The use of image analysis in evaluation of the fibers orientation in Wood-polymer composites (WPC)

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Abstract: In this paper a novel way of a digital analysis of fibers orientation with a five-step algorithm was presented. In the study, a molded piece with a dumbbell shape prepared from wood-polymer composite was used. The injection molding process was examined in experimental and numerical way. Based on the developed mathematical algorithm, a significant compliance of fiber orientation in different areas of the molded piece was obtained. The main aim of this work was fiber orientation analysis of wood-polymer composites. An additional goal of this work was the comparison of the results reached in numerical analysis with results obtained from an experiment. The results of this research were important for the scientific and also from the practical point of view. In future works the prepared algorithm could be used to reach optimal parameters of the injection molding process.

Keywords: image processing, fiber orientation, injection molding, numerical simulation

1 Introduction and the aim of the study

WPC composites are materials which consist of a polymer and in addition wood fiber in different proportions. These composites have better properties compared with standard polymer without fiber. WPC composites show, in comparison to wooden materials, significantly lower water absorption and swelling and a lower linear shrinkage. Furthermore, they are characterized by good mechanical properties and higher stiffness. An important reason for the use of wood composites with a polymer matrix are environmental considerations. They pose no danger to the environment during processing and recycling. In addition, these composites, after an appropriate modification, are partially biodegradable. Other advantages of this type of material are: high durability, non-skid in dry or wet surface, the appearance of natural wood, UV resistance, resistance to mildew and fungus, flame retardance, lack of requirements for additional processing such as grinding. Composites such as wood-polymer constitute forward-looking materials, that can be used in industries such as: automotive, construction, furniture and household appliances [1–3].

Type of fibers and their orientation in a polymer matrix is an important factor determining a lot of properties of produced material [4–7]. Orientation of the fibers in injection moulding process affects shrinkage of the composite, which directly influences the dimensional accuracy of a molded piece. This orientation depends on many factors, among which the most important is the injection speed. The aim of the study was to analyze the orientation of the wood fibers in a polymer matrix of wood-polymer composites (WPC) at the chosen example which, at present, are very popular group of composite polymers [8–10], using developed algorithm of image analysis.

An image could be analyzed in two main ways [11, 12]. First of them is an optical information. In this case, an observer looks at the picture and can see a little information. The results were based on subjective observation. Such information is of qualitative value and less quantitative. The second way of understanding an image is to treat an image as a matrix with information, where each expression is correlated with only one pixel. For example pictures saved as a *.bmp (bitmap) have 3 matrices, and each of them had row and column dimensions like the whole image. Every matrix contains information about values of color in each pixel. The matrix was correlated with different color. The *.bmp image consists of three main colors:
red, green, blue. Black pixel has value (0,0,0), white pixel (255,255,255), every color from range from black to white have values from 0 to 255. The image in grayscale has only one matrix. If on an image some parts of it are brighter than other parts of picture, then the corresponding pixels have higher values. This information was the basics to prepare a mathematical algorithm to calculate an angle in the image. Pictures of molded wood-polymer composite have a few characteristics. One of them is that wood fiber is brighter than polymer. If the image of the examined piece was saved in *.bmp format and next translated to grayscale, areas with wood fibers would be observed as white regions.

2 Experimental procedure and simulation of injection molding process

In order to produce wood-polymer composite, a polypropylene polymer matrix in grade: Moplen HP 648T was used. As the filler of the wood fiber, in grade Lignocel C120, made by Rettenmeier & Sohns company was applied. Furthermore, the Fusabond type P613 promoter with MFR = 49 g/10min was added. The composite with 15% of wood fibers polymer was manufactured in extrusion process by means of Zamak EHP 25 extruder. For samples manufacturing the Dr. Boy 55E injection molding machine equipped with two cavities injection mold was used. We performed the simulation of injection molding process by means of Autodesk Moldflow Insight 2013 commercial code. The numerical simulation was made for an identical composite as in experiments and then we conducted the same type of injection molding process. Processing and selected strength properties of the WPC composite were determined from other papers [13, 14]. The numerical model of molded piece was discretized by approx. 100 thousand tetra finite elements.

The analysis of fibers orientation in the numerical simulation was performed on the basis of the flow analysis in the mold and orientation of the flow vectors. The adopted aspect ratio of fibers was 10 by means of microscopic measurement. In simulations of fiber orientation the following micromechanical models were used: Tucker-Folgart, Halpin-Tsai and Rosen-Hashine. In the results of numerical simulations (Fig. 1) the high value of the tensor orientation in the area of narrowing dumbbell was observed, which provided the highest fibers orientation. With a change of cavity geometry, the flowing composite, passing through the neck region of dumbbell, expanded, which increased the disorientation of the fibers. The lowest value of orientation tensor could be seen in the region of molded piece-end area. The biggest disturbance in this area was due to wood fibres strike the wall at the end of the mold cavity.

Digital analysis of fiber orientation

In order to analyze the orientation of the fibers, we prepared a mathematical algorithm using Matlab©. This program is widely used in scientific research [15, 16]. The created algorithm consists of four main parts. The overall task of this algorithm was: the image transformation of molded piece to black-and-white (BW) scale, BW image division into a number of smaller images identified with the individual fibers, determination of the fibers angle orientation relative to the polymer flow axis direction and the presentation of this angle in a graphical form.

Figure 1: Fibers orientation tensor in the final stage of manufacturing determined by means of Moldflow Insight 2013 commercial code.

Figure 2: Stages of processed (fibers orientation) images: a) real image, b) BW image with bord=100, c) BW image with bord=150, d) BW image with bord=170.

The first part of algorithm converts colour image of molded part from *.bmp format (256-color) to the binary image, by means of two kinds of colour. The use of the al-
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Algorithm allows to prepare the matrix which contains only two values. The control parameter in this algorithm is new "bord" value, which is set up by the user and determines the upper limit of colours distribution. If the pixel has a value less than “bord,” a value 0 is generated in a prepared matrix, and if higher – a value 1.

Sizing "bord" depends on the analysis of images and each case should be verified. In the Figure 2 some examples of the selection are shown. Figure 2a shows how image looked before using the algorithm. Figures from b to d show the effect of "bord" to the resulting image. Depth of focus (in the case of analysis of fiber orientation - the depth of detection) is directly linked to the value "bord".

The second part of the algorithm divides a newly created image matrix “Mcell” into several smaller matrices “mcell”. It was established that every small matrix had to be associated with one analyzed fiber. The control parameter in this algorithm is the number of cells created horizontally and vertically.

The third part of the algorithm scans a small matrix "mcell" in order to find a row and a column, which is the largest number of black pixels. This point becomes the center of the image (center of the fiber). Based on this point, the algorithm is looking for a pixel located the farthest to the right and to the left, from the specific centre. Knowing the coordinates of all three points, we calculated four angles. The first angle is located between the middle point and the farthest to the right, the second one is between the middle point and the farthest to the left, the third angle is measured between the farthest point to the left and to the right. The fourth angle is the average value of the first and the second angles.

The main angle is calculated based on a few parameters (Fig. 3). Point coordinates, a and b, are connected with the center of the image (information in which row and column is the biggest number of black pixels). Coordinates e1 and f1 are related to the farthest black pixel located to the left from the center (a, b). Coordinates e2 and f2 are obtained as a column and row number of the farthest pixel located to the right side from the center. The scheme definition of fiber location angle is presented in Figure 3. The distance between e2-e1 and f2-f1 are used in equation which calculates angle. This equation is based on arctangent trigonometric function.

The last part of the algorithm evaluates which angle is really connected with the analyzed fiber. Based on an earlier prepared set of eight cases of orientation fibers (Fig. 4), the algorithm inserts an image associated with a given angle. The result is a digital image of the fiber orientation. Similar algorithm was used to prepare statistical information about the angles. This code returns information about how many cells (small images from bigger part) this angle exactly has. The discussed algorithm is presented below:

```
kat0,kat22,kat45,kat67,kat90,katm22,katm45,katm67 = zliczanie_katow (Nox,Noy,kat)
% Nox – number of cells in one lines of Mcell matrix
% Noy – number of cells in one rows of Mcell matrix
% kat – matrix with information about calculated angle in every each cell
kat0=0; % angle = 0 degree
kat22=0; % angle = 22.5 degree
kat45=0; % angle = 45 degree
kat67=0; % angle = 67.5 degree
katm22=0; % angle = -22.5 degree
katm45=0; % angle = -45 degree
katm67=0; % angle = -67.5 degree
kat90=0; % angle = 90 degree
kat4=kat;
for z1=1:Nox
do
  for z2=1:Noy
do
    if ((kat4(z2,z1) >= -11.25) & (kat4(z2,z1) <= 11.25))
      then
        kat0=kat0+1;
      else if ((kat4(z2,z1) >11.25) & (kat4(z2,z1) <= 33.75))
        then
          kat22=kat22+1;
        else if ((kat4(z2,z1) >33.75) & (kat4(z2,z1) <= 56.25))
          then
            kat45=kat45+1;
        else if ((kat4(z2,z1) >56.25) & (kat4(z2,z1) <= 78.75))
          then
            kat67=kat67+1;
        else if ((kat4(z2,z1) >= -33.75) & (kat4(z2,z1) <= -11.25))
          then
            katm22=katm22+1;
        else if ((kat4(z2,z1) >= -56.25) & (kat4(z2,z1) <= -33.75))
          then
            katm45=katm45+1;
```
else if ((kat4(z2,z1) >= -78.75) & (kat4(z2,z1) <- 56.25))
    then
        katm67 = katm67 + 1;
    else
        kat90 = kat90 + 1;
end if
end for
end for

3 Results and discussion

We used an experiment, that initially was carried out on the basis of a mathematical model. A number of molded piece representative regions were selected (Fig. 5): an area with disturbed fibers orientation – 1, an area with little fibers orientation – 2, and an area with largest directional fibers orientation – 3. The main goal of this analysis was to define fibers orientation in specific regions and for the whole molded piece on the basis of camera image made by measuring Nicon MM800 microscope.

The mathematical algorithm was developed to analyze the fibers orientation, for instance, for the three pictures indicated in Figure 5. The results of digital analysis were depicted in Figure 6. It can be seen that the greatest disorientation of fibers occurred in the area 1, the average disorientations occurred in area 2 and unidirectional fibers arrangement was placed in area 3.

![Figure 4: Eight examples of fiber orientation representation.](image1)

![Figure 5: Areas of different fibers orientation: area with disturbed fibers orientation – 1, an area of the average disturbances – 2, areas with largest directional fibers orientation – 3.](image2)

![Figure 6: The selected areas of the molded piece after the digital image analysis.](image3)

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The obtained results were verified statistically. In order to present the results better, the special part of developed program, which counts the number of different types of alignment in examined area was created. This allowed to prepare the statistics about the percentage of a particular fiber orientation type in the analyzed region (Figure 7). In case of region 1 it can be observed almost 43% of 90° fiber orientation type, which indicates the highest disorientation in this area. In the area 2 more than 31% of 45° fiber orientation type, also 19% of type 0° and 19% of type 90° were found. The above results indicate a decrease of disorientation in this molded piece region. In the case of the region 3 almost 60% of fibers were oriented with 0° angle, which may suggest the considerable fiber orientation in polymer flow direction.

4 Conclusions

Based on the results of the mathematical analysis of the image, we can observe some similarities between experimental and numerical results. Changes of cavity geometry affect the degree of fibers disorientation. The analysis of these regions confirms that unidirectional arrangement of
fibers are noticeable in the undisturbed flow of material. In the case when plastic strikes the cavity walls, the results show a drastic disorientation of the fibers. These phenomena occurred both in numerical analysis and also experimental studies and they were confirmed supported by the digital image analysis.

For the central of the molded piece, we can observe the directional orientation of fibers. About 60% of fibers are at 0 degree angle and they are parallel to the flow direction of polymer composite. Almost 43% of fibers are oriented at an angle of 90 degrees at the end region of the cavity. These disorders are probably due to an agglomeration of the fibers and form particles with a shape impeding the correct evaluation of the angle orientation and due to reflection of the flowing polymer from the wall of mold cavity.

The developed computer program gives the possibility to confirm experimental results reached in numerical analysis performed by means of Autodesk Moldflow Insight 2013 commercial code. Additionally, this mathematical code could be used to determine the set of filler particles in the case of composites, where their arrangement is seen.

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