DEVELOPMENT OF ADVANCED 3D PROCESS SIMULATION FOR CARBON FIBER SHEET MOLDING COMPOUNDS IN AUTOMOTIVE SERIES APPLICATIONS

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Abstract

Carbon Fiber Sheet moulding compounds (CF-SMC) are fiber-reinforced thermosetting semifinished products. Common Glass Fiber Sheet moulding compounds (G-SMCs) are already widely used in automotive applications for roof panels, spoilers and supports. Since the usage of more expensive carbon fibers as reinforcement, process simulation tools to help predict manufacturing and final part properties are gaining significant importance. So far, existing virtual tools are unreliable for predicting important process and part behavior e.g. fiber orientations for CF-SMCs. In this work the Coupled-Eulerian-Lagrangian (CEL) method in Abaqus® will be presented as a new approach for carrying out mold filling simulations. Firstly, a benchmark with previous work using the Arbitrary-Lagrangian-Eulerian (ALE) approach in LS-Dyna® will be performed to show the differences between the two methods. Secondly, a simulation is carried out for a support part of the C-pillar using the CEL method. Results for the filling behavior show a good agreement with experiments.

1. Introduction

Since the introduction of the BMW i3 and i8, it has been proven, that composites can be used for automotive body parts and can be manufactured efficiently in an industrial environment in small to medium series production runs. The next step is to qualify composite parts for big series applications. The first step in this direction has been realized with the new BMW 7 series Carbon core, which successfully combines different composite manufacturing technologies to produce CFRP parts combined with advanced metals in a hybrid body structure. In particular, for the production of geometrically complex three-dimensional parts with medium stiffness and strength requirements, carbon fiber sheet molding compounds (CF-SMC) provide an attractive alternative for the common materials in automotive series applications. In the new BMW 7 series, CF-SMCs were firstly used in parts for the reinforcement of the C-pillar as illustrated in Figure 1.

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Figure 1. Reinforcement of the C-pillar (right side) made of Carbon Fiber Sheet molding compound (CF-SMC) in the body structure of the BMW 7 (G11/G12) series [1].

The key to predicting the flow front behavior and key parameters like tooling forces, is the correct description of the material behavior, which several authors have described as crucial for SMCs including Dumont et al. [2]. To maximize the potential of the technology and to minimize costs involved in finding the right parameter sets to produce parts with high quality, it is necessary to use the support of virtual simulation tools.

In the past a very limited number of tools were developed for compression molding simulation of sheet molding compounds. According to Neitzel [3], earlier on, the only commercial software available was EXPRESS, which uses a 2,5D simulation approach for mold filling. This leads to systematic errors in areas of the part where 3D flow phenomena play a significant role, such as areas with varying part thickness and ribs [4].
First approaches to full 3D simulation of SMC compression molding have come from commercial injection molding simulation software such as Moldex3D® [5] and Moldflow® [6] using the finite volume method (FVM) to solve the governing equations of flow and heat transfer. As shown in [7] there are so far only shear based material models available in these commercial software tools, which cannot predict the material behavior of a compressible, high performance SMC material, which has been used for the C-pillar part shown in Figure 1. Furthermore, the material flow and the fiber orientation calculations are decoupled [8], which is a strong simplification of reality and leads to unreliable results in the case of high fiber volume contents and long reinforcing fibers (25-50 mm). In the presence of fibers, an anisotropic flow can also occur, which is currently not supported in the state-of-the art process simulation software for SMC materials [9].
Other issues are the inability to take the interaction of molding sheets with preimpregnated unidirectional sheets or tapes into account, which requires the modeling of fluid-structure interactions (FSI).
With further hybridization and combinations of different composite manufacturing technologies, more advanced 3D finite-element-simulation solutions are necessary to predict part properties and process parameters.
Promising approaches to deal with the described problems are shown in Schommer [10] and Müller [11]. Schommer uses the FSI-capabilities in LS-Dyna with a macroscopic, isotropic elastic-plastic material model to fit to the material behavior observed in experiments for a CF-SMC material similar to the one used for the C-pillar shown in Figure 1.

The focus of this work is to show a new closed concept for a virtual process chain for CF-SMC which includes the mold filling simulation, data transfer and warpage simulation. As a first step, the Coupled-Eulerian-Lagrangian (CEL) approach of [11] for mold filling is used to carry out a benchmark with the Arbitrary-Lagrangian-Eulerian (ALE) press rheometry model from [10]. This approach is then used for an early stage process simulation model of the C-pillar from Figure 1 and is

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compared to an experimental mold filling scenario. The outputs from the mold filling simulation are used to create a simplified fiber orientation model, which uses the basic principles presented in Tucker and Advani [12]. The fiber orientation information is then transferred from the filling simulation to the warpage simulation.

2. Benchmarking Fluid-Structure-Interaction (FSI) capabilities for mold filling simulations

The results for material characterization using press rheometry and the ALE-method in LS-Dyna are described in detail by Schommer in [10]. The alternative CEL model built in Abaqus/CAE is shown here in Figure 2.

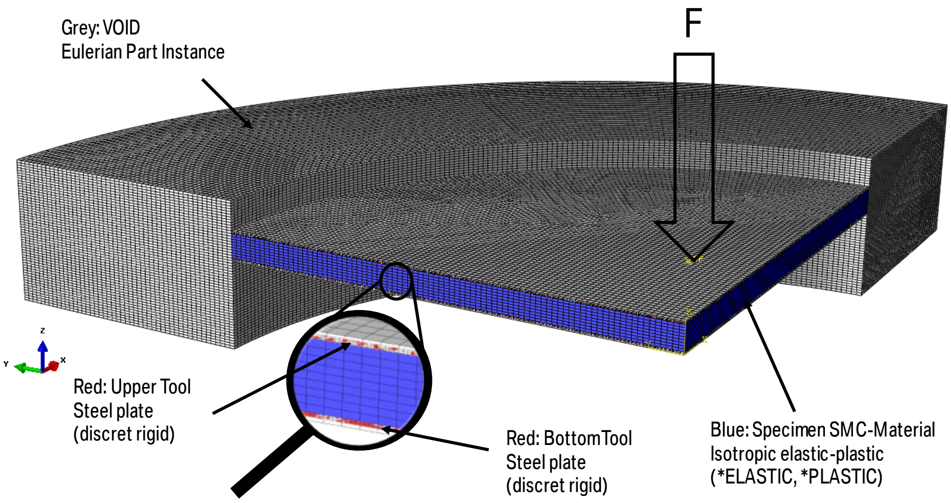

Figure 2. 3D-CEL one quarter model of the press rheometry characterization test setup used by Schommer in [10].

The model consists of four meshed parts (VOID, Upper Tool, Bottom tool and the initial SMC charge). The upper and bottom tool are modelled using a Lagrangian formulation with rigid body constraints. The VOID part represents the whole control volume in which the SMC material is able to move. It is modelled using a fixed mesh geometry with continuum eulerian (EC3D8R) elements. The SMC part represents the initial position of the SMC material and is only used to assign a volume fraction to the eulerian elements of the VOID. The current position of the material is tracked through the eulerian volume fraction (EVF), which can have values between 0 and 1. If an Eulerian element is completely filled the EVF is 1, if it is empty the EVF is 0. The material boundaries are visualized through a surface reconstruction algorithm, which takes the EVF values of neighboring elements into account.

To define the initial position of the SMC a scalar discrete field has been be created containing the Eulerian element-ids with their corresponding EVF values. For this procedure the volume fraction tool in Abaqus/CAE has been used, which uses the SMC-part to set the appropriate values inside each element. To model only a quarter of the press rheometer material characterization test, symmetry boundary conditions have been set. In the case of an Eulerian analysis, velocity boundary conditions perpendicular to the symmetry planes (xz- and yz planes) have to be set.

The results from the simulation compared to a real specimen following pressing are shown in Figure 3. Three deformation states from the beginning to the end are shown. Compared to a real specimen the simulation shows a good agreement. The splitting of the material in the simulation is based on exceeding the maximum plastic strain defined in the strain-stress property definition for the material model and does not represent a real failure model. Another difference is the stronger folding of the real

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specimen in the outer regions of the pressed part. As stated in [10] this might be explained by the fact that the real specimen consists of stacked layers of material, which can separate when leaving the tool because they are no longer under pressure.

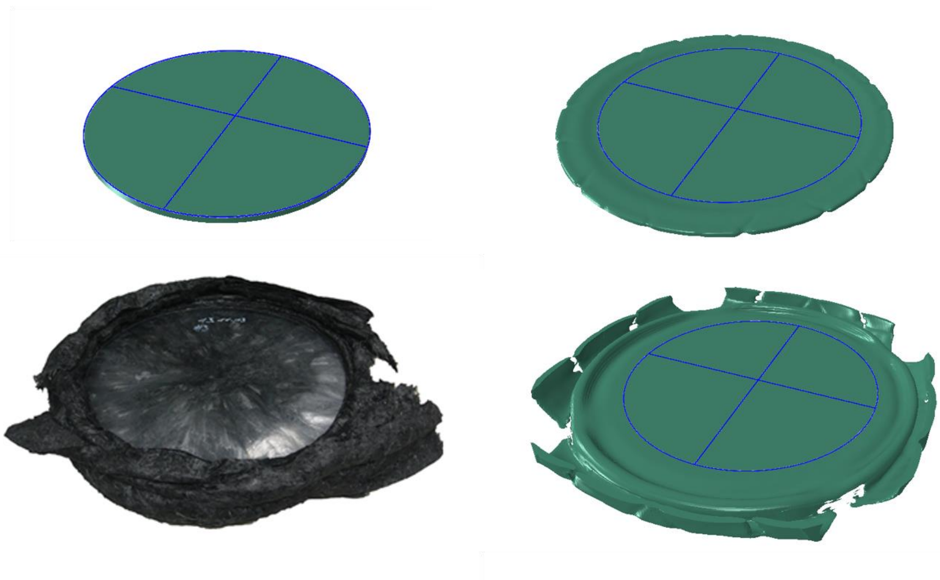

Figure 3. Comparison of simulated compression states and press rheometry characterization experiment for CF-SMC.

In Figure 4, the comparison of the experimental and simulated compression stress versus compaction curves for the CEL model and the ALE model from [10] is shown. In the CEL-model the same data pairs for the definition of plasticity were used as in [10].

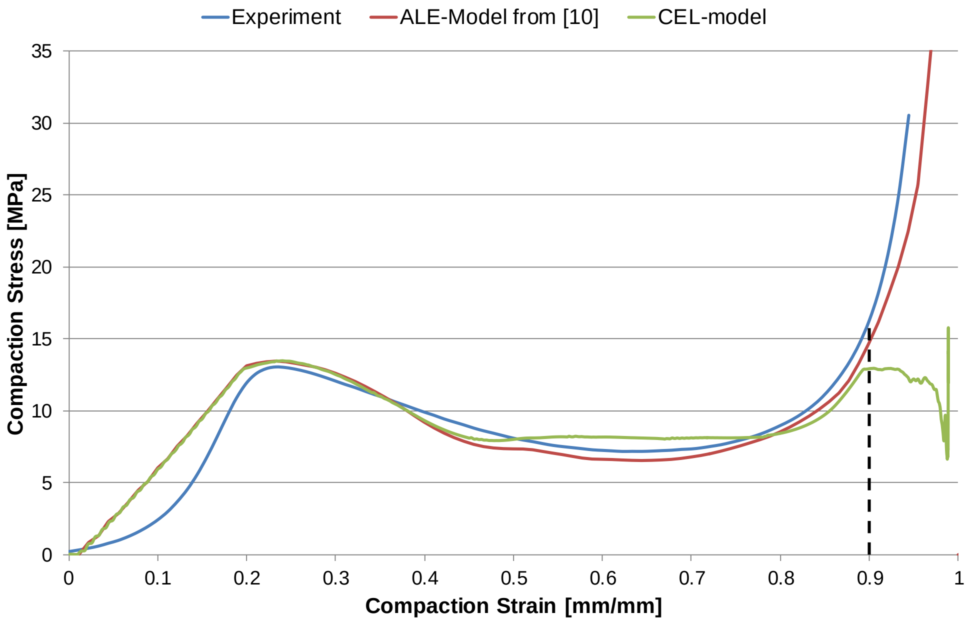

Figure 4. Comparison of experimental and simulated compression stress versus compaction strain curves.

The major difference in the curves of the CEL and ALE-model is the interruption of the increasing stress for the CEL-model at 0.9 level of compaction strain. The reason for this effect is the element size of the Eulerian mesh, which leads to a loss of contact, when the current material thickness is smaller than the eulerian element thickness (here: 1 mm).

In future work the CEL method has been chosen and will be used for the mold filling simulations. The main reason is the more plausible output for the plastic strain tensor, which can be used for a first fiber orientation prediction model similar to the approach of Advani and Tucker [12].

3. C-pillar model for CEL simulation

The material model described in the previous section is used to simulate the filling behavior for an early stage series part of the C-pillar which was shown in Figure 1. The corresponding CEL-model is shown in Figure 5. The Eulerian mesh is not visualized for clarity and details regarding the creation of the Eulerian mesh are not part of this work.
A draped geometry for the SMC-Material is used as a reference geometry to assign the volume fraction to the Eulerian mesh. In the experiment, the real stack was also slightly predraped, to make sure that a complete filling can be achieved.

The results for the filling simulation for the closed tool with the main deformation direction at different locations are shown in Figure 6 a). The deformation distribution is as it would be expected for such a material and geometry. In Figures 6 b) and c) two regions are displayed in more detail to underline the statement above. It can been observed, that at the dipping edge the main direction of deformation rotates and is parallel to the edge at the end. It can be also seen, that at both of the later attachment point position features, the deformation direction points towards the center.
Both these effects can be observed on real part surfaces and are an indication for the main fiber orientation. A validation for fiber orientation on the part in bigger areas will be discussed in a separate publication.

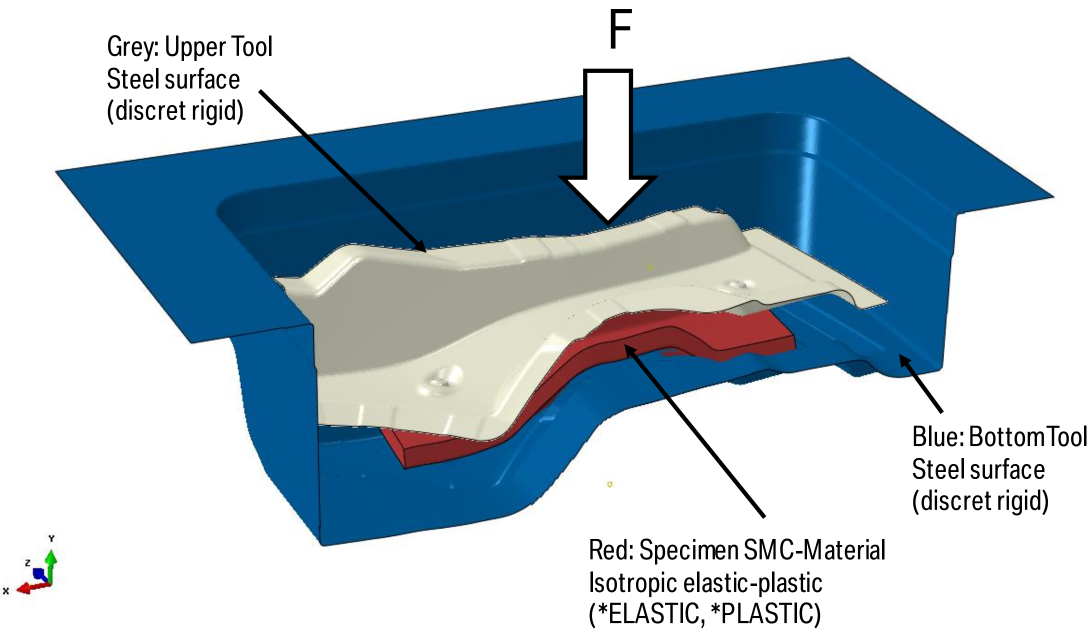

Figure 5. Model for C-pillar with initial position of material (Eulerian Mesh not displayed).

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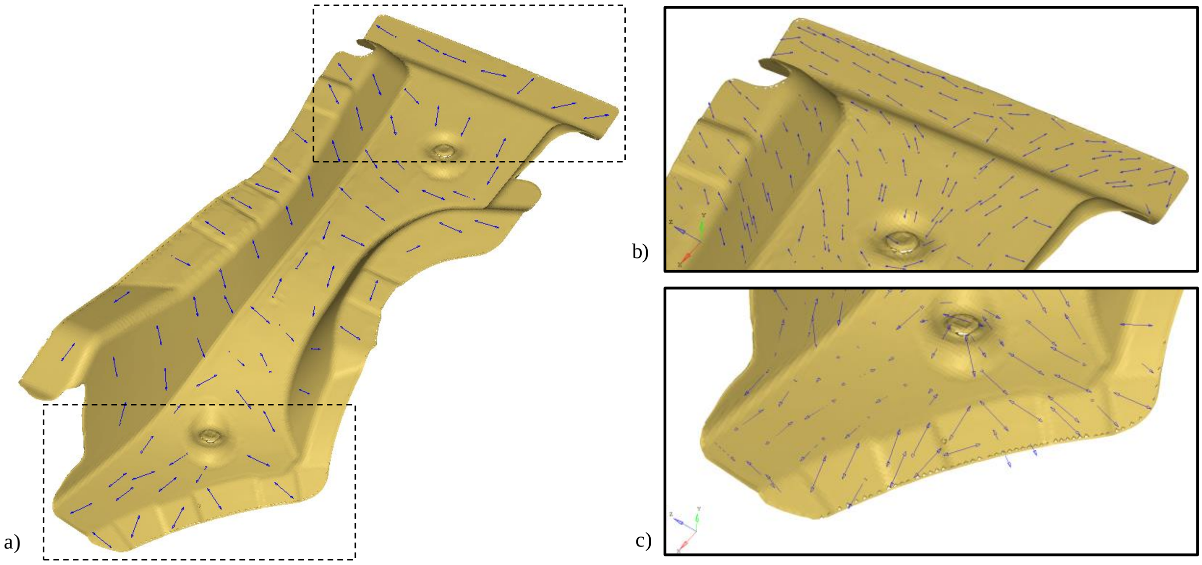


Figure 6. Results from the CEL-simulation of the C-pillar with arrows showing the main deformation.

A comparison for the filling behavior between first experiments and simulation results is shown in Figure 7. It is noticeable, that at position 1 of Figure 7 the flow front in the simulation is faster than for the real part. It can also be seen, that at position 2 the flow front in the experiment is faster than in the simulation. The reason for this difference is the exact stack shape and position for the real tooling and the stack geometry used for material assignment for the Eulerian elements. This leads to differences in the exact position and amount of material in the simulation. As for SMC materials already shown by different authors from [2], the stacking shape and charge location are crucial parameters for predicting the flow behavior and final part properties.

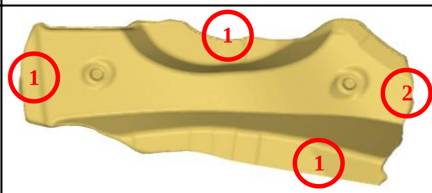
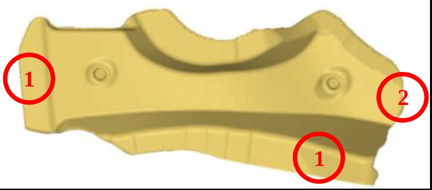
Closing Height	Experiment	Simulation	Closing Height
5 mm			5 mm
3 mm			3 mm
1 mm			1 mm

Figure 7. Comparing first simulation results to experiments at different tool closing heights.

4. Interface and data transfer for warpage simulation

The output for the deformation of the SMC material is used for a first simplified, macroscopic fiber orientation model. Since in the filling simulation only hexahedral elements can be used, a commercial pre-processor is used to map element tensor information from the filling mesh to the warpage mesh. The mapping procedure is necessary, due to different element sizes and the topologies required for both simulations. The results for the mapping are shown in Figure 8. For the warpage simulation a hexahedral mesh is used with a solid section definition.

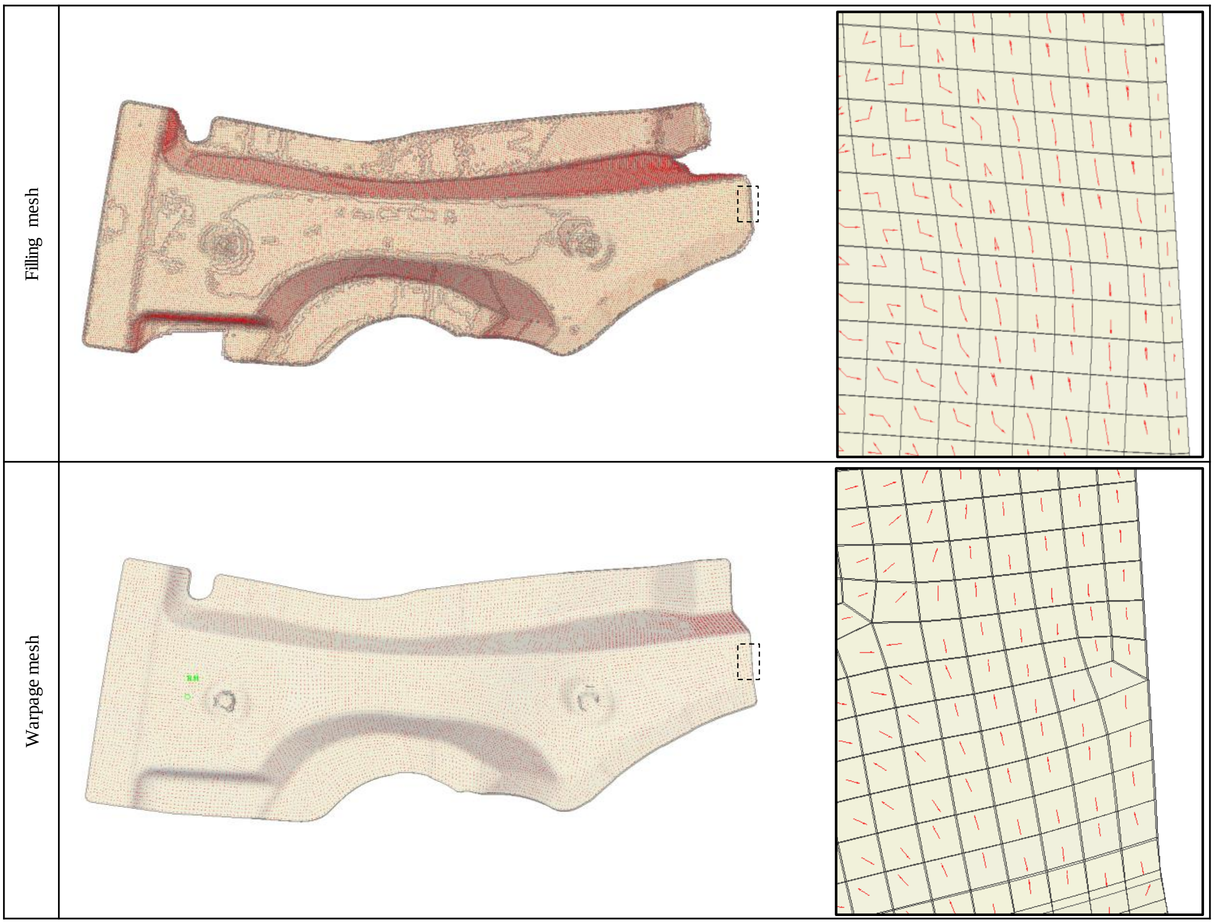


Figure 8. Mapping of the main fiber orientation from the filling mesh to the warpage mesh

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5. Conclusions

In this paper, a new approach for compression mold filling simulations using carbon fiber sheet molding compounds has been shown. First results underline the capability of the CEL-method available in Abaqus for fully 3D applications and potential usage for complex real part simulation. Steps for further improvements include the standardization of the CEL-method, especially to study numerical effects in the simulation and for more accurate material property (temperature and strain rate dependency) assignment. The overall goal is to develop a closed CAE-chain for the filling simulation, data transfer and subsequent warpage simulation. Further work also includes a validation concept and the experimental measurement of fiber orientation distribution via non-destructive eddy current testing of pieces cut from the C-pillar part.

References

[1] BMW Group PresseClub. Retrieved from https://www.press.bmwgroup.com/deutschland/photo/compilation/T0221224DE/die-neue-bmw-7er-reihe (accessed: 28.02.2016).

[2] L. Orgéas, P. J. J. Dumont and L. Nicolais. Sheet Molding Compounds. *Wiley Encyclopedia of Composites*, 1-36, 2012.

[3] M. Neitzel. *Handbuch Verbundwerkstoffe. Werkstoffe, Verarbeitung, Anwendung.* Hanser, 2014.

[4] K. Skrodolies. *Optimisation of the surface quality of sheet moulding compound-parts*. Mainz, 2007.

[5] C.-C. Hsu, H.-S. Chiu, C.-T. Huang and R.-Y. Chang. Through fiber orientation investigation to visualize compression molding. *Proceedings of the 29th International Conference of the Polymer Processing Society PPS-29, Nuremberg, Germany*, July 15-19 2013.

[6] M. Hohberg. Process Simulation of Hybrid SMC Structures with Local Continuous Fiber Reinforcements. *Proceedings of the 6. CONNECT! European Moldflow® User Meeting, Frankfurt, Germany*, June 23-24 2015.

[7] T. Böhlke, L. Kärger, K. A. Weidenmann, T. Seelig, and F. Henning. Integrated engineering of continuous-discontinuous long fiber reinforced polymer (CoDiCoFRP) structures in the framework of the International Research Training Group GRK 2078. *Proceedings of the 5th Composite Simulation Congress FCS-5, Hamburg, Germany*, February 24-25 2016.

[8] M. Piry. *Mechanical dimensioning of SMC-components and characterization of the relevant material properties*. Mainz, 2004.

[9] A. Radtke. *Steifigkeitsberechnung von diskontinuierlich faserverstärkten Thermoplasten auf der Basis von Faserorientierungs- und Faserlängenverteilungen*. Fraunhofer IRB, 2008.

[10] D. Schommer, M. Duhovic, F. Gortner and M. Maier. Advanced Simulation of Polymer Composite SMC Compression Molding using Fluid-Structure Interaction in LS-Dyna®. *Proceedings of the 13th International LS-DYNA® Users Conference, Detroit, USA*, June 8-10 2014.

[11] T. Müller and F. Henning. Simulation of combined forming and injection molding processes. *Proceedings of the 2015 Simulia Community Conference, Berlin, Germany*, May 18-21 2015.

[12] S. G. Advani and C. L. Tucker III. The Use of Tensors to Describe and Predict Fiber Orientation in Short Fiber Composites. *Journal of Rheology*, 31: 751-784, 1987.

Excerpt from ISBN 978-3-00-053387-7