The Influence of Fiber Volume Fraction on Thermal Conductivity of Pultruded Profile

V. Lukášová, P. Peukert, V. Votrubec

Abstract—Thermal conductivity in the x, y and z-directions was measured on a pultruded profile that was manufactured by the technology of pulling from glass fibers and a polyester matrix. The results of measurements of thermal conductivity showed considerable variability in different directions. The caused variability in thermal conductivity was expected due fraction variations. The cross-section of the pultruded profile was scanned. An image analysis illustrated an uneven distribution of the fibers and the matrix in the cross-section. The distribution of these inequalities was processed into a Voronoi diagram in the observed area of the pultruded profile cross-section. In order to verify whether the variation of the fiber volume fraction in the pultruded profile can affect its thermal conductivity, the numerical simulations in the ANSYS Fluent were performed. The simulation was based on the geometry reconstructed from image analysis. The aim is to quantify thermal conductivity numerically. Above all, images with different volume fractions were chosen. The results of the measured thermal conductivity were compared with the calculated thermal conductivity. The evaluated data proved a strong correlation between volume fraction and thermal conductivity of the pultruded profile. Based on presented results, a modification of production technology may be proposed.

Keywords—Numerical simulation, pultruded profile, volume fraction, thermal conductivity.

I. INTRODUCTION

THE paper deals with determination of thermal conductivity for a pultruded profile which consist of long glass fibers held by a polymer matrix. The pultruded profiles are used for a wide area of applications from the building branch to machine engineering [1]. The main advantage for constructions lies in its lightweight and high strength. For some applications, other parameters are also important, like thermal conductivity or electric insulation. For specific cases matters a given insulation range to minimize the thermal bridge effect. In this direction were no publications found. To expand knowledge in this branch, some experimental work was done to get thermal conductivity of pultruded samples. To testing some methods to predict thermal conductivity also some computation approaches were tested and compared with measurements.

The thermal conductivity was measured by the TCi C-Therm. An image analysis of a profile cut was used as the base for numerical simulation of heat diffusion for the two

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component system. The simulation was done in ANSYS Fluent and shows the uneven temperature field. Also a simple volume fraction based calculation was done.

II. STRUCTURE OF THE PULTRUDED PROFILE

A. Pultruded Profile

The investigated composite profile was produced by a continuous pultruded process. The reinforcement is continuously impregnated with a liquid matrix and drawn into the forming and curing head (Fig. 1). The resin is hardened in the heated extrusion head and the final profile is pullet out.

The Pultruded profile consists of textile reinforcement and the matrix. In the production of pultruded profile, the most commonly used matrix are unsaturated polyester (UP) and vinyl ester resin (VE). Textile reinforcement are most often glass or carbon fibers. The investigated pultruded profile was made of glass fibers and of UP. [2], [3]
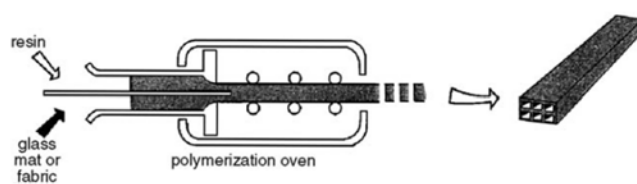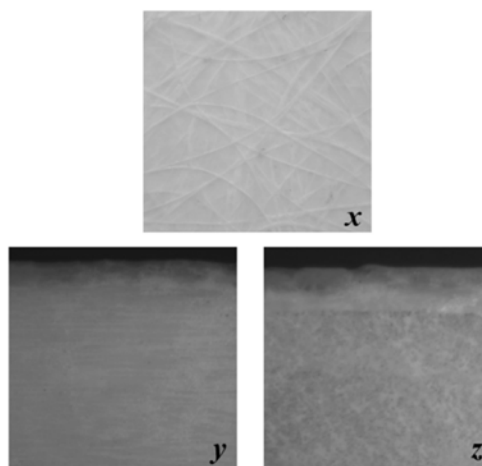

Fig. 1 Pultruded process [7]

Fig. 2 Pultruded profile (*y* and *z* magnification 23x)

The pultruded profile had a bonded nonwoven surface of glass fibers. The nonwoven fabric had a considerable impact on the properties of the pultruded profile. The sample was

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obtained from the profile measuring 30x4x27 mm. The image processing was observed in an area measuring 3x4 mm.

B. Image Processing of the Pultruded Profile Cross-Section Sample

To perform the numerical computation, the structure of the pultruded profile had to be known. The position, shape, and distribution of glass fibers are necessary to be known for successfully modelling because they have a substantial influence on the results. The image of the cross-section sample was taken by the optical microscope Olympus BX 51 at a 20x magnification for further processing for that reason and desired information were obtained by image processing methods. [4]
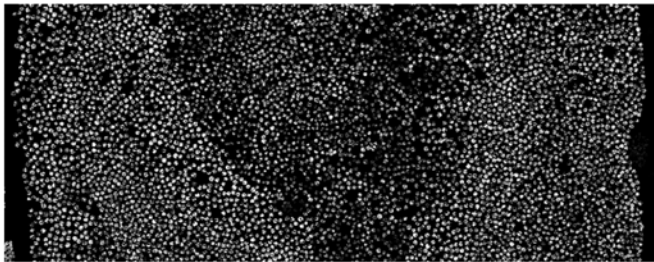

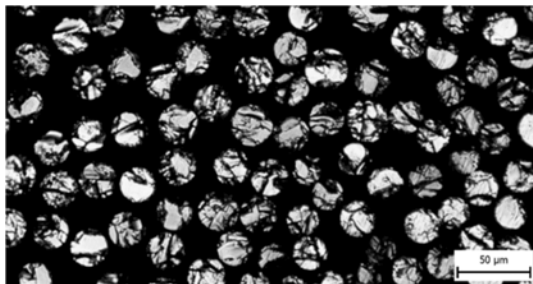Fig. 3 Trimmed image of the pultruded profile cross-section sample

Fig. 4 Detailed image of the pultruded profile under a microscope

The investigated sample area had a resolution of 10953 x 4321 with almost 5000 fibers (Fig. 3). Main purpose of image processing was identifying fibers in the matrix and specifying its properties. Pultruded process uses glass fibers with similar diameter, therefore this dimension is considered as a constant. Mathematical software Wolfram Mathematica is useful tool for image processing. Various functions for image enhancement and shape detection had to be used because the borders of the fibers had different contrast levels at the borders and also the brightness of the fiber objects changed significantly.

The image processing includes several operations in which the binarization is the first and basic step. It converts the image to a black and white image that has only two possible values for each pixel. All pixels with values above the threshold value are classified as white and all others as black. Finding one threshold compatible to the entire image such as this one is very difficult. If the value is too high, some fibers can join to one bigger white area while if the threshold is to low, some fibers are even not detected. Therefore, trade-off

value is chosen although there exist much more complicated methods that allow adaptive threshold on different areas of the image.

Other Mathematica´s functions that follow are DistanceTransform, MaxDetect, GradientFilter, Watershed-Components and SelectComponents. The first operation gives an image in which the value of each pixel is the absolute Euclidean distance in pixels to the nearest pixel of background. Function MaxDetect gives a binary image in which white pixels correspond to maxima of threshold value or higher. It means sufficiently bright areas are detected. GradientFilter function gives an image corresponding to the magnitude of the gradient of image, computed using discrete derivatives of a Gaussian of given pixel radius. The operator WatershedComponents computes the watershed transform of the image where a binary image marker is used for indication of regions where basins should by created. Finally, the areas with specific interval of number of pixel are selected, replaced by circles and their position is computed. After these computations some manual additional work had to be done because some fibers were not detected and some duplicated circles had to be deleted. Detail of the resulting image is on Fig. 5.

Fig. 5 Detail of the resulting image with highlighted circles representing edges of fibers

The circles do not align exactly with fibers due to different brightness levels of the objects. Each fiber has lighter and darker areas and the algorithm assigns the center of circle to the brightest area of fiber. Hence, in some cases circles can intersect. Generally, it can be said that the distribution of circles correspond well to the origin image, the distribution in plane is good and those intersections do not represent a problem for the following simulation. The output of this partial work was a list with coordinates of circle positions which were used for creation of a relevant model in ANSYS DesignModeler.

C. Volume Fraction

Volume fraction is one of the most important factors that indicate what properties will achieve a composite material. Volume fraction, which can be expressed as the relative ratio of the textile reinforcement and the matrix, describes the behavior of the final product. [5]

The volume fraction of the reinforcement (fiber) vf in the pultruded profile is defined as:

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$$vf = Vf / Vc, \qquad (1)$$

where Vf is the fiber volume and Vc is the volume of the composite. [6]

The volume fraction the pultruded matrix vm is defined as:

$$vm = Vm / Vc, \qquad (2)$$

where Vm is the volume of the fibers and Vc is the volume of the composite. [6]

The sum of the volume fractions of the composite component must be equal to 1. [6]

From the image processing was evaluated a selected site volume fraction. Volume fraction of fibers vf in a pultruded profile is 38.7% and the volume fraction of the matrix vm is 61.3%. The fibers in a pultruded profile oriented randomly, which results in variation of volume fraction in the area (cross-section).

The thermal conductivity can be estimated by calculation. If known thermal conductivity values of each component – fiber and matrix. Substituting into (3) was obtained by estimating the thermal conductivity pultruded profile based on the volume fraction of glass fibers.

$$\lambda c = \lambda f * vf + \lambda m * (Vc - vm), \qquad (3)$$

where λc is thermal conductivity of the pultruded profile, λf is thermal conductivity of fibers (λ glass fibers = $1 W.m^{-1}K^{-1}$[7]) and λm thermal conductivity of matrix (λ polyester matrix = $0.2\ W.m^{-1}K^{-1}$[7]). On Fig. 6 is easy to see that with the growing volume of glass fibers will increase the thermal conductivity pultruded profile. This way you can estimate the thermal conductivity pultruded profile prior to its production.
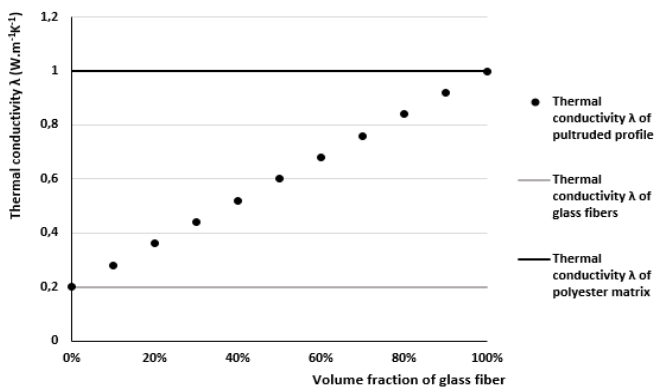

Fig. 6 Dependence of thermal conductivity λ in the growing volume fraction of glass fibers

The Voronoi diagram displays the map around the convex planar polygons fibers (filament center) in a plane within which, the piping length to a respective fiber is smaller than a distance to any other fiber. The Voronoi diagram was obtained from coordinate data of individual fibers and color levels polygons (shade of gray). [8] The 2D Voronoi diagram was obtained in the program Mathematica, which is used to create the chart their own algorithms.

Lightest shades of gray indicate areas with high volume fraction of fibers. Dark shades of gray then show a low volume fraction of fibers. The Voronoi diagram clearly shows the fluctuations in the volume fraction of the monitored region of the pultruded profile.
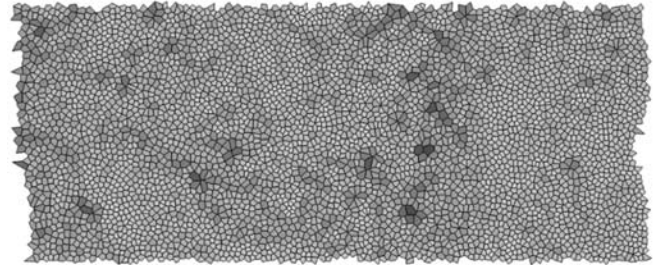

Fig. 7 The Voronoi diagram – pultruded profile

III. NUMERICAL COMPUTATION OF THERMAL CONDUCTIVITY

To obtain the average value of the conductivity for the pultruded sample a numerical simulation was used. An image of the cross-section was taken and later evaluated to create a geometric model by ANSYS DesignModeler. The sample had a length of 3.56 mm and width of 0.5 mm. An area of a typical distribution of the glass fibers was used. In the next step was created the 2D computational mesh with ANSYS meshing with 136 thousand elements. The boundary regions and zones were set.
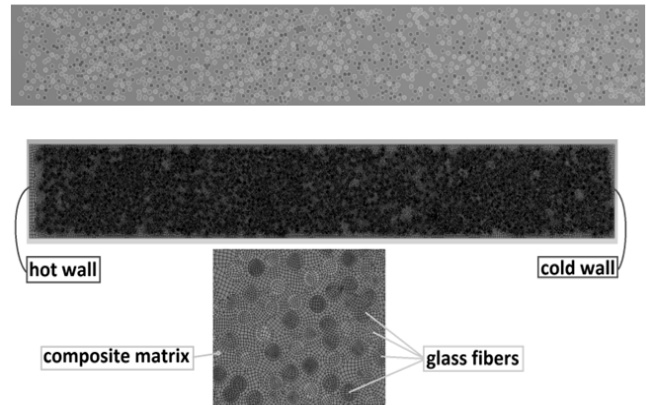

Fig. 8 Geometry in ANSYS DesignModeler

In ANSYS Fluent was set the conductivity of glass fibers to $1\ W.m^{-1}K^{-1}$ and $0.2\ W.m^{-1}K^{-1}$ for the plastic material of the matrix. [7] To get heat flow a temperature difference of 20°C was used between the hot and cold wall. The case was solved as steady and was 0.946 W/m (2D). With the equation 4 was obtained an average heat conduction of $0.315\ W.m^{-1}K^{-1}$.

$$\lambda = \frac{Q * \Delta}{(A * \Delta T)}. \qquad (4)$$

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Fig. 9 Numerical computation of thermal conductivity

IV. EXPERIMENT

The measurements of thermal conductivity were performed for temperatures of -20°C, 20°C and 40°C and in three directions (Fig. 10).
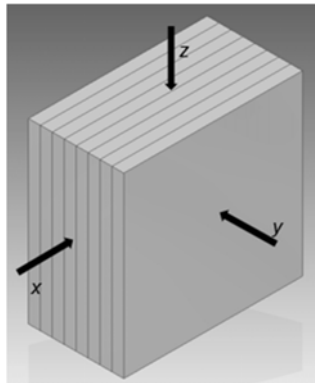

Fig. 10 Test sample

The TCi C-Therm device was used for conductivity measurement of the pultruded profile. Its benefit is the ability of measurement of small samples. The apparatus use a one-sided contact between the thermally reflective sensor, which consists of the measuring sensor, the control electronics and a special software.

To ensure proper contact between sensor (plain surface) and test sample (pultruded profile) was used contact liquid. Glycerin was selected as the contact liquid, because of the high temperature range of the measurement. The usage of the contact liquid does not affect the results. To ensure a proper contact a 0.5 kg steel weight was used. The weight was separated from the sample by a polystyrene insulation to avoid any affect. To avoid distortion of the results of measurement by said weights being between the test sample and penetration inserted polystyrene insulation.

TABLE I
THE RESULTS OF MEASUREMENT OF THERMAL CONDUCTIVITY λ

Direction	-20 °C λ (W.m^{-1}K^{-1})	20 °C λ (W.m^{-1}K^{-1})	40°C λ (W.m^{-1}K^{-1})	40°C λ (W/mK)
x	0.317	0.362	0,397	0.397
y	0.519	0.567	0,569	0.569
z	0.591	0.626	0,673	0.673

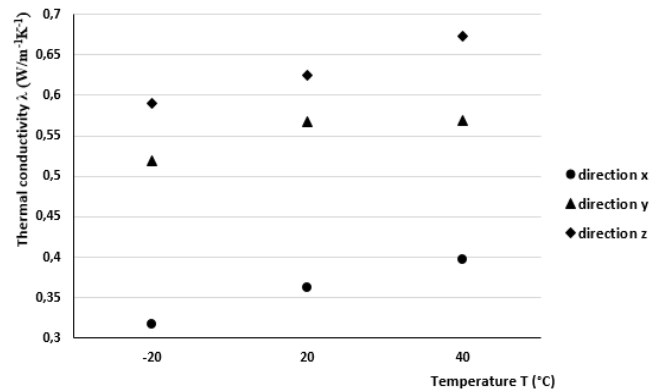Fig. 11 Measurement of the thermal conductivity with TCi C-Therm

Fig. 12 Measured thermal conductivity in different direction

Fig. 12 shows a dependency of the thermal conductivity with the temperature. The conductivity for the measured range clearly increase with the temperature. The dependence on the direction is significantly. The smallest conductivity is in the x direction which is near half compared to the maximal z direction

V. CONCLUSION

The paper describes procedures for determining the thermal conductivity of pultruded profile and measurements of the thermal conductivity with TCi C-Therm Analyzer. The image processing of image sample was conducted to find the volume fraction and the outputs were also used for simulations. The value of volume fraction was obtained from calculations end simulations. The fluctuation of volume fraction was described by statistic method. The volume fraction of fibers was shown on Voronoi diagram.

Table II shows the results of thermal conductivity of pultruded profile which were obtained by calculations, simulations and measurements. Results of the measurement device TCi (see Table I) demonstrated that the thermal conductivity of pultruded profile is proportional to increasing temperature. The thermal conductivity in the directions of axes

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x, y and z is different. This is caused by the orientation of the fibers, a nonwoven textile. The calculations proved that the volume fraction has an impact on the thermal properties of pultruded profile. The calculations also show that thermal conductivity is increasing when the filling of the fibers in pultruded profile rise. Glass fibers have a higher thermal conductivity than the polyester matrix. The comparison of calculation and measurements shows that the calculated value approaches the value of thermal conductivity measured in the y direction. It was also proved that the resulting value of thermal conductivity obtained by simulation is very close to the value obtained by measurement in the reference direction x. The objective of next work will be reconstruction of image from the image processing in 3D and validation of the measured thermal conductivity in directions y and z.

TABLE II
THE RESULTS

Method	20°C λ (W.m^{-1}K^{-1})	Volume fraction (fiber/matrix) [%]	Directions
Calculation	0.509	38.7/61.3	y
Calculation	0,460	32.5/67.5	y
ANSYS Fluent	0.315	32.5/67.5	x
TCi C-Therm	0.362	-	x
TCi C-Therm	0.567	-	y

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