CORRELATION OF FLOW INDUCED STRAIN STATES AND YOUNG'S MODULUS IN CARBON REINFORCED MOULDING COMPOUNDS

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Abstract

Recent research in the field of composites has focused on the promising technology of carbon-reinforced sheet moulding compound. Good material usage combined with the ability to form complex geometries in structural loaded parts are part of the technology's potentials. The flow of the randomly distributed short fibre compound in the pressing process is a great advantage over continuously reinforced materials. Since the knowledge of fibre orientation in the laminate is crucial for the assessment of the mechanical performance of a part the rheology of the material has to be examined. Therefore, a method is developed to track and quantify the strain state of the material at the end of the moulding process. Using an adequate contrast material combined with x-ray imaging it is possible to evaluate mentioned strain state dependent on the flow rate of the moulded material in a plate geometry. This data can be correlated with the young's modulus and the thermal expansion coefficient in specific directions of reference test plates. The combination of mentioned correlations can be used to determine a main fibre orientation in the material depending on the specific flow rate. Therefore, fibre orientation and mechanical properties can be assessed in areas of a part where traditional testing cannot be applied.

1. Introduction

Sheet moulding compound (SMC) is a composite technology traditionally using cut glass fibres (GF-SMC), which are randomly distributed and combined with a thermoset matrix to form a preimpregnated mat. In the process, the raw material is cut into sheets, stacked on top of each other and placed into a heated, two part steel tool which carries the formative cavity. With the help of hydraulic presses the tool is closed and by the heat flow into the material and the rising pressure in the cavity the viscosity of the material is lowered which transforms the material into a flow able state. The ability of the material to change its physical appearance from an often square or rectangular stack to a complex part including 3D-geometries like ribs and bosses provides the superior potential of the technology. Latest development within the SMC-industry focus on improving the mechanical performance of the material in order to enter the field of structural applications. To achieve this the traditionally used glass fibres are substituted by strong carbon fibre (CF-SMC) and the fibre content of available material is increased drastically in order to achieve high modulus of the laminate. [1–3] Since fibre orientation determines the mechanical performance of a part it is crucial for safety relevant applications to be able to assess these especially in neuralgic zones. In contrast to GF-SMC it is not suitable anymore to think of the material behaviour as isotropic within the raw material and the moulded part. This is why it is necessary to characterise the rheology of the CF-SMC-material in the process and determine the influences of the flow of the material on the orientation of the reinforcing carbon fibres. [7]

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Overall little work was done so far to characterise the rheology of the material in the process. Dumont et al. introduced a method to describe the flow of the material using white GF-SMC and a grid consisting of black lines which was drawn on the top most layer of the stack. [9] Since the measurement of distortion in this method is done manually and it is only possible to track the movement of the first layer, this methods is not fully applicable for detailed investigation. Consequently, a method has to be developed which helps to track and quantify the movement of the material in the process not only on the surface but in the laminate itself and providing a good resolution and precision additionally.

To gather information about the orientation of carbon fibre state of the art systems which have already been established to measure fibre angles in endless fibre reinforced materials appear unrewarding since these optical procedures track resin rich areas on the surface of i.e. braided or woven materials. Since in the case of SMC fibre orientation varies over the thickness of the part these methods do not deliver satisfying results. Another way to visualize fibre in composites materials is x-ray or computer tomography (CT) technology. Whereas the difference in density of resin to fibre is low and further more due to the small diameter of the carbon filaments the area of investigation has to be reduced to some millimetres in order to gain high contrast of the fibres. It is possible to trace fibres in the grey scale picture visually but the examined area represents only a very small portion of the part. The effort in time and costs is one disadvantage of this method. Therefore, a method has to be developed which allows to state the main fibre orientation in a macroscopic scale covering different areas of a part. [10, 11]

2. Material and test method

2.1. Material

In this investigation a standard CF-SMC by Quantum Composites (AMC® 8590, 126-76-8) is used containing 1 ” chopped 12K-fibre at a fibre content of nominal 53 w%. In order to keep complexity low this material is moulded into test plates (500x340 mm) realizing a 1D-flow (only one direction of material movement) and creating different levels of mould coverage. The material is processed following the moulding suggestions of the compounder (T= 145 °C, p= 205 bar, t= 120 sec). It is known that this material shows a distinct anisotropy regarding its mechanical performance (ϑ_E= 1,57; ϑ_σ= 1,70). Therefore, the direction of production is registered and each stack is created maintaining the same orientation of each sheet. Since the main orientation of the fibre in the raw material defines its rheology this has to be controlled carefully. [8, 9] Plate thickness is defined as d= 3,5 mm which allows in combination with the given nominal area weight of the material (M= 2745 g/m²) three different load patterns (100 %, 66 % and 40 %) to create comparable plate thicknesses. Same sized sheets for each pattern are used allowing flow only in one direction (see Figure 1).

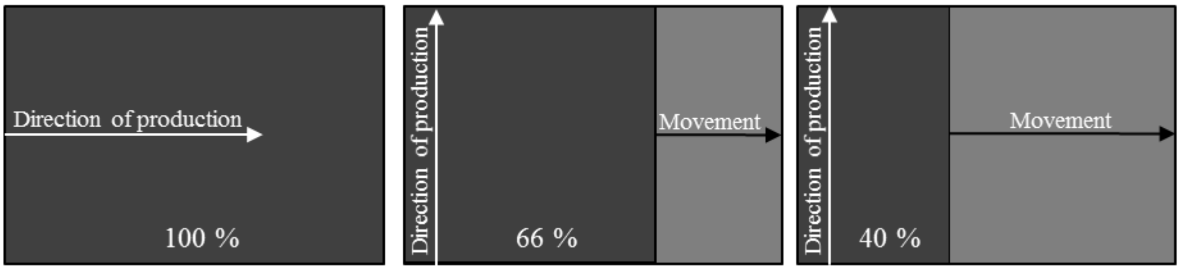

Figure 1. Scheme of different loading patterns.

In order to track and measure the movement of the material depending on the load pattern two plates per each scheme are moulded carrying a suitable contrast agent for x-ray imaging. Therefore, a

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constant grid of points (10x10 mm) is created on the surface of the middle sheet using a perforated metal plate (see Figure 2).

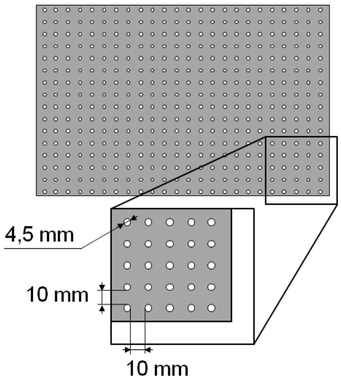

Figure 2. Perforated metal plate for grid application.

The laminate quality of each plate is examined by ultrasound technology in order to assure perfect void free test specimen. [12] Waterjet cutting is used extracting the needed specimen for tensile, thermal expansion coefficient (TEC) and fibre volume fraction (FVF) measurements, which results in smooth edges without defects or delamination. All tests are carried out in the two directions of the plate (0° and 90°) and the area of the plate is classified into three domains (loading position A, flow area B and -C). This leads to the following plan for the extraction of the samples (see Figure 3).

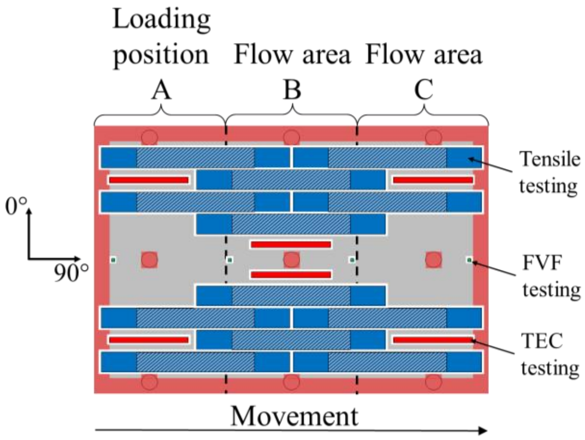

Figure 3. Plan for the extraction of the samples in 90°-direction.

In order to gain comparable data four tensile bars, two TEC- and one FVF-specimen are taken out of each area A-C in both 0°- and 90°-direction.

2.2. Test method

X-ray images of the reference plates carrying the contrast agent are taken and processed using suitable software to extract the coordinates of the contrast points. Theses coordinates are used to create a FE-net in which four points represent a FE-element (FE-software ANSA). In reference to the size of the origin grid it is possible to calculate the strain in each direction which had to take place to deform the grind into the appearance it shows in the x-ray images for each loading pattern (MATLAB).

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Tensile test are performed following DIN ISO 527 in 0°- and 90°-direction. The TEC- and FVF-values are measured following DIN 53752-A and DIN EN 2564 respectively. [4–6]

3. Results and discussion

The x-ray images are taken and their information processed. To illustrate the results these images are masked with the created FE-net which can be visualized with the help of ABAQUS (see Figure 4).

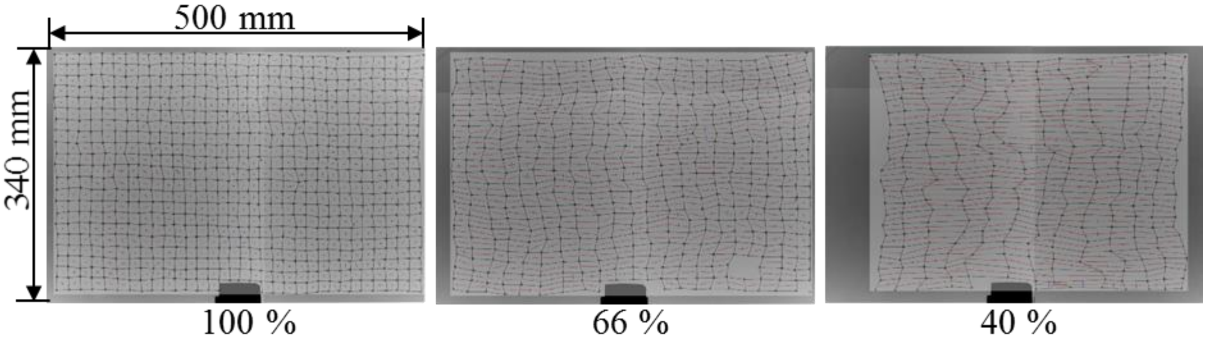

Figure 4. X-ray images masked with FE-net.

The x-ray images show a homogeneous distribution of the incorporated contrast agent which can be detected easily in the grey scale picture because of its high difference in specific gravity. At a mould coverage of 66 % the particular elements show an overall constant elongation in the direction of the flow with almost no disturbance in the cross direction. Using a smaller stack and covering the mould area by 40 % the centre of the contrast agent distribution lies slightly on the right hand side of the plate at the end of the material movement. The change of the element size starts to appear slightly inhomogeneous and show a broader variation of element distortion. In general the pictures show a relatively constant flow of the material in the tool with little disorder.

The distribution of strain levels that can be derived from the change in element size is illustrated exemplary in Figure 5 for loading pattern 100 % and 66 %

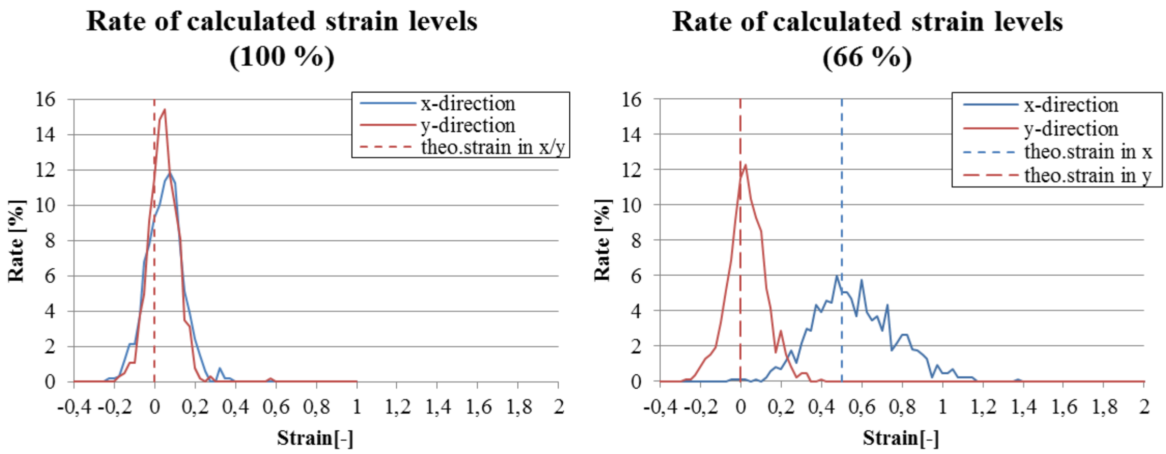

Figure 5. Rate of calculted strain levels for loading pattern 100 %/66 %.

Above graphs show a good correlation of the calculated strain levels with the theoretical distortion of an element considering the individual mould coverage. In the plate which is fully covered with

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material no flow should occur theoretically. Since the dimensions of the stack need to be slightly smaller than the mould itself the material is able to flow minimally causing a peak in the strain rates at 0,075 (7,5 %) in x-direction and 0,05 (5 %) in y-direction. The average strain in both direction is calculated at 3,7 % in x-direction and 3,1 % in y-direction which shows the precision of the method. At 60 % mould coverage the distribution of the strain rates in both directions gets wider and therefore the peaks lower. In the direction of the flow (x-direction) the peak of the strain rates lies near to the theoretical strain of 0,5 (50 %) and is calculated by 0,475 (47,5 %). In the cross direction the strain is calculated at 0,025 (2,5 %). At this mould coverage the average in x-direction is calculated at 0,55 (55 %) and 0,019 (1,9 %) respectively. The broad distribution of strain rates with different strain levels show the slight inconsistency of flow when the mould coverage is reduced.

In the next step the tensile properties and the measured TEC-values are compared. To characterize the general behaviour of the basic material Figure 6 shows the gathered data for a mould coverage of 100 % in a polar diagram.

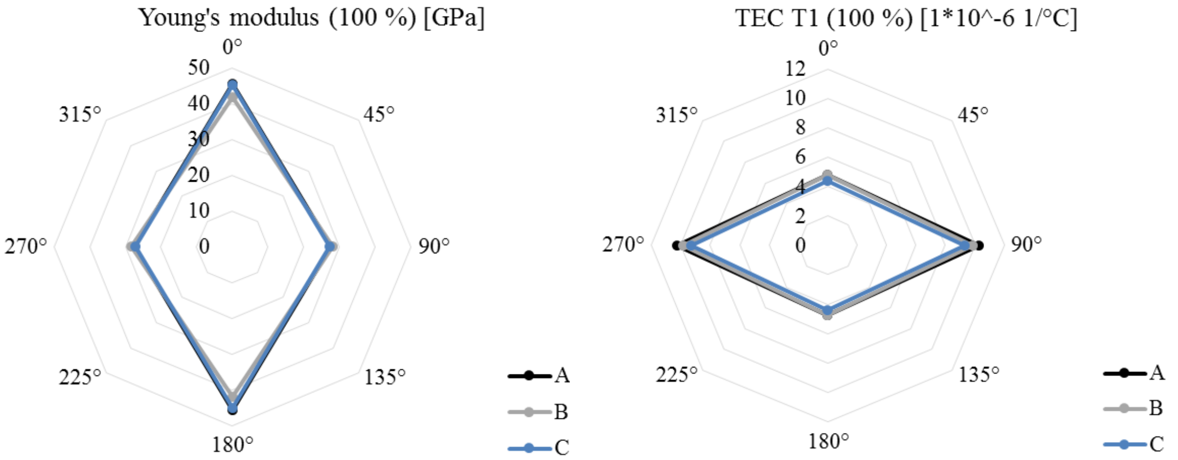

Figure 6. Comparison of young’s modulus and TEC-values at 100 % mould coverage.

The illustration of the young’s modulus of the material shows its anisotropic behaviour in its mechanical properties as mentioned in the beginning. The mean value measured lies at E_0= 44,2 GPa for the stiffness in 0°-direction and E_{90}= 27,6 GPa in the cross direction. The deviation of the values of each area is very low and lies within the range of the standard deviation of the test groups. The values of the TEC show consequently a higher thermal elongation in 90°-direction (TEC_{90}= 9,807*10^{-6} 1/°C) respectively lower values in 0°-direction (TEC_0= 4,642*10^{-6} 1/°C). Since thermal elongation in composite materials is dominated by the matrix but controlled by fibre these values show that the main orientation of the fibres lies in the 0°-direction which correlates strongly with the values of the young’s modulus.

When comparing the individual loading patterns with the different values which could be gathered, the following graphs can be drawn (see Figure 7).

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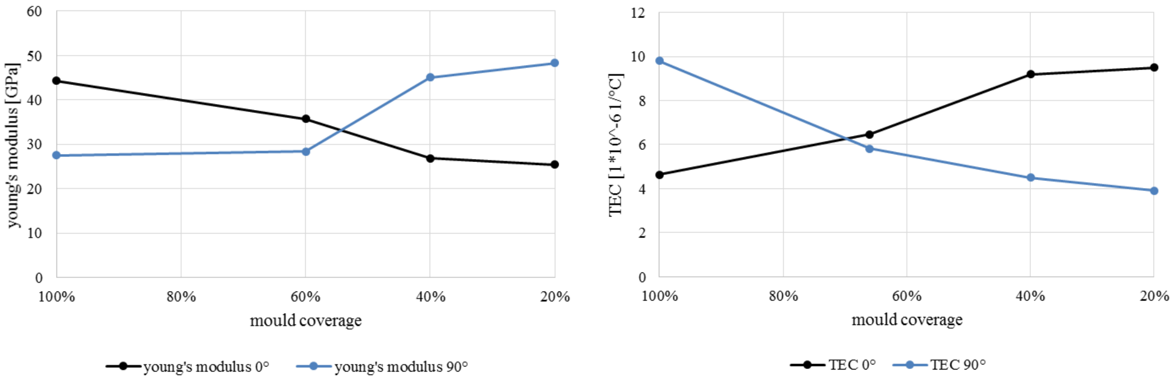

Figure 7. Correlation of young's modulus and TEC in relation to the mould coverage.

Looking at the above figure it is clearly noticeable that the fibre in the material gets reoriented depending on the flow which occurs in the moulding process. The level of anisotropy is reduced in the step from 100 % to 66 % mould coverage. This can be seen in a reduction of the young's modulus in 0°-direction and a slight increase in the cross direction. When comparing this to the TEC-values a similar effect is noticeable but the thermal expansion at 66 % coverage is already showing a tendency of lower values in 90°-direction compared to the 0°. Both values point out that the main orientation of the fibres is changing and starting to lie in the 90°-direction. When following the graph to values which are gathered at 40 %-mould coverage the tendency which could be seen in the first step is enhanced drastically. The anisotropy of both values is turned by 90° and the stronger direction is now the 90°-orientation. The values of the young's modulus can be found upon nearly the same level when comparing 100 % and 40 %-coverage but each in the opposite direction. Same effect can be seen in the values of the TEC. When reducing the mould coverage even more, distortion and deviance are increased but the main tendency of the effect of fibre reorientation can be noticed all the same.

3. Conclusions

Overall two different findings can be drawn out of the shown results. First, an innovative method can be introduced using a contrast agent to visualize material movement in the mould during the pressing process. This technique enables the characterization and comparison of the specific behaviour of different materials. It could be seen that the used material is showing a very homogeneous rheology only with small disturbances in the elongated grid when a low mould coverage (<40 %) level is applied.

Concerning fibre orientation in CF-SMC-materials it can be shown that the reinforcing medium is rearranged in the flow process. The lower the percentage of mould coverage the higher the effect of fibre reorientation occurs due to higher flow rates in the tool. This effect can be measured in both variations in young's modulus and TEC. In this research the direct link between those two material properties could be validated for short fibre reinforced materials consequently. With the help of these findings it is now possible to assess the main orientation of fibre in CF-SMC-parts even in areas where specimen for tensile testing cannot be extracted. Furthermore, the change in mechanical properties can be estimated with the knowledge of the strain the material experiences to reach a certain point of the part. Following that, it is now possible to define the shape and the position of the SMC-stack or the position of stiffening elements or thicker areas of the part where they are needed due to changed material properties induced by flow in the process. These findings are essential for the development of structural parts in the CF-SMC-technology and help to reduce time and cost in this process drastically. Further work will focus on the correlation of this data with the tensors of fibre orientation in the material which can be measured by eddy current and CT-technology. These facts can then be used as input for process- and warpage simulation in order to optimize tooling design.

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