NATURAL FIBRE-REINFORCED, INJECTION MOULDED POLYMERS FOR LIGHT WEIGHT CONSTRUCTIONS – SIMULATION OF SUSTAINABLE MATERIALS FOR THE AUTOMOTIVE INDUSTRY –

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Abstract
Besides low fuel consumption and vehicle safety, more and more clients focus on sustainability issues buying a new car. Here not only the energy consumption during the production but also during the usage of the product has to be considered. To fulfil all these requirements natural fibre-reinforced polymers are a very good solution, combining light weight construction with renewable resources. To guarantee the crash-safety numerical simulations are essential in the product development process. Until now only functions to simulate glass fibre- or carbon fibre-reinforced polymers exist in the common software programs, but not for natural fibres. To close this gap the project NFC-Simulation was established. One of the main parts of this project was the characterization of natural fibres (like hemp, flax, sisal and regenerated cellulose fibres), including mechanical & morphological analyses and fibre orientation measurements. Crash-relevant components, glove boxes, were injection moulded with 30 mass% sisal fibre-reinforced polypropylene and experimental crash-tests were performed. The experimental results fit very well with the results from the process and crash-simulation.

Keywords: Natural fibres, Simulation, Lightweight construction, Sustainability, Ecodesign

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1 INTRODUCTION

The main aspects for clients, who buy a new car, are low fuel consumption and vehicle safety (TNS Market Research in Gruber et al., 2011). Therefore lightweight constructions combined with a high crash-safety are a very good solution to satisfy the customer's needs. Lightweight constructions can be achieved by (Harig & Langenbach, 1999):

- Analysis of the loading case
- Advanced constructions
- Advanced production processes
- Light and high-strength structural materials

Constructions with fibre-reinforced polymers are an excellent solution for light and high strength materials with a variable fibre orientation and directional characteristics (Wambua et al., 2003). Besides the use of carbon fibres, glass fibres are most commonly used as reinforcement material, especially in the automotive industry. Fibre composite constructions are a synergetic combination of the positive characteristics of at least two materials, namely of the fibres and the matrix. The fibres with a high stiffness and strength can transfer loads and are consequently the reinforcing component. (Karger-Kocsis, 2014) Fibre-reinforced polymers are often used as lightweight constructions in the aircraft, wind turbine and automotive industries. Due to combination possibilities of different fibres and different matrices well adapted composites for specific applications can be performed.
For the selection of an appropriate material it is nowadays also important to choose sustainable materials. The sustainability of a product needs to be analysed along the complete product life-cycle. One criterion in a LCA (Life Cycle Assessment) is the cumulative energy demand, for example, of the production phase or during the usage phase of the product. Exemplarily the energy consumption of a steel, an aluminium and a carbon fibre-reinforced plastic (CFRP) fender for a family car are compared in Figure 1. This diagram shows that even though the steel bumper has a much lower energy consumption considering the material production than the aluminium or the CFRP bumper, the total energy use is the highest for the steel bumper. This is due to the fact that the steel bumper (mass: 14 kg) has the highest energy consumption during use when compared to the lighter aluminium (mass: 10 kg) and CFRP bumper (mass: 8 kg). In this comparison steel and aluminium are calculated as virgin materials. Considering recycled metals as an input material the energy consumption for the aluminium bumper decreases drastically from 2.1 GJ to 1.1 GJ, whereas the energy consumption for the steel bumper decreases only slightly from 0.45 GJ to 0.31 GJ (Ashby et al., 2011). The total energy consumption of the production and the usage phase by using recycled metals is for the aluminium fender with 6.3 GJ lower compared to 7.6 GJ for the steel fender. These examples show that for the

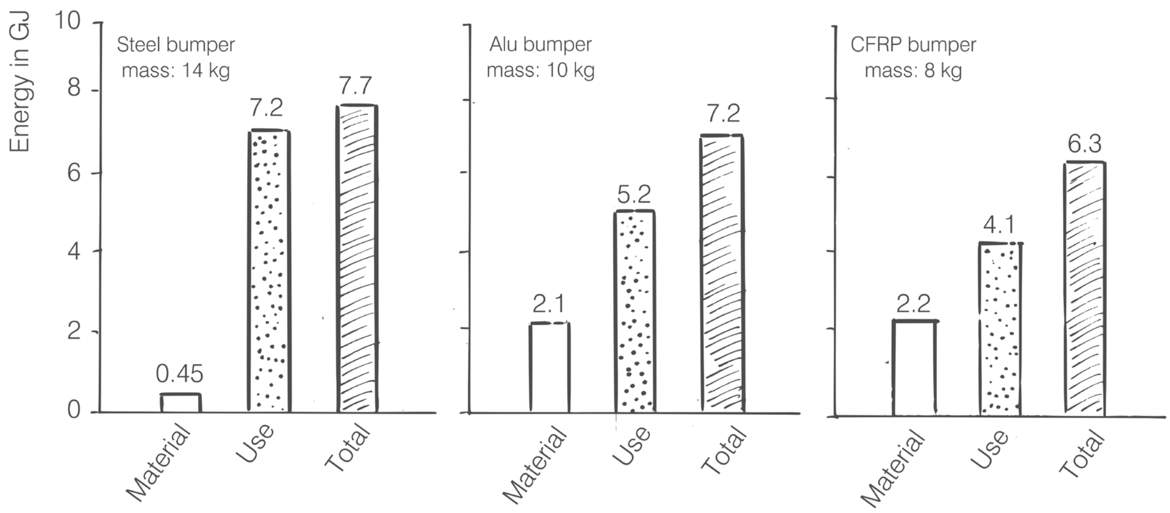

Figure 1. The comparison of the energy audits of a steel, an aluminium and a carbon fibre-reinforced plastic fender for a family car (usage of virgin material; use: 250,000 km). (adapted from Ashby et al., 2011 in Müssig, 2013)

selection of a material for a sustainable product it is not enough to consider only the material production itself, it is also important to analyse all steps of a product life-cycle. In the given example the last phase of the product life (end of life phase) was not considered, which is, of course, necessary for a complete LCA.

Considering only the production and use phase the CFRP bumper has the same total energy consumption as the aluminium bumper with recycled content. Using carbon fibre-reinforced polymers it is possible to perform excellent lightweight constructions. CF/epoxy (T300/5208) has a much lower density (1.6 kg/m³) compared to aluminium (3.4365-T6/7075), which has a density of 2.8 kg/m³ (Neitzel et al., 2014). Mass reduction with excellent performance is demonstrated in the BMW i3 which uses carbon fibres composites as reinforcing structures for the complete car body.
In times of growing environmental concern, the demand for renewable resources is increasing consequently. Therefore a lot of research has been done in the last years to integrate natural fibres (NFs) in fibre composite constructions (Müssig, 2010; Magnani & Wehmeyer, 2010, Baltazar-Y-Jimenez and Sain, 2012; Graupner et al., 2013; Summerscales and Grove, 2014). The global warming potential is significantly reduced using natural fibres instead of glass fibres. In a study of Ford it could be shown that for the same automotive part a glass fibre-reinforced polymer (polypropylene) causes more than the double amount of carbon dioxide emission than a natural fibre (hemp) reinforced polypropylene (Figure 2). Further advantages of natural fibres over glass fibres are their lower density, less abrasive behaviour and that they do not leave fibre slag after incineration.

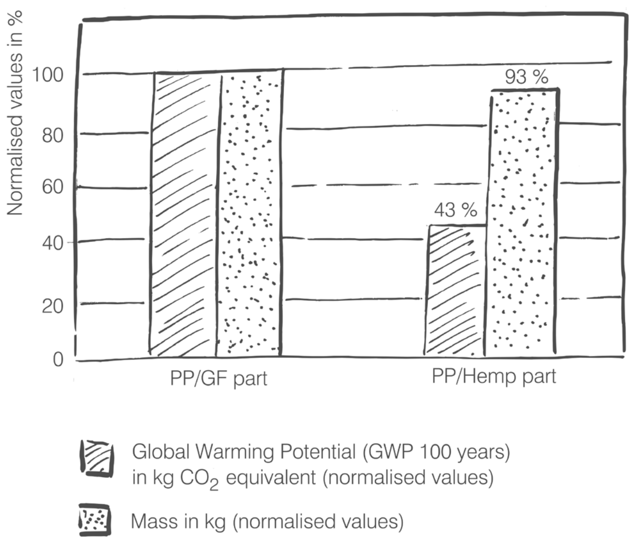

Figure 2. Global warming potential and mass comparison of PP/glass fibres versus PP/natural fibres (hemp). Ford: "carbon dioxide reduction by using biobased materials" (Magnani & Wehmeyer, 2010. - adapted)

Looking at another example from the automotive industry, it can be seen that the energy consumption for the production of a door trim is almost half for a hemp fibre-reinforced epoxy resin when compared to ABS (Acrylonitrile butadiene styrene). Figure 3 shows that the main part of the energy consumption of the hemp fibre-reinforced epoxy resin is caused by the epoxy resin and its hardener and only one fourth is caused by the production of the natural fibres. Natural fibre-reinforced materials are therefore a very good solution for sustainable applications from an ecological point of view.

To satisfy the requirements of the clients whose concerns, besides low fuel consumption and vehicle safety, tend more and more environmental issues, the automotive industry is looking for materials which combine all these desires. Natural fibre-reinforced polymers (NFRPs) can suit many of these requirements. The use of NFs combines two positive aspects, the lower density of NFs compared to glas fibres (1.5 g/cm³ in comparison to 2.5 g/cm³) and the usage of renewable resources. Focusing on lightweight constructions, one main aspect for the component design is to avoid oversizing and still guarantee vehicle safety. Therefore reliable material models are important for designers to predict the

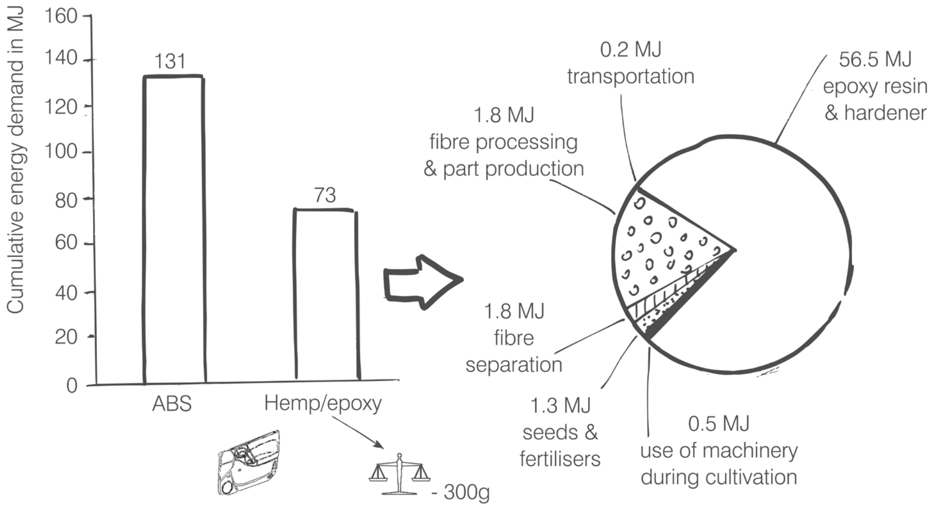

Figure 3. Energy consumption for a door trim production - ABS versus hemp fibre-reinforced epoxy resin (cradle-to-gate). (Adapted from Flake & Wötzel, 1999; Wötzel et al., 1999)

behaviour of the NF-reinforced components. New design and construction methods need to be considered for NFRPs in automotive components. Natural fibre-reinforced, form-pressed composites are already used for interior panels. But increase interest is now focusing on large-scale productions. Therefore the injection moulding process is a very common and efficient production method. To guarantee the crash-safety of the components numerical simulations are essential. Experimental pre-tests require considerably longer development times and are much more expensive than numerical simulations (Paredis, 2001). In Figure 4, possible steps for a component development process of injection moulded fibre-reinforced parts for the automotive industry are shown. The process (injection moulding) simulation and crash simulation are necessary for the tool and process design.

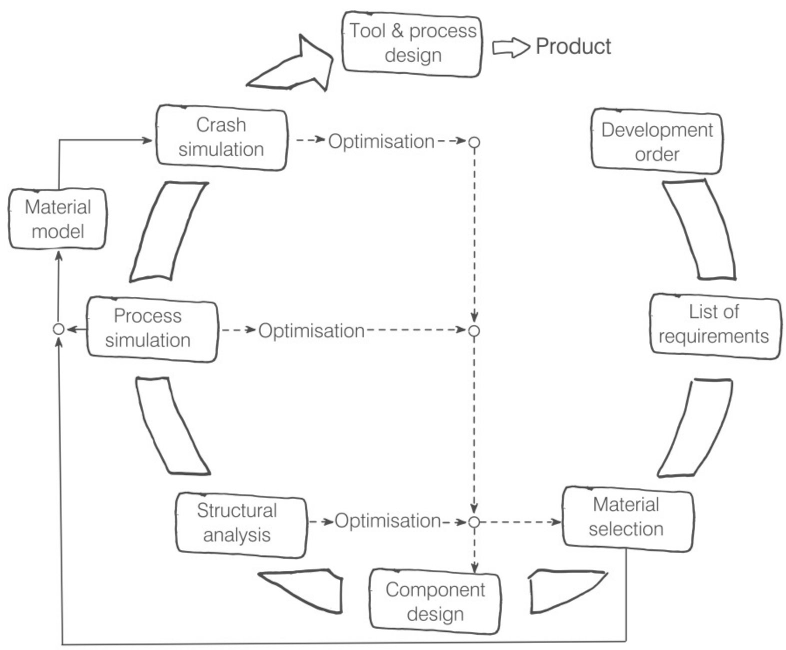

Figure 4. Possible steps in a component development process of injection moulded fibre-reinforced parts for the automotive industry (Müssig, 2014).

Until now only functions to simulate glass fibre- or carbon fibre-reinforced polymers existed in the common software programs (such as CADMOULD, MOLDFLOW or MOLDEX3D), but not for natural fibres. The first major developments in the injection moulding simulation with natural fibres, like fibre motion in a fountain flow velocity field, fibre-fibre interaction and fibre attrition, have been accomplished (Osswald, 2012). More progress is needed to develop modules ready for practice. A research project "Material and Flow Model for Natural Fibre Reinforced Injection Moulding Materials for Practical Use in the Automotive Industry" (NFC-Simulation) was established to close this gap for injection mouldable, natural fibre-reinforced polymers. Parts of the results of this research project will be presented as follows.

2 CONCEPTUAL FORMULATION

The characterization of the natural fibre plays a central role in the before mentioned project. The fundamental question is therefore: Which fibre properties are necessary for the injection moulding simulation and crash-simulation in the project NFC-Simulation?

Three central questions were asked for this research project:

1. Which mechanical properties of natural fibres are relevant for the simulation?

2. How can morphological fibre properties be determined reproducibly and the results of the micro-mechanical model be validated via experimental analysis?

3. How can the orientation results of the injection moulding simulation be evaluated by experiments?

3 MATERIALS AND METHODS

3.1 Materials

3.1.1 Used natural fibres

- Hemp: bast fibres, pelletized by BaVE Badische Faserveredelung GmbH, Malsch, Germany
- Flax: bast fibres, pelletized by BaVE Badische Faserveredelung GmbH, Malsch, Germany
- Sisal: leaf fibres, pelletized by BaVE Badische Faserveredelung GmbH, Malsch, Germany
- Cordenka® (CR, 500 tex, f 2700): Regenerated cellulose fibres, Cordenka GmbH & Co. KG, Obernburg, Germany, cut by W. Barnet GmbH & Co. KG, Aachen, Germany

3.1.2 Used matrix material

- Polypropylene: Moplen EP 500V, LyondellBasell, Frankfurt, Germany

3.2 Methods

To determine the mechanical properties of the natural fibres, tensile tests with single fibres (regenerated cellulose fibres) and fibre bundles (hemp, flax, and sisal) were performed. The fibres were conditioned for at least 24 h at 20 °C and 65 % relative humidity according to DIN EN ISO 139 in the climate chamber Vötsch VCL 4003 (Vötsch, Balingen, Germany) before testing. The tensile properties of the natural fibres like tensile strength, Youngs' modulus and strain at break were analysed using the tensile testing machine Fafegraph M (Textechno, Mönchengladbach, Germany). The fibres were tested with a clamping length of 3.2 mm and an extension rate of 2 mm/min. The experimentally determined mechanical properties were used as input-parameters for the simulation.

Granules of 30 mass% fibres in a polypropylene matrix were produced for each fibre (hemp, flax, sisal and Cordenka®), with a twin screw extruder at the Institute for Bioplastics and Biocomposites at the University of Applied Science and Arts, Hanover (Germany). Furthermore, plates (30 x 16 x 3 mm^3) of each granule were injection moulded in Hanover. The natural fibres were extracted with an organic solvent from the granules and from four plate positions (Figure 5). Therefore circa 1 g of the granules and the injection moulded plate, respectively, were cooked in a bath with the organic solvent in a filter

crucible until the polymer had melted and sucked into a flask. This procedure was done several times until the solvent was clear and only the fibres remained in the filter crucible. Before and after the extraction procedure, the samples were conditioned for at least 24 h at 20 °C and 65 % relative humidity according to DIN EN ISO 139 and the mass was determined to analyze the fibre mass content of the samples.
The extracted fibres and the original regenerated cellulose fibres were prepared on slide frames (40 x 40 mm², glass width 2 mm; Gepe, Zug, Switzerland). The slide frames were scanned with a Canonscan scanner CS 4000 (Canon, New York, USA) with a resolution of 4000 dpi. The original hemp, flax and sisal fibres were scanned with an Epson Perfection V700 Photo scanner (Seiko Epson Cooperation, Japan) with a resolution of 1200 dpi. Before scanning, all samples were conditioned for at least 24 h at 20 °C and 65 % relative humidity according to DIN EN ISO 139. For the analysis of the object length and width, the image analysis software FibreShape 5.1.1 (IST AG, Vilters, Switzerland) was used. Standard long-fibre measuring masks, calibrated at 4000 dpi and 1200 dpi, respectively, with 8 IWTO wool standards, were adapted to each type of fibre. The results of the length and width measurements were used to evaluate the numerical simulation results obtained by M-Base Engineering + Software GmbH (Aachen, Germany) and the University of Madison (USA).

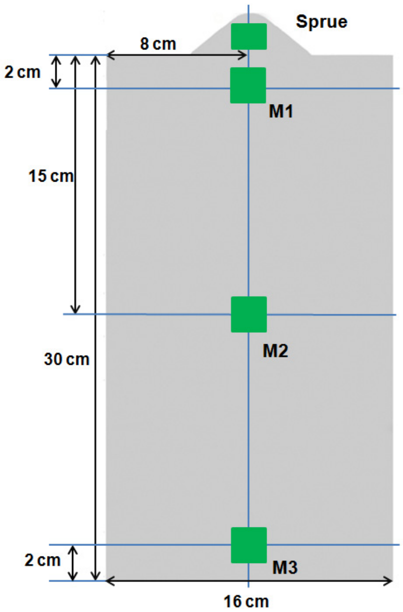

Figure 5. Natural fibres were extracted from four positions (Sprue, M1, M2, and M3) of the injection moulded plates (thickness: 3 mm).

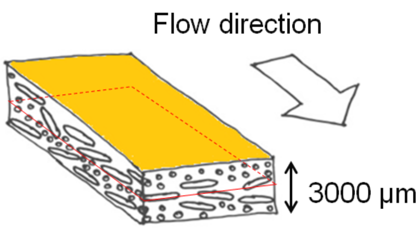

Figure 6. Left: Withdrawal of the microtome sections over the thickness of the plate. The red labelling corresponds with a microtome section at a sample depth of 1500 µm. Right: Exemplarily, microtome section of a sisal fibre-reinforced plate (thickness of the section: 35 µm, length: 7 mm).

To determine the fibre orientation in the injection moulded plates, microtome sections were produced. Therefore samples (7 x 7 x 3 mm³) were taken from the plates at two positions (M2 and M3, Figure 5). At seven defined positions over the thickness of the plate microtome sections (thickness: 35 µm) were taken using a microtome. The seven layers were chosen for the 3000 µm thick plate at the following plate depths: 100 µm, 500 µm, 1000 µm, 1500 µm (red labelling in Figure 6), 2000 µm, 2500 µm and 2900 µm. The fibre orientation was determined via image analysis software FiberScan (by M-Base Engineering + Software GmbH, Aachen, Germany). The experimentally measured orientations were used to validate the results of the injection moulding simulation done by Simcon (Würselen, Germany).
Furthermore, rheological analyses and static & dynamic tests of the NF-reinforced compounds were done by the project partners of the University of Clausthal, Germany (El-Sabbagh et al. 2014) and the Fraunhofer LBF, Darmstadt, Germany (Mönnich, 2013). These data are also essential for the material model, but not further discussed in this paper.

4 RESULTS AND DISCUSSION

The data for the tensile strength and the Young's modulus vary strongly between the different natural fibres. This leads to different breaking behaviours of the fibres. The experimentally determined mechanical properties were integrated in the micro-mechanical model which was developed at the University of Madison (USA) and helped therefore to simulate the breakage of the fibres and to determine the fibre orientation parameter for the injection moulding simulation.

An example of the influence of the compounding and injection moulding process on the fibre / fibre bundle length and width is shown for the sisal fibre bundles in Figure 7. The width and the length of the fibre bundles were decreased significantly during the compounding process, whereas the injection moulding does not seem to damage the fibres much further. A similar behaviour can be observed for the other natural fibres like hemp (data not shown). The regenerated cellulose fibres were only reduced in their length during compounding, while the width was not decreased (data not shown).

During the compounding process the fibre bundles of sisal and hemp were split and broken due to the shear force in the twin screw extruder. Therefore their lengths and widths were decreased significantly. However, during the injection moulding process no further reduction of the fibre size could be observed. Steuernagel et al. (2013) observed during a recycling process of natural fibre-reinforced polypropylene a significant reduction of the fibre width after the first recycling step; whereas no further reduction could be observed in the following three recycling steps.

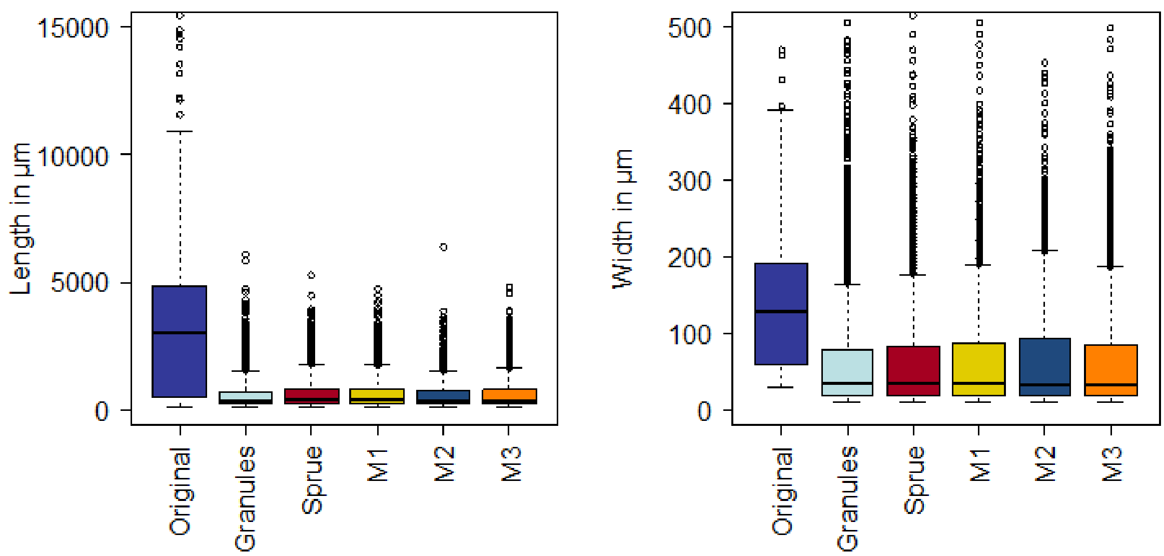

Figure 7. Box-and-whisker plots (whiskers with maximum 1.5 IQR, outliers shown as circles) of the length (left) and width (right) of the sisal fibre bundles, originally and extracted from the granules and the plate.

The regenerated cellulose fibres, which only consist of single fibres, were only reduced in their length; no fibrillation of fibres was observed. Comparable results are presented during a recycling process for glass fibre-reinforced polypropylene by Steuernagel et al. (2013); the width of the glass fibres remained over four recycling steps, whereas the aspect ratio decreased from 40 down to 30.
The length of the sisal fibre bundles was already reduced to such an extent during the compounding, that a further reduction in length could not be measured after the injection moulding process. Within the project NFC-Simulation, the influence of the manufacturing processes on the fibre morphology was simulated in close cooperation with M-Base Engineering + Software GmbH (Aachen, Germany). This simulation based on a mechanistic model, which is clarified further by Baur et al. (2014), showed the same results for short fibres as the experimental analysis (circa 600 µm for sisal fibre bundles and circa 500 µm for hemp fibre bundles; Figure 8). However the simulation also showed that longer fibres (> 2000 µm for sisal fibre bundles and > 1000 µm for hemp fibre bundles; Figure 8) would break during the injection moulding process. The difference in the breaking behaviour between sisal and hemp fibre bundles is due to their differences in Young's modulus, strength and fineness.

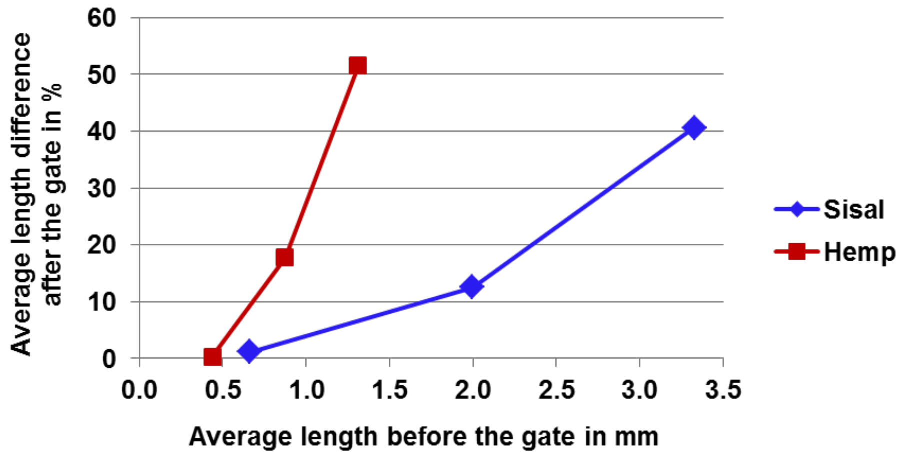

Figure 8. Relative fibre shortening during injection moulding simulated with a mechanistic model.

The analysis of the microtome sections shows that the fibre orientation in the outer layers of the plate is parallel to the flow direction of the polymer melt (Figure 9, right, cutting depths: 2900 µm). Whereas the fibres in the core layer of the plate are less oriented (Figure 9, left, cutting depths: 1500 µm). These results correspond quite well with the injection moulding simulation.

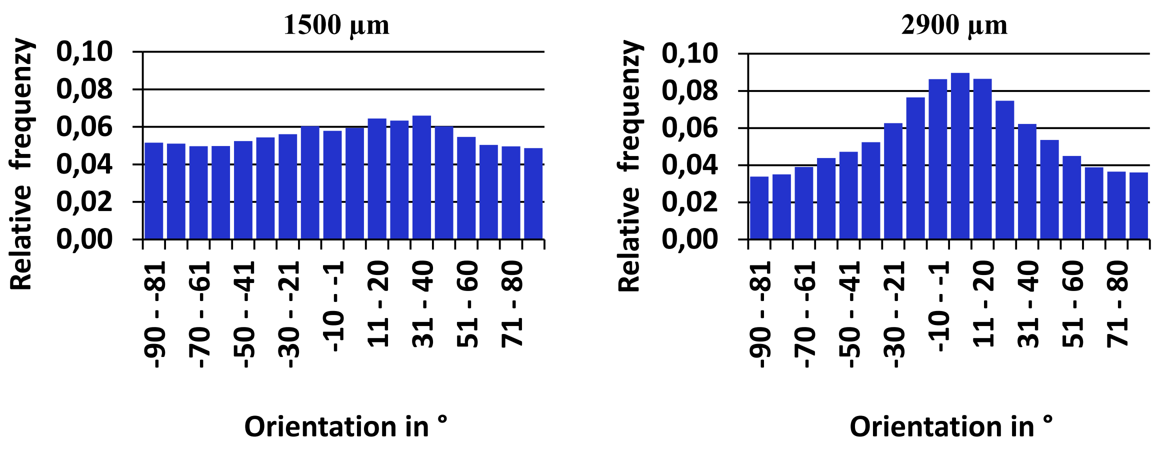

Figure 9. Results of the fibre orientation measurements of the microtome sections of the sisal fibre-reinforced plate at position M2 (Figure 5); exemplarily for two different cutting depths: 1500 µm (core layer) and 2900 µm (outer layer); thickness of the plate: 3000 µm, 0° is equivalent to the flow direction of the injection moulding process.

5 CONCLUSION

The compound of polypropylene and 30 mass% sisal fibres was chosen to run further tests with a crash-relevant component. Therefore glove boxes (Figure 10) were injection moulded at IAC (International Automotive Components, Ebersberg, Germany) to run experimental crash-tests at Ford (Forschungszentrum Aachen GmbH, Aachen, Germany). The injection moulding simulation by Simcon and the simulated crash-test at Ford corresponded very well with the results of the component testing. The first closed development cycle, as illustrated in Figure 4, for a sisal fibre-reinforced component could be realised from the process (injection moulding) simulation, over the component manufacturing & component test to the crash-simulation in the project NFC-Simulation.

The developed material models can now be used by engineers to design components with sisal fibre reinforced polypropylene for lightweight constructions. NFs used as a polymer reinforcement in the automotive industry instead of glass fibres can provide the advantage of reduced carbon footprints (Makarian, 2015): starting with the usage of a renewable resource, following with lightweight car components (lower specific density compared to glass fibres) for reducing the fuel consumption of the vehicle and closing with not leaving a fibre slag after incineration (as glass fibres do). The implementation of material models of NF-reinforced polymers in software programs opens the market for sustainable, biobased compounds in various automotive components.

Figure 10. Injection moulded glove box of sisal fibre-reinforced polypropylene.

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