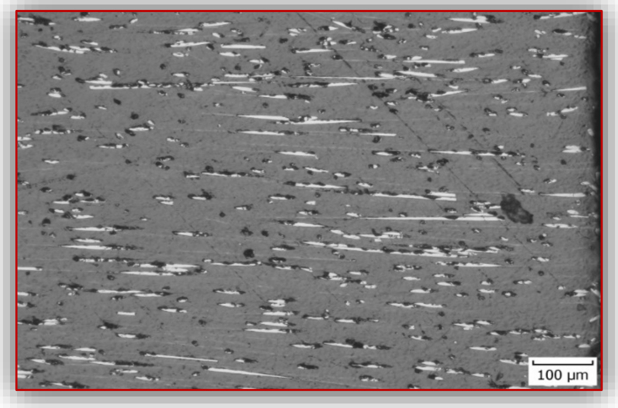

Figure 21. Cross section of fibres in 2nd sample, at edge, tangential section (orthogonal direction)

Number of cross-sections between test longitudinal plane and fibers is 555.

Number of cross-sections between test tangential plane and fibers is 384.

Degree of orientation between longitudinal plane and tangential plane is 18.21%.

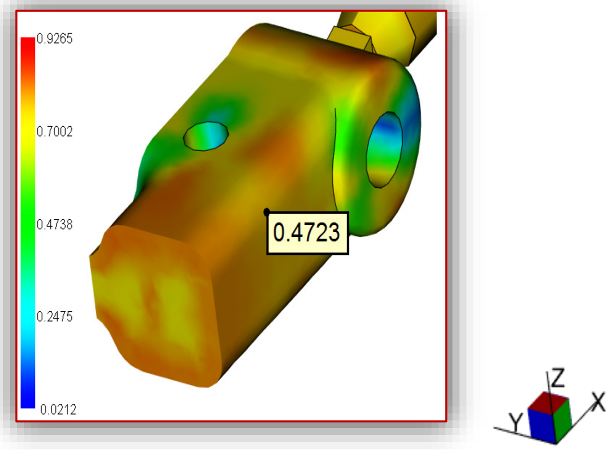

Figure 22. Fibre orientation in 2nd sample in X direction

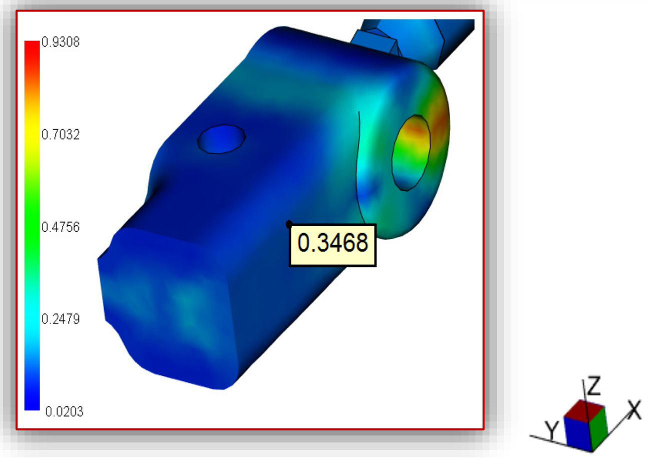

Figure 23. Fibre orientation in 2nd sample in Z direction

Sample in the X direction is shown in Figure 22 and sample in the Z direction is shown in Figure 23. Orientation of simulation is calculating by the second order tensor.

Degree of orientation between a_{11} and a_{33} plane is 15.34%

DISCUSSION OF RESULTS

Degree of orientation the 1st sample, parallel plane and orthogonal plane is negative. It means in fact, that orientation has the same value, but it is perpendicular to assumed one. This orientation is not desired and mechanical properties are decreased. However it is not so critical, because it is situated in the surface layer. In surface layer (1st sample-parallel plane- longitudinal plane and 2nd sample – both measurement) the fiber orientation is favorable and mechanical properties (crack propagation resistance) increase.

Table 1. Comparison of orientation at samples

Measuring	Orientation at real sample [%]	Orientation of numerical simulation [%]	Difference of orientations [Δ%]
1st sample Parallel plane and orthogonal plane	-12.51	-13.21	0.7
1st sample Parallel plane and longitudinal plane	13.28	10.78	2.5
2nd sample Parallel plane and longitudinal plane	21.72	26.19	-4.47
2nd sample Longitudinal plane and tangential plane	18.21	15.34	2.87

Difference of orientation has been calculated by subtraction orientation at real sample and orientation of numerical simulation. These differences are low – less than 5%.

CONCLUSION

To exploit the capabilities of the composites is necessary to have detailed information on the fiber orientation in the component. In general, the only way to have this information for injection moulding parts is to use process simulation results including fiber orientation prediction. To determine the accuracy of a numerical simulation, model must be compared with experimentally determined fiber orientation distributions.

Stereological metallography enables simple and effective experimental estimation of short fiber orientation by measuring the relative length of fiber orientation in different places of injection moulding parts.

In one case orientation is negative which means, that orientation has the same value, but it is perpendicular to expected direction. This orientation is not desired and mechanical properties are decreased, but it is not so critical because it is situated in the surface layer. Numerical simulation allows to view of fiber orientation in these parts. Ratio of these simulated values can be compared with previous orientations. The fiber orientation can be control by injection moulding parameters, but it is empirical method only [8]. A new way to improvement of injection moulding precision parts mechanical properties is an advanced technology – shear-controlled orientation in injection mouldings (SCORIM) [9].

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