Advanced Simulation of Polymer Composite SMC Compression Molding using Fluid-Structure Interaction in LS-DYNA®

Dominic Schommer; Miro Duhovic; Florian Gortner; Martin Maier
Institut für Verbundwerkstoffe GmbH, Erwin-Schrödinger-Str., Building 58
67663 Kaiserslautern, Germany

Abstract

Thermoset Sheet Molding Compounds (SMC) are becoming more and more popular as lightweight construction materials in the automotive industry. SMC compression molding is a forming process in which a pre-cut SMC-Prepreg is placed within a heated mold and is first pressed into shape before being cured. The flow behavior of the SMCs can be characterized by press rheometry. In a typical press rheometry test, certain data are recorded during the test, specifically press force, tool closing speed, position and time together with the known tooling geometry (plate surface area), are used to develop and verify a finite element characterization model in LS-DYNA using the relevant Arbitrary Lagrange Eulerian (ALE) capable material model. In this work, the Fluid Structure Interaction (FSI) capabilities in LS- DYNA are used to model the flow ability of the SMC material. No independent effects of the resin cure on the materials rheology are taken into consideration. As an example for forming a complex real part, the compression molding of a ribbed automotive spoiler test part is analyzed upon complete closing of the mold.

1-Introduction

Compression molding structural/sheet molding compound (SMC) material is the most common process for large scale production of fiber reinforced plastic parts, especially in the automotive industry. With the right material and process parameters, parts can be produced with the intricate geometries seen in an injection molding or pure bulk molding compound (BMC) forming process including thin walled ribs, bosses and other protrusions while also containing continuous reinforcements in the main structural areas of the part. The simulation of such a process requires the modeling of fluid-structure interactions where the flow of the SMC material affects the movement and resulting orientation of the fiber reinforcement and in turn the fiber reinforcement affects the flow paths and resulting fiber orientations of the SMC material. The complex material behavior of the SMC-Material has been analyzed by several researchers including Dumont et al. [1]. Schmachtenberg and Skrodolies also made some experimental analysis of the flow behavior of compression molding compounds in order to calculate the viscosity of the material [4]. With an experimental visualization of the flow during mold closure in compression, Odenberger et al. analyzed the flow front behavior of the SMC-material [5].
The focus of this work is the development of a finite element analysis simulation technique to allow the prediction of the key elements of such a molding processes. As a first step, the processing characterization of SMC material consisting of long carbon fiber reinforcement at various processing parameters has been carried out. The material characterization tests were performed on the press rheometer equipment developed and designed at IVW GmbH at different temperatures and different tool closing speeds. The press rheometry data recorded during testing (more specifically press force, tool closing position together with the tooling geometry and press setup) are all used to develop and verify a finite element characterization model, whereby the

exact material characterization test carried out on the press rheometer is simulated. The model of the actual press rheometer test was developed in the finite element software LS-DYNA using its fluid structure interaction capabilities. The characterization data obtained from the press rheometry tests is then used to calibrate the material model so that it can then be used to predict the mold filling of more complex tooling scenarios.

The complex tooling used within the scope of this work consists of a non-confidential in-house tooling of a rear automotive spoiler (herein referred to as the “IVW tooling”) used in the past to compression mold short fiber reinforced thermoplastic melt materials [6]. The component has a very intricate thin rib feature which is usually difficult to form.

All the pressing trials that were carried out herein were performed using the 800 tonnes Dieffenbacher press equipment available at IVW GmbH. A fixed number of tests involving both short and full shots, where the mold is partially closed to different heights larger than the final part thickness were also performed to provide further verification in terms of the filling behavior for the finite element simulations.

2-Material Characterization using Press Rheometry

To characterize the material behavior press rheometry measurements of a long carbon fiber based SMC material was carried out at different tooling temperatures and closing speeds. As shown in Figure 1, the material was first cut into circular shaped specimens with a diameter of 350 mm and stacked for pressing between two flat circular plates mounted on the press. The diameter of the used pressing plates is 344 mm and both the top and bottom plates could be heated by oil to the desired tooling temperature. Due to the known constant pressing area, the pressing force could then be used to calculate a compression stress and a compaction in thickness direction of the stack.

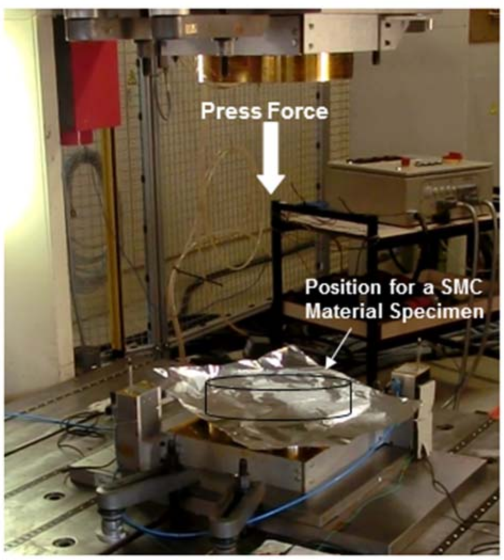

Figure 1 Long fiber SMC press rheometry testing experimental set-up at IVW GmbH

Figure 2 shows the typical compression stress versus compaction curve for the SMC material being investigated. The curve is characterized by an initial parabolic region which is believed to represent the initial compaction of the stacked fibrous material. During this phase of the pressing no real material flow is expected to take place and the material simply compresses in the thickness direction without any significant lateral expansion, expelling the air trapped within the fiber network. At some point, a peak stress is reached after which the material then begins to rapidly flow in the in-plane direction exhibiting also a drop in the pressing force. Following this phase, the stress once again increases exponentially upward.

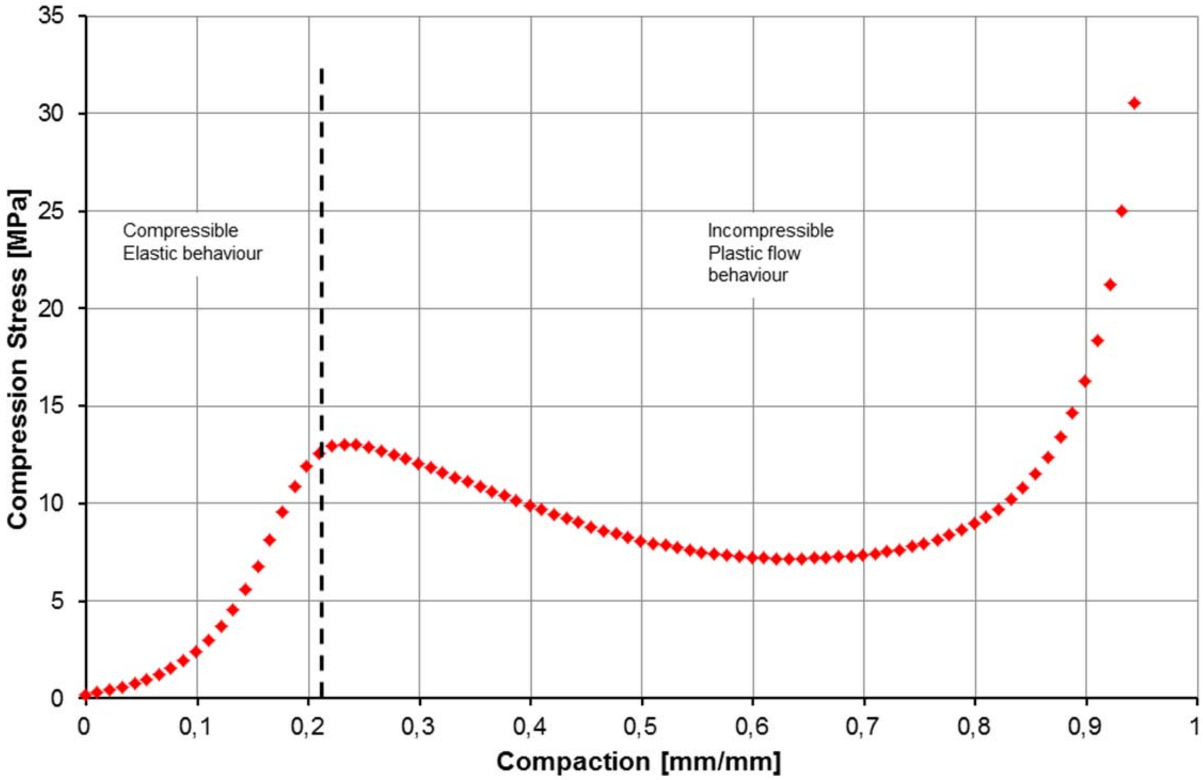

Figure 2 Typical compression stress versus compaction for measured SMC material

A further validation of the explanation given for the phenomena causing the shape of the pressing curve was given by observing several frames of a video recording of the pressing. Here 16 layers of the material were used instead of the usual 8 to amplify the effects described previously and to make visualization of the pressing process possible.
It was physically observed that only compaction took place without any lateral expansion as the material decreases in height and volume. The onset of flow was then seen on the top and bottom layers of the material stack where the onset of an in-plane flow became readily apparent.

3-Press Rheometry Finite Element Model

Following on from the initial experimental procedures of material characterization, a finite element model of the press rheometry experiment was set-up using the fluid structure interaction (FSI) capabilities of the FEA software code LS-DYNA. This part of the work involved the development and verification of a press rheometer finite element characterization model, whereby the exact material characterization test carried out on the press rheometer was simulated. The press rheometer tool plates show a perfect symmetry, so it is possible to model only a quarter of the actual geometry.

As shown in Figure 3, the correct flow behavior of the SMC material is modelled by using an Arbitrary-Lagrangian-Eulerian (ALE) formulation. The specimen and the surrounding air are combined to an ALE_Multi-Material_Group (AMMG). The air represents the space in which the SMC material is supposed to flow and is modelled using fixed mesh geometry. Only the upper tool plate is built up as an existing rigid body part which moves and interacts with the fluid. The constraint of the bottom tool surface is implemented using an Ale_Essential_Boundary condition. The interaction between the Lagrangian part the "upper tool" and the ALE-part the SMC "specimen" is defined by a lagrange_in_solid constraint.

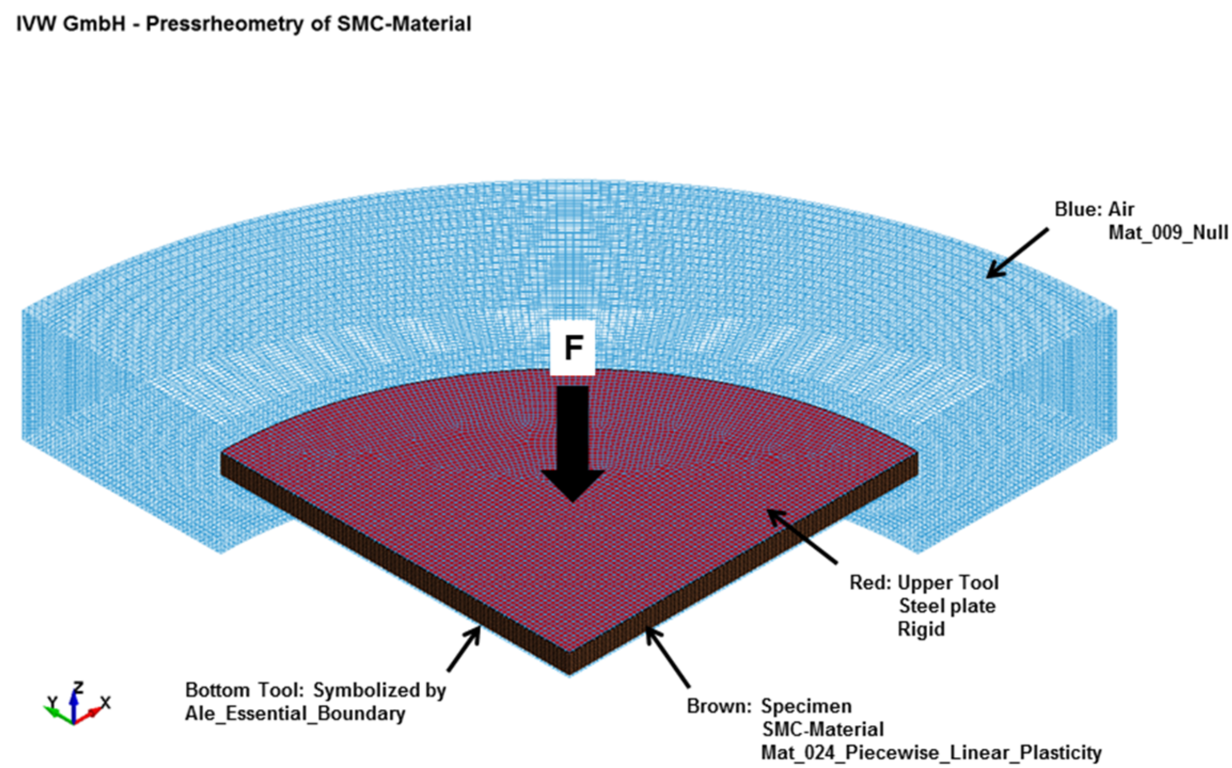

Figure 3 ALE-Formulation of the press rheometry characterization test setup in LS-DYNA

Several of the existing material models available in LS-DYNA were trialed including various foam models as well as available temperature and strain rate dependent material models. Many of these could not properly reproduce the observed behavior of the material, in particular the drop in pressure (or stiffness) once the material completes the compression phase and begins to flow laterally. The material model which allowed the best representation of the observed behavior was the piecewise linear elastic plastic material model MAT_024 available in LS-DYNA.The characterization of the mechanical behaviour in this material model is based directly on the experimental stress-strain curve.

As shown in Figure 2, the experimental curve can be split into two regions where the material first shows a compressible elastic behaviour and then a second region where incompressible plastic flow of the material dominates.

In Mat_024 the first compressible elastic part is simplified as a linear elastic behaviour defined by an elastic modulus. The full compressibility of the material is achieved by assigning a Poisson's ratio of 0.

The plastic behaviour is then defined as an effective stress versus effective plastic strain curve given by a maximum of eight points. The strain rate dependency of the material can be added in the future in the form of a Cowper-Symonds scale factor that scales the yield stress dependent on the strain rate. The experimental curve for the press rheometry gives the compaction of the material in the thickness direction of the SMC stack (z-direction). The effective plastic strain can be calculated using the plastic strain in z-direction from the experiment and the Von Mises-criterion, as follows:

$$\varepsilon_{eff}=\sqrt{(\varepsilon_x-\varepsilon_y)^2+(\varepsilon_x-\varepsilon_z)^2+(\varepsilon_y-\varepsilon_z)^2}$$

Because the plastic flow of the material is incompressible and the shape of the press rheometry specimen is circular, the strains in the x- and y-direction follow:

$$\varepsilon_x=\varepsilon_y=-\frac{1}{2}\varepsilon_z$$

This gives: $\varepsilon_{eff}=\frac{3}{\sqrt{2}}\varepsilon_z$

It must be remembered that the simulation does not take into account some effects from the experiment, such as the curing of the resin. Another point is that in the plastic part of the material behavior, the material flows out of the tool. Therefore the theory does not consider the decreasing of mass between the tool plates. Material outside the tool is able to move freely and experiences a much lower stress than the material inside the tool.

To take these missing effects into account and to achieve better simulated flow behaviour of the material, it is necessary to perform a short fitting process which fits the effective stress of the plasticity curve closer to the real behaviour. The resulting input-curve of this fitting process is shown in Figure 4.

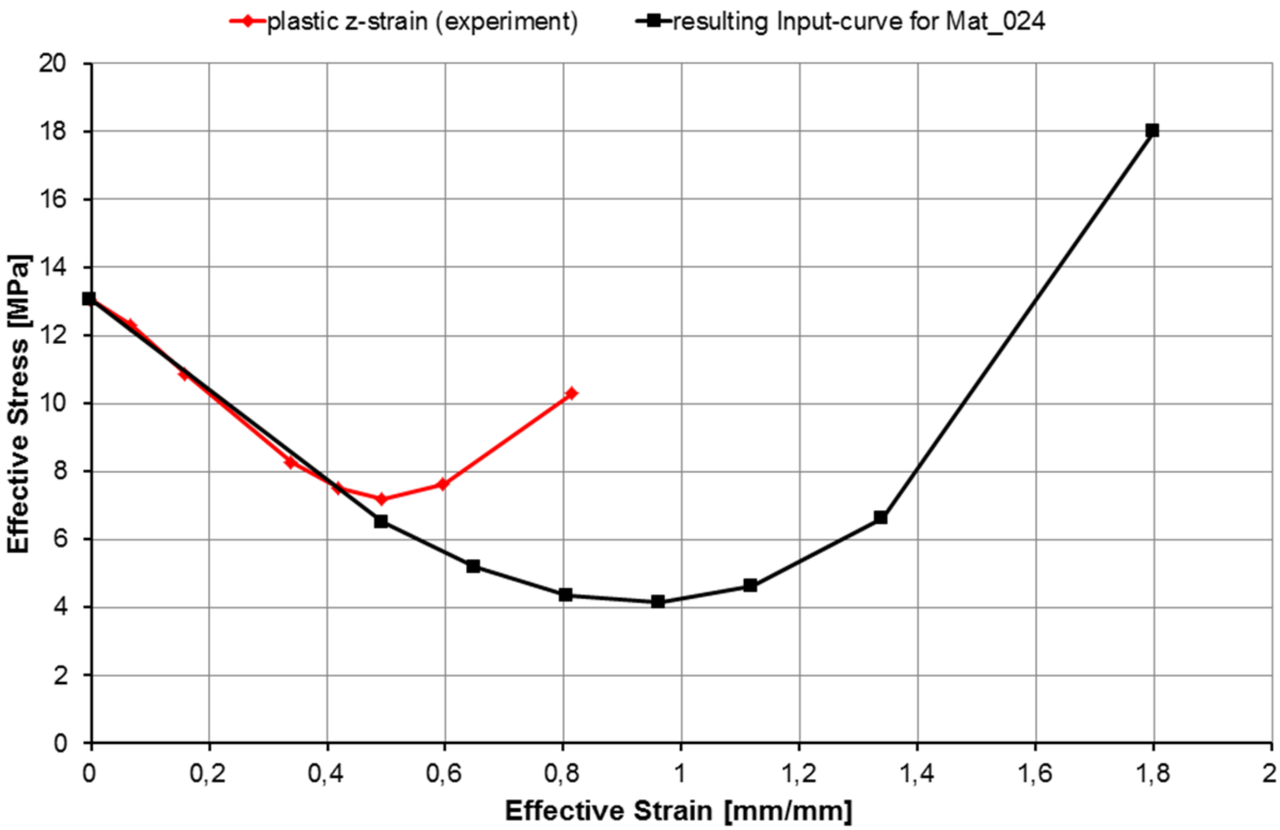

Figure 4 Resulting input curve for Mat_024 plastic stress- strain compared to the experimental data

By using the described input data, the simulation shows a very good compression stress versus compaction curve inside the standard deviation of those experimentally measured as shown in Figure 5.

Just as important as the stress strain curves which aim to predict the press forces necessary for the molding procedure is the actual deformation and flow of the material. Figure 6 shows the initial, intermediate and final simulated deformation states of the SMC material. Compared to a real specimen it showed a good visual agreement of deformation in the final state. A small difference appeared in the outer part of the specimen where in the real specimen spreading occurred and was not reproduced in the simulation model. This can be explained by the fact that the simulated geometry model is not built up as a multi-layer material. The real specimen is comprised of a stack of 8 individual layers which can spread when leaving the tool and are no longer under pressure. For future work it is also possible to use the AMMG formulation to realize a multi-layered model.

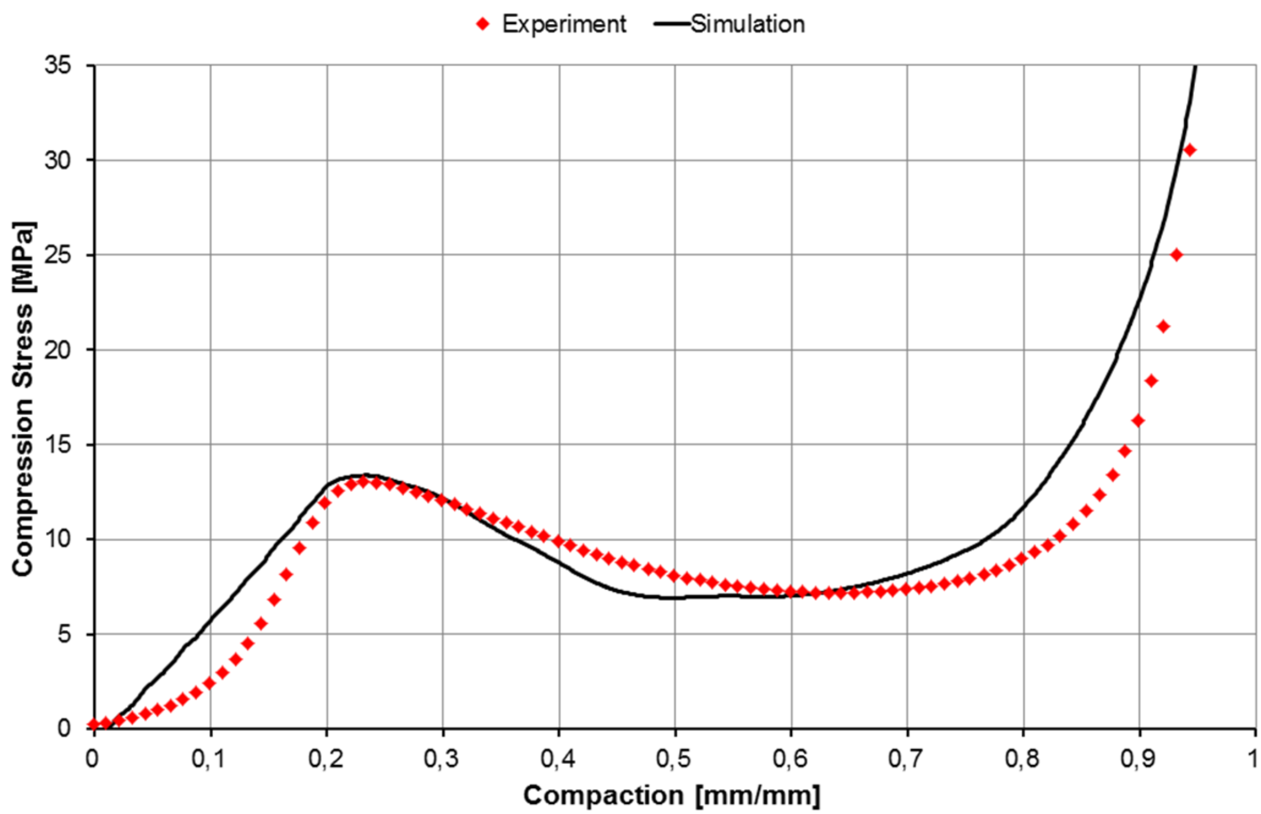

Figure 5 Comparison of experimental and simulated compression stress versus compaction curves

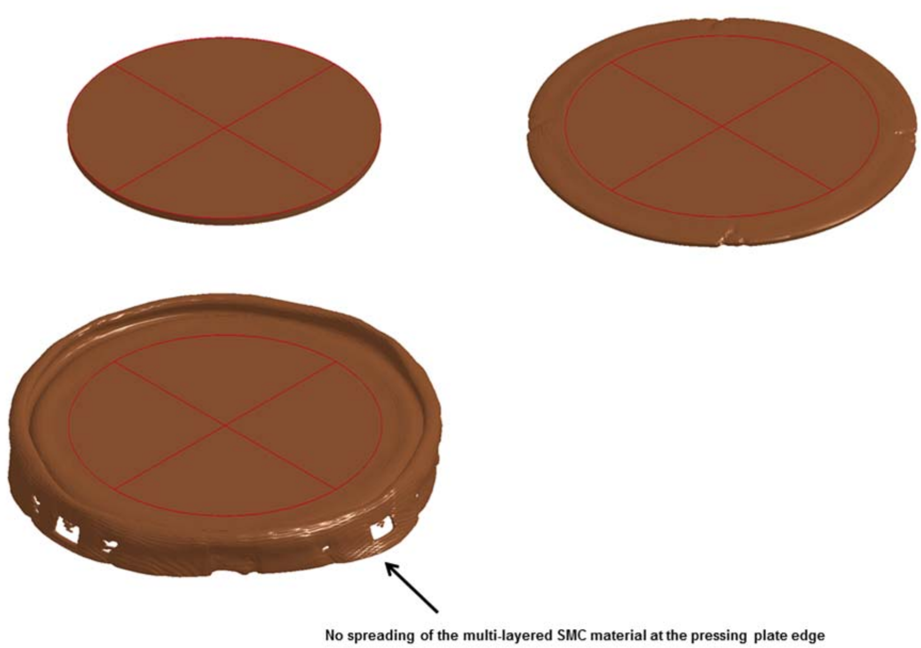

Figure 6 Simulated and actual press rheometry SMC material combined compression and flow deformation

4-IVW Automotive Spoiler Test Tooling

Following validation using the press rheometry simulation, real part geometry can be trialed and ultimately virtual parts may be manufactured to help predict problems before any expensive real tooling is made. The part chosen for investigation is an automotive spoiler test part containing a thin stiffening rib feature along its center, an attribute that is usually desired in typical automotive parts but difficult to form with long fiber reinforced SMC materials.
The SMC charge placement before pressing and the experimentally fully molded part are shown in Figure 7 respectively.

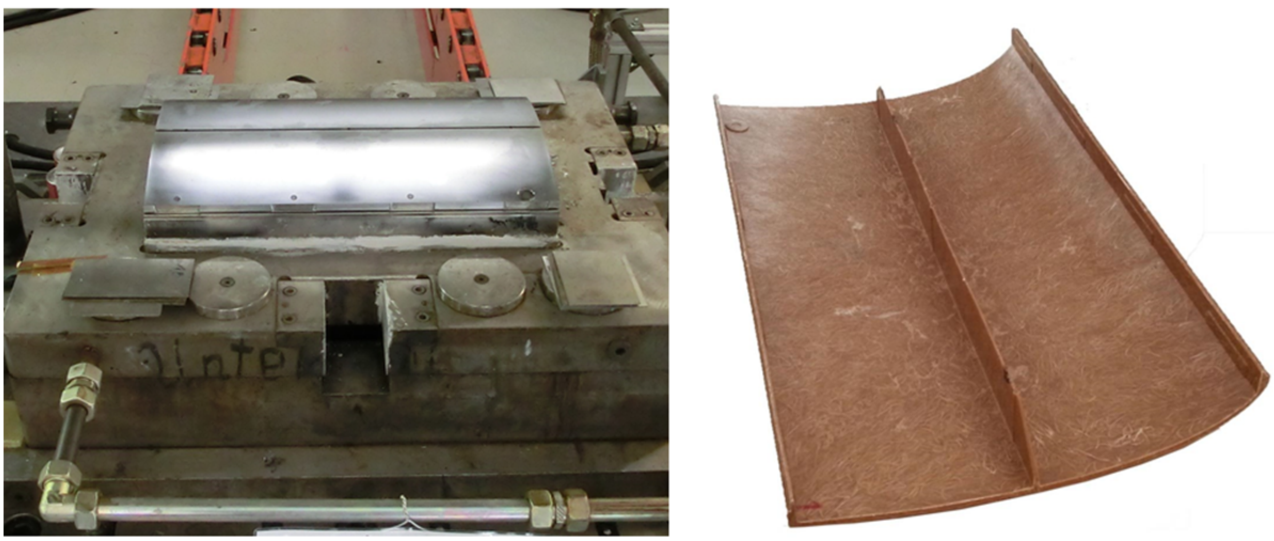

Figure 7 Institut für Verbundwerkstoffe GmbH SMC compression molded automotive spoiler

Figure 8 shows the two dimensional model which was firstly developed in order to setup the same physical functions as present in the real press equipment and to study more quickly the flow into the rib region. Like the press, the model works on a prescribed motion control and a sensor then monitors the load in the pressing direction. Once the desired load is reached, the motion control is switched off and a load control applies a defined loading boundary condition to the tooling and therefore the material.

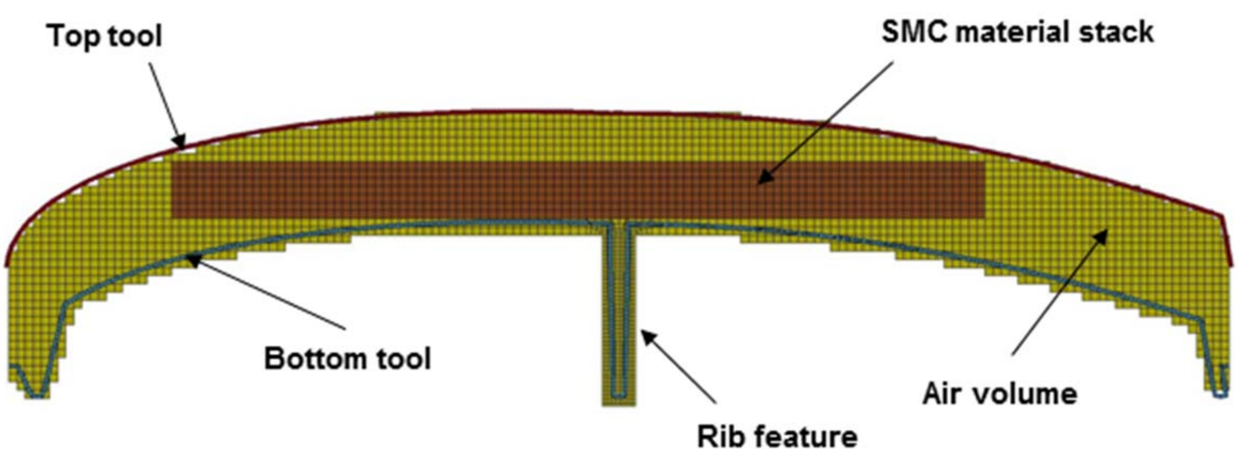

Figure 8 Two dimensional SMC compression spoiler tool model developed in LS-DYNA

In this model a 2 mm solid element mesh has been used and it can be seen that a finer 1 mm mesh has been created in the rib region, ensuring at least two elements across the width of the rib feature.
Several animation states showing the stages of pressing from the developed simplified model are shown in Figure 9. As it is shown in Chapter 2, the material again is compressed first before any lateral flow begins.

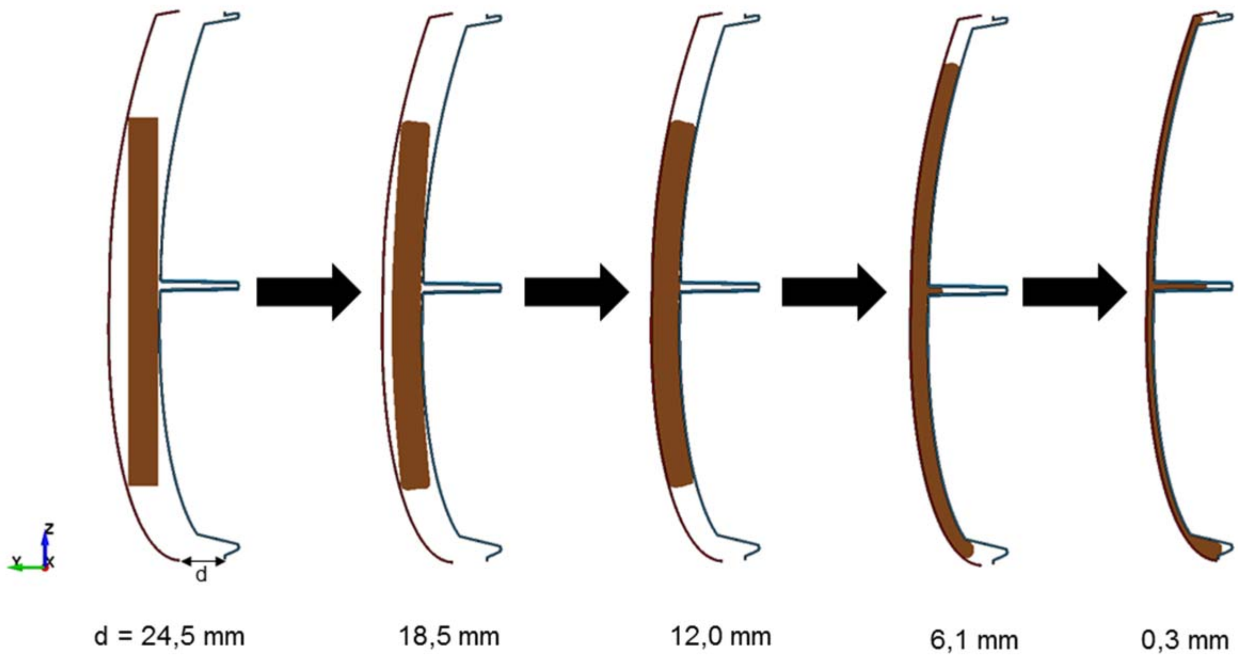

Figure 9 Animation states showing the various stages of SMC compression and flow in the two-dimensional automotive spoiler model.

Using the material properties calibrated in the press rheometry model, it was observed that in the simulation complete filling was not predicted as in the real situation. Especially the outer details in the rib are not completely filled. In the case of the outer details, one reason for this can be that the ALE-mesh is not fine enough to allow the material to flow completely into these regions. As was shown in Figure 8, the mesh in the rib region is a finer mesh with a 1 mm element size. Therefore, this is unlikely to be the reason why the rib is not filled. Another possible reason could be that the fiber volume content in the rib region is reduced or the resulting fiber orientation changes to support the flow ability in the real case. At the moment the composite material is modelled as a single material, so changings in the fiber volume content or any information about the fiber orientation are not considered in the simulation. To confirm this assumption experimental analysis of the fiber distribution inside the part is necessary.

5-Conclusions

In this paper, the first steps towards the simulation of the real flow behavior of an SMC material have been shown. By using the ALE capabilities of LS-DYNA and an elastic-plastic material model, it is possible to reflect the right behavior in a characterization model. However, by looking at a simulation of the compression molding of a real part, it can be seen that the filling of a cavity is not as complete as occurs in the real forming process. The current simulation represents a simplified flow model of an SMC material that has no inputs for additional real effects occurring inside the material. A goal for future work is to implement data for fiber volume content, distribution and orientation along with chemical curing of the resin. This should make it also possible to design new material that can be produced in a low cost way and that can be processed on standard equipment.

References

[1] *P.Dumont;L.Orgéas; S.LeCorre; D. Favier:* "Anisotropic viscous behavior of sheet molding compounds (SMC)during compression molding", International Journal of Plasticity 19 (2003), p. 625-646.

[2] *P.Dumont;L.Orgéas; D. Favier; P. Pizette; C. Venet:* "Compression molding of SMC: In situ experiments, modelling and simulation", Composites: Part A 38 (2007), p. 353-368.

[3] *O. Guiraud; P.Dumont; L.Orgéas; D. Favier:* "Rheometry of compression moulded fibre-reinforced polymer composites: Rheology, compressibility, and friction forces with mould surfaces", Composites: Part A 43 (2012), p. 2107-2119.

[4] *E. Schmachtenberg; K. Skrodolies*: "Improved measurement and modelling of the fluidity of compression moulding compounds", Institute of Plastics Processing, RWTH Aachen University, 2006, Aachen, Germany.

[5] *P.T. Odenberger; H.M. Andersson; T.S. Lundström*: „Experimental flow-front visualisation in compression moulding of SMC", Composites: Part A 35 (2004), p. 1125-1134.

[6] *K. Edelmann*: "Prozeßintegrierte Analyse des Fließverhaltens von faserverstärkten thermoplastischen Preßmassen für die Serienfertigung", IVW Schriftenreihe Band 18, 2001, Kaiserslautern, Germany.