# Simulating the hot press processing of structural thermoplastic foams

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**Abstract.** Thermoplastic foams allow the manufacture of lightweight parts with good thermal and acoustic insulation properties, particularly suited for aircraft interior and cabins structures. Such foams can be combined with skin layers of organic sheet materials (e.g. glass fiber (GF) polycarbonate (PC)) forming sandwich structures, enhancing the mechanical properties, but which unfortunately do not fulfil strict FST (Fire, Smoke and Toxicity) standards. An alternative approach uses the foam itself to create an integrated sandwich structure of an unmodified core and two skins of high density from the same material. In this work, structural foams were manufactured using a closed-cell polyethersulfone (PES) foam. The thermoplastic foam was transformed into structural foams using a newly developed hot press process, which does not change the part weight. A shell element-based model was developed that allows the simulation of the hot press process for thermoplastic foams under non-isothermal conditions using LS-DYNA® standard material models. The objective of the simulation model was to predict the final foam thickness resulting from the hot press process which can be subsequently used to perform mechanical property (bending stiffness) calculations. Material characterization tests were conducted at room temperature (23°C) and six elevated temperatures (215°C, 222°C, 225°C, 230°C, 235°C, 240°C,) close to the glass transition temperature of PES ($T_g$ = 222°C). The final model was evaluated simulating the force-controlled, non-isothermal hot press process. Two different processing conditions were simulated using a target pressing force of 500 N or 1000 N and a temperature of 230°C. The results of the simulations show that the usage of this shell model approach is a viable option to simulate the temperature dependent compression of foams using standard LS-DYNA® material models. Further accuracy in the prediction of the final foam thickness resulting from the force-controlled hot pressing process can be achieved by incorporating more details regarding the process control into the simulation model.

## 1 Introduction

Addressing global issues like lowering energy use and $CO_2$ emissions necessitates the creation of sustainable lightweight structures and components for automobile and public transport uses. Materials used in public transport vehicle construction must adhere to fire safety standards [1] [2]. Despite recycling options like mechanical recycling and repurposing as filler material for end-of-life parts made from thermoset polymers, these methods typically result in a degradation of the material properties. However, composites made from thermoplastic polymers facilitate a circular economy and the reduction of waste at the end of the product lifecycle, without any significant degradation of the polymer. Thermoplastic polymers offer various benefits such as semi-finished products with an indefinite shelf life and a short manufacturing cycle. Efficient continuous compression molding techniques can be employed to produce flat semi-finished thermoplastic parts, which can be then molded into the final part geometry through short-cycle thermoforming processes.

Polymer foams are cellular materials with a 3D structure, which may be open or closed cell, and can be manufactured to relative densities as low as 3% of the polymer density. These foams are superior engineering materials in terms of thermal and acoustic insulation, but their mechanical properties tend to be low due to their reduced densities. Structural foams, which have a sandwich-like structure with a low-density foam core and high-density polymer skin, can attain higher stiffness than uniform density foams at the same overall density due to the density gradient across the part thickness. This also allows them to achieve the same stiffness as solid materials at lower weights. Current methods for manufacturing structural foams involve either chemical or physical foaming techniques in injection molding processes and are utilized to fabricate the final part geometries.

Polyethersulfone (PES) is one of a family of high performance thermoplastics particularly well suited for structural parts in public transport vehicles due to their intrinsic flame retardant capabilities and excellent thermal stability. In this work, a novel hot press manufacturing process has been developed to allow the transformation of commercially available PES thermoplastic, semi-finished foams into structural foam

sheets under isothermal and isochoric process conditions. In addition, a simplistic shell-element simulation approach to model this process has been developed, allowing for an estimation of final foam skin and core morphology resulting from the hot press process. The simulation results can subsequently be used to perform mechanical property (e.g. bending stiffness) calculations. In the following sections, the hot press process, the necessary material characterization tests, model calibration and the final simulation of the hot press process for the PES foam Divinycell F50 are described.

## 2 Manufacturing of structural foams

State of the art manufacturing for structural foams usually deploys chemical or physical foaming in injection molding processes. The novel hot press process that is simulated in this work, transforms commercially available thermoplastic foams into structural foams by applying heat and pressure in two consecutive processing steps. A schematic of the process is shown in Fig. 1 [3].

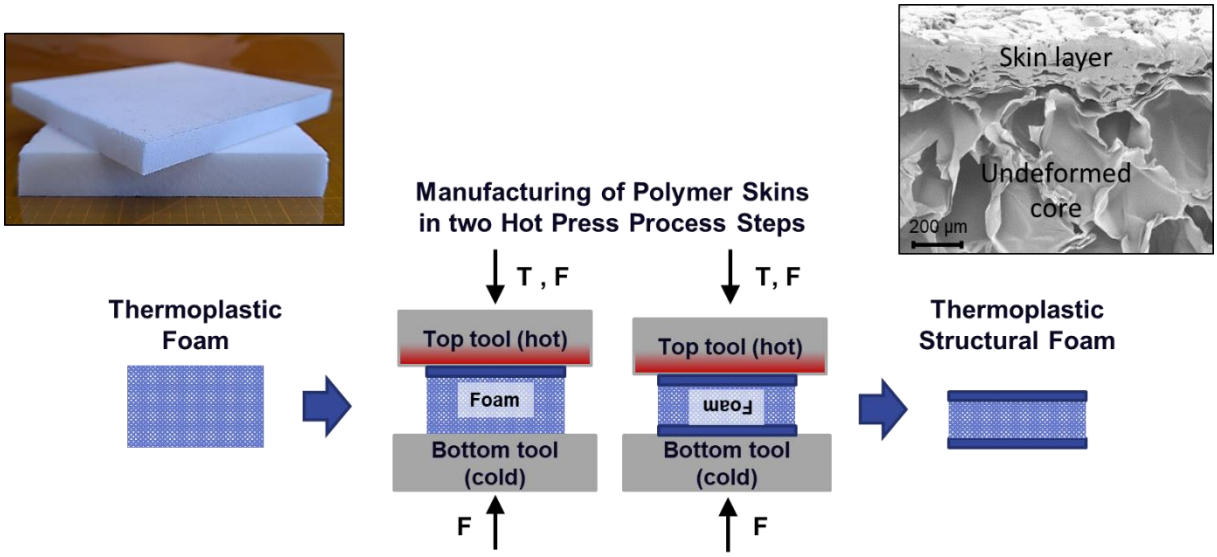


*Fig. 1: Foam material as it enters the process (top left), schematic of the two-step hot press process used to create thermoplastic structural foam (middle), scanning electron microscopy (SEM) image of a foam specimen after the hot press process (top right) [3].*

First, the thermoplastic foam is placed in the press and the top tool is heated to a target temperature typically above the glass transition temperature ($T_g$) of the foam. Subsequently, the upper tool applies a defined force profile on the foam, which causes the cells in the top area of the foam to compress into a polymeric skin while reducing the overall thickness. The foam is then turned around and the process is repeated, resulting in a sandwich-like structure with a high-density skin layer on the top and bottom enclosing a low-density foam core in the middle.

Modeling this process is challenging due to the large temperature difference in the foam from room temperature to above glass transition temperature leading to a steep decline in stiffness. Furthermore the deformation of the foam causes a densification of the material leading to changes in thermal conductivity. In the following sections, a simplified modelling approach for this hot press process is presented.

## 3 Characterization of physical and mechanical properties

The most important physical properties of the Divinycell F50 foam are summarized in Table 1:

| Material | Polymer | Cell structure | Density (kg/m³) | Initial thickness (mm) | Glass transition temperature (Tg) |
|---|---|---|---|---|---|
| Divinycell F50 | Polyethersulfone (PES) | Closed | 50 | 5 | 222°C |

*Table 1: Most important physical properties of the characterized foam material Divinycell F50.*

The compression properties were characterized over a wide temperature range from room temperature (23°C) to process temperature (approx. 230 - 240 °C). For this purpose, quasi-static compaction tests were performed on the thermoplastic foams using a NETZSCH GABO Eplexor® Dynamic Mechanical Thermal Analysis (DMTA) instrument at elevated temperatures. At room temperature, the compressive forces exceeded the maximum force of 150 N of the DMTA load cell, so these tests were performed on a ZWICK 1485 static materials testing machine using a load cell of 250 kN.

A 21 mm diameter specimen geometry was selected for the investigations using the DMTA equipment. Before the test, the temperature chamber of the DMTA was heated to the desired test temperature. The sample was then placed in the center of the lower plunger and heated for 300 s in the chamber to ensure a homogeneous temperature distribution. Compacting was then performed at a constant rate of 1 mm/min until an excess of the maximum permissible compressive force of 150 N was reached. The contact force between the plunger and the specimen during heating was set to 1 N. For the lower temperature test, a square specimen geometry with dimensions of 100 x 100 mm was selected for the tests on the ZWICK 1485 static materials testing machine. Analogous to the tests using the DMTA equipment, the chamber was also brought to the test temperature before the specimen was inserted and heated for 300 s. The tests at room temperature were carried out without a heating chamber. Regardless of the testing machine, 5 repeat tests were performed for each test condition. Fig. 2 shows the test setups using the DMTA (left) and Zwick equipment (right).

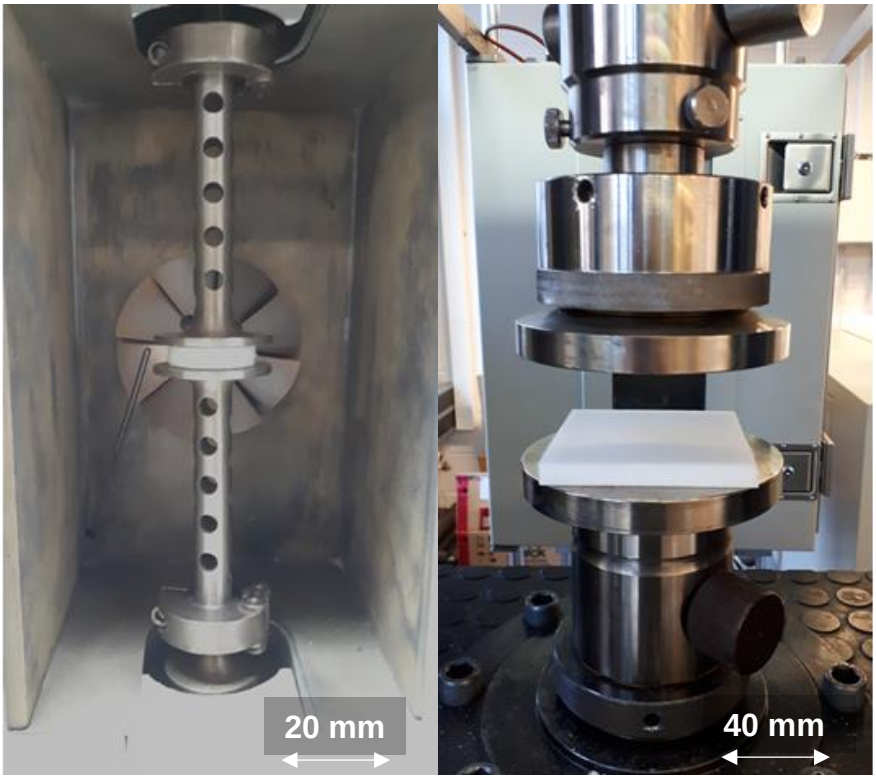


*Fig. 2: Hot press material characterization test setup using the DMTA equipment (left) and Zwick universal testing machine (right).*

Fig. 3 and Fig. 4 show the results of the compaction tests for temperatures below $T_g$ and for temperatures above $T_g$, respectively. The stresses are shown here as a function of the degree of compaction, with the error bars representing the standard deviation from the mean value of 5 measurements. At temperatures up to 225°C, the three characteristic regions of deformation for foam materials can be seen, which divide the compaction curve into a linear-elastic region, a plateau during which plastic deformation with no or only a minor increase in stress occurs, and a region of material densification with an exponential increase in stress. On the microstructural level, these three regions are associated with cell wall bending, cell wall buckling (collapse) and increasing contact between neighboring cell walls. With further increases in temperature, the foam loses these characteristics.

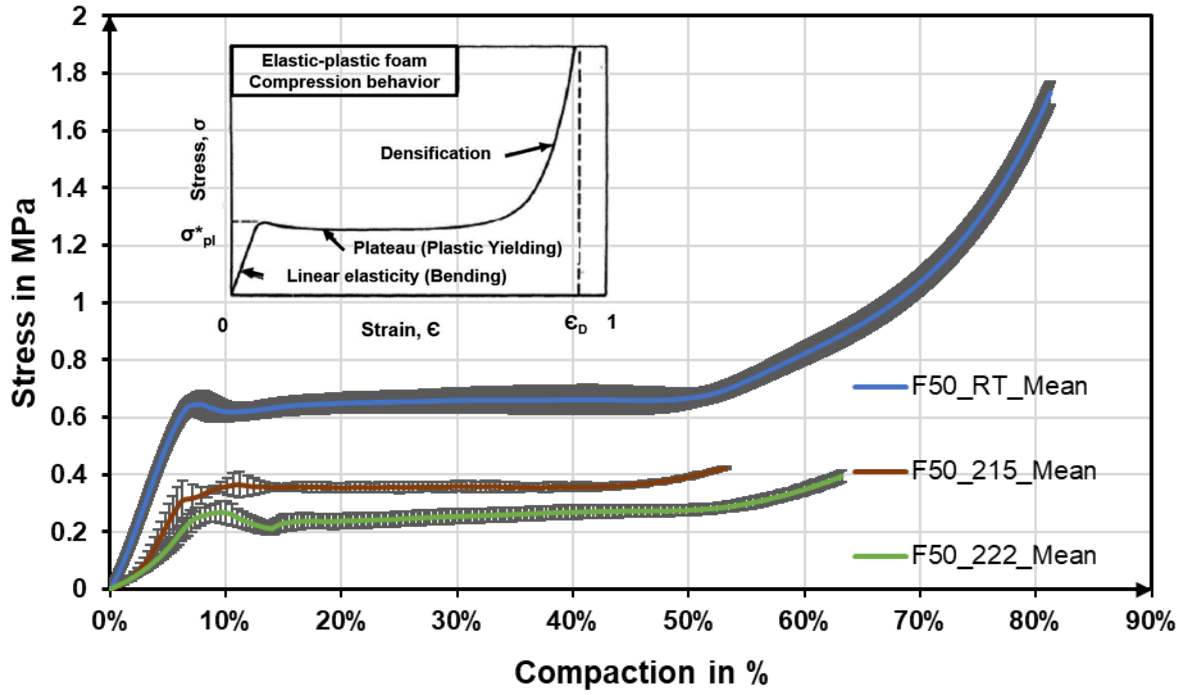


*Fig. 3: Experimental results for Divinycell F50 from the compaction tests for temperatures ≤ Tg. Top left corner shows the typical stress stain behavior of polymeric foam materials including the three distinct regions: linear elasticity, plateau and densification [4].*

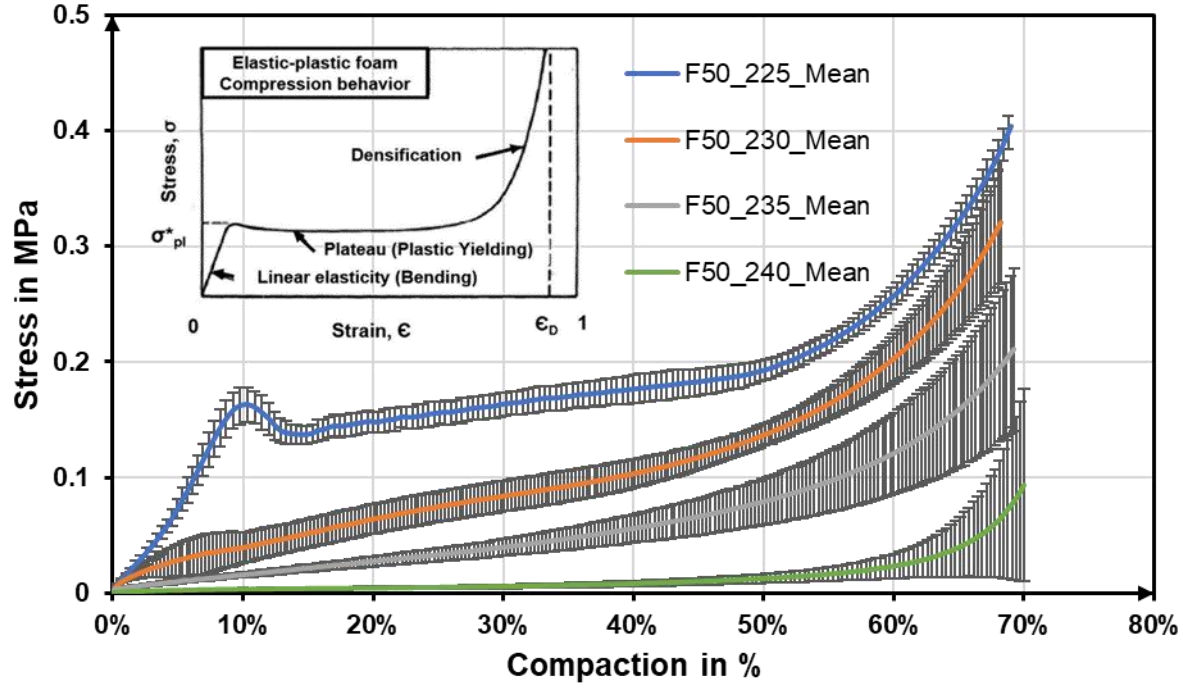


*Fig. 4: Experimental results for Divinycell F50 from the compaction tests for temperatures > Tg. Top left corner shows the typical stress strain behavior of polymeric foam materials including the three distinct regions: linear elasticity, plateau and densification [4].*

## 4 Comparison of simulation methods and material models

The simulation of the complex compaction behavior of thermoplastic foams, i.e. cell wall bending in the elastic range, cell wall buckling (collapse) in the plateau range and contact between neighboring cell walls in the compaction range, represents a major challenge. For the process simulation at the component level, these effects on the microscale cannot be resolved explicitly due to the computational effort required. Therefore a macroscopic approach was chosen. Further complexity is added by the temperature-dependent behavior of the foam. The commercially available simulation software LS-DYNA® currently does not offer a temperature-dependent model explicitly for modelling foam materials. The aim of the approach presented in this work was to develop an easy-to-use work-around, utilizing a combination of a suitable simulation methods and a standard material model. For this purpose, a comparison of simulation methods was first carried out using different element formulations: solid elements, Smooth Particle Hydrodynamics (SPH) and shell elements. Fig. 5 shows an overview of the simulation methods and how well they were able to predict the exhibited behavior.

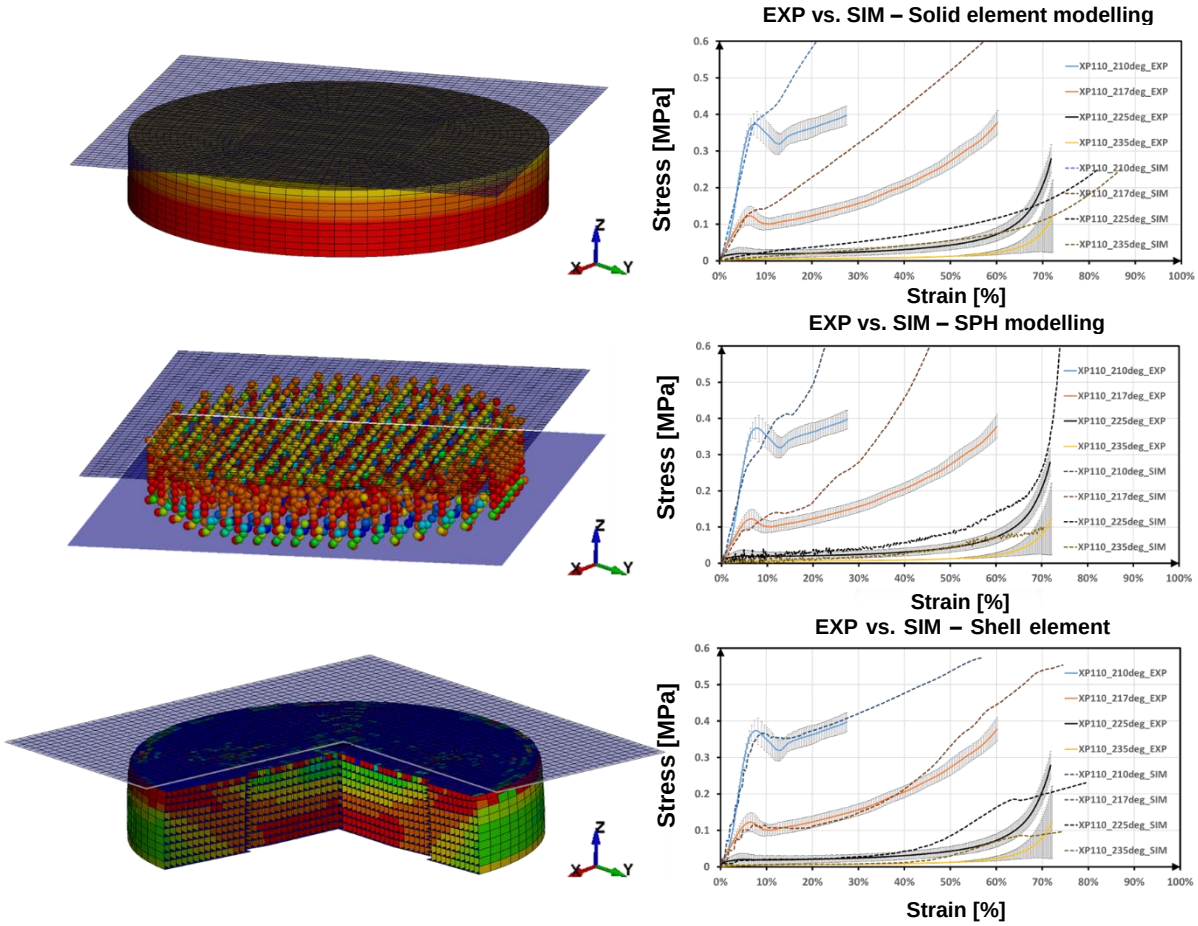


*Fig. 5: Overview of the simulation methods investigated for foam compaction simulation.*

When employing solid elements for simulation of the foam material, the linear elastic range is reproduced effectively. However, challenges arise with regards to material behavior specifically in the plateau region, where the response is observed to be too high. Additionally, the force increase at very high deformation and high temperatures is predicted too low.

Smoothed Particle Hydrodynamics (SPH) elements, a meshless method, represents the foam as an aggregation of particles. Similar to the simulation with solid elements, the material response in the area of the plateau is too high, and the force increase at high deformation too low. However, the SPH elements excel in simulating material response at temperatures above the glass transition temperature (Tg), showing higher accuracy than solid elements. Nevertheless, they tend to encounter more contact problems, such as oscillations, loss of contact, resulting in abrupt termination of the simulation.

Perhaps at first unintuitive, using shell elements provides a different modelling scenario. In this method, the foam is modeled at a somewhat mesoscopic level as a cell-like structure, separating the resulting material behavior to a joint contribution from the structure of the shell elements and the material model assigned to the shells. One of the advantages of this method is that the model can be calibrated using

actual physical parameters and the cell wall thickness. In the initial trials, the material response was typically within the standard deviation up to approximately 40% deformation. Moreover, the presence of cells or cavities in the model supports the simulation of the foam's volume loss.

Given the results presented in Figure 5, it was ultimately decided to model the Divinycell F50 foam using shell elements and the material model **`*MAT_188_THERMO_ELASTO_VISCOPLASTIC_CREEP.`** This material model offers the possibility to implement strain-rate dependency, temperature dependency and material creep which is necessary to accurately capture the foam behavior during the hot press process. However, due to the large number of material characterization experiments required, this work only focuses on the implementation of the temperature dependent compaction behavior.

## 5 Simulation of the characterization tests

The simulation model of the characterization tests consists of the compaction specimen (cylindrical ≙ DMTA; square ≙ Zwick) and the upper plunger. The bottom of the sample is fixed in the z-direction, although node movement in the x- and y-directions is allowed. The mesh of the specimen is generated by first creating a circular or square block of solid elements. Using the "Element Generation→ Shell→ Solid Surface" function in LS-PrePost®, the shell elements are subsequently automatically created from the faces of the solid elements. For isothermal simulations, each node in the model is assigned the desired test temperature. Fig. 6 shows the Divinycell F50 PES foam material in its original undeformed configuration for both the room temperature and elevated temperature tests which require the different test configurations at about 60% compaction.

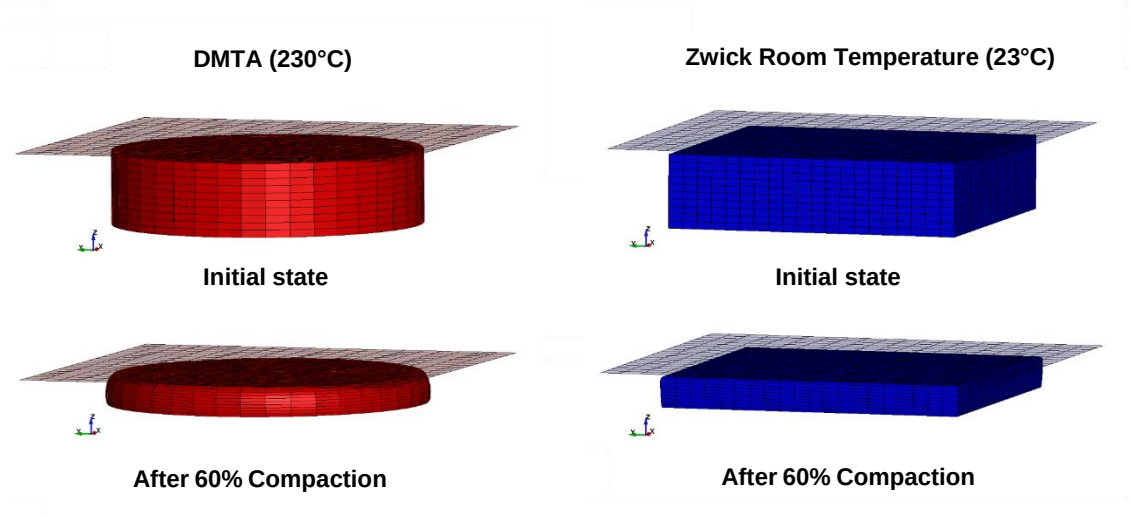


*Fig. 6: Divinycell F50 PES foam material in undeformed state (top) and after 60% compaction (bottom) for the two material characterization test configurations.*

In the material model, the density of the pure polymer of the foam is used for the sample, i.e. 1370 kg/m³ for PES. The thickness of the shell elements is chosen so that the mass of the simulated sample corresponds to the real foam mass. The modelling approach can also be used for other foam materials. For each new foam material, a parameter fitting must be performed in order to best represent the isothermal compaction tests. For this purpose, the elastic modulus, the yield stress and an additional scaling factor for the stress-strain input curve are automatically adjusted for each tested temperature via LS-OPT®. Fig. 7 and Fig. 8 show the comparison of the experimentally determined (solid lines) and simulated compaction curves (dashed lines) for the Divinycell PES foam F50 after parameter fitting.

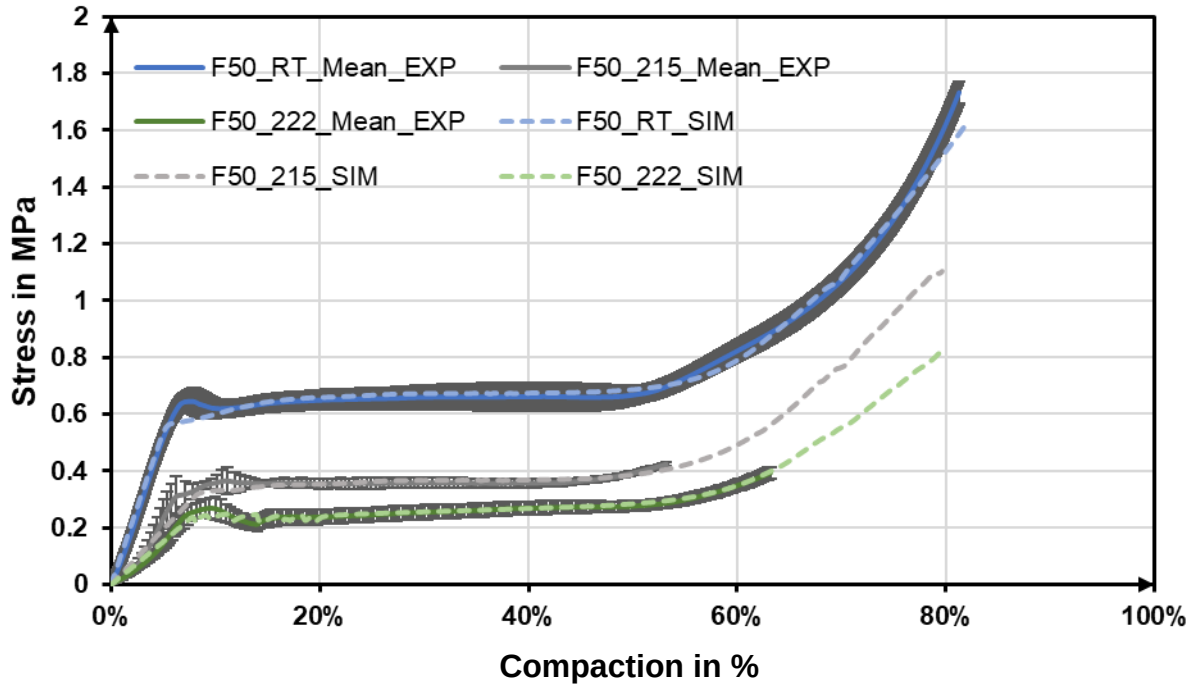


*Fig. 7: Comparison of experimental (solid lines) and simulated (dashed lines) compaction curves for Divinycell F50 at temperatures ≤ $T_g$.*

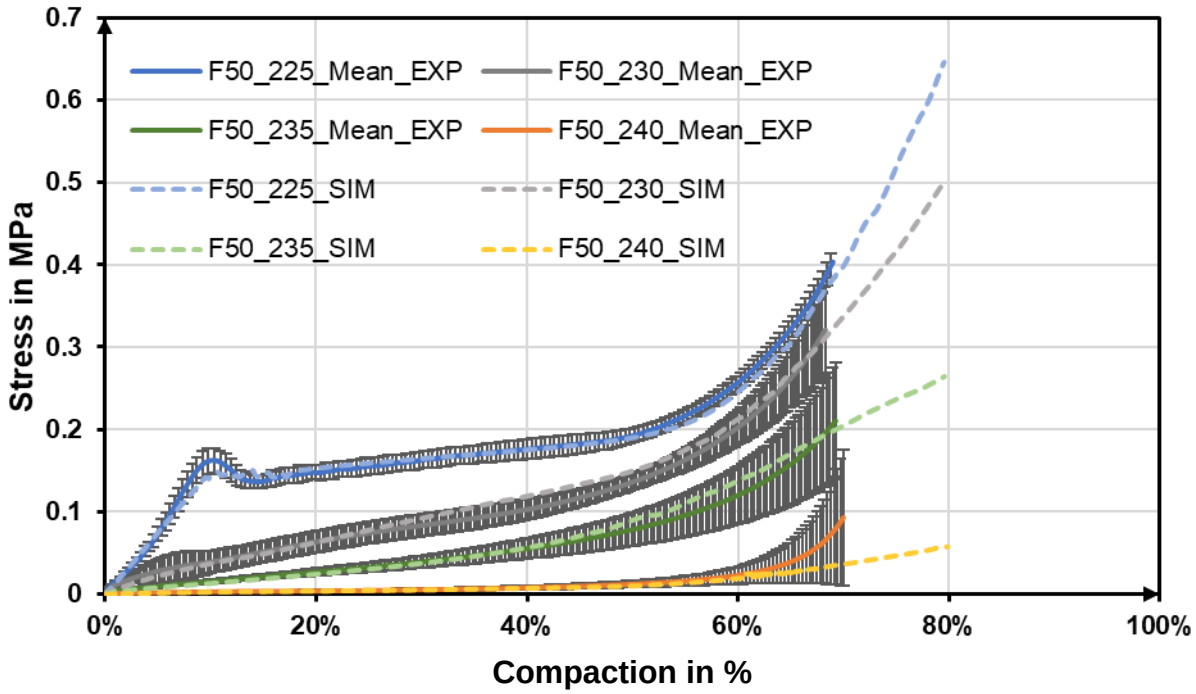


*Fig. 8: Comparison of experimental (solid lines) and simulated (dashed lines) compaction curves for Divinycell F50 at temperatures > $T_g$.*

The results show that the experimental curves can be simulated well within the given temperature and compaction range. The simulated results are also within the standard deviation range for all measured temperatures.

Fig. 9 shows the calibrated material model over the complete temperature and compaction range. The manufacturer of the foam guarantees dimensional stability up to 180°C, which is why it is assumed that no loss of stiffness occurs up to this temperature.

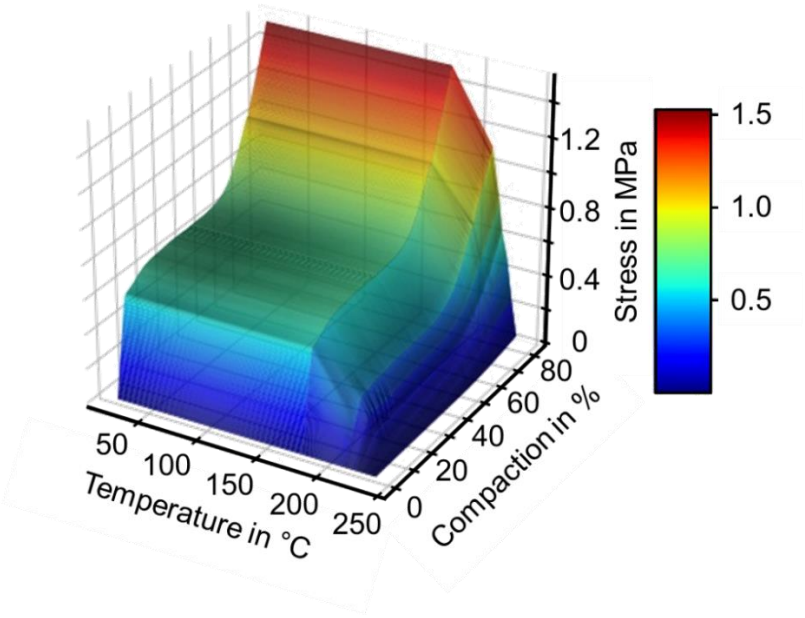


*Fig. 9: Final material model for Divinycell F50 over the complete processing temperature and compaction range.*

## 6 Simulating the hot pressing process at the specimen level

To validate the material model, hot pressing tests were carried out at the specimen level. For this purpose, square specimens with dimensions of 40 x 40 mm were placed in a hot press and then compacted with a defined force progression over time. The upper press tool was heated to the process temperature of 230°C or 240°C before starting the pressing process, while the temperature of the lower tool was held at 50°C for all tests. Fig. 10 shows the comparison between the target and achieved force in the non-isothermal hot press process for the Divinycell F50 foam at the four process conditions investigated. It can be clearly seen that the actual force follows the specified target force with a distinct delay and that the specified maximum force is not reached. This is due to the very low pressure resistance that the foam exerts on the press at high temperatures (collapsing of the foam cells). At the same time, very fast force control of the press would be necessary to achieve the specified target force curve.

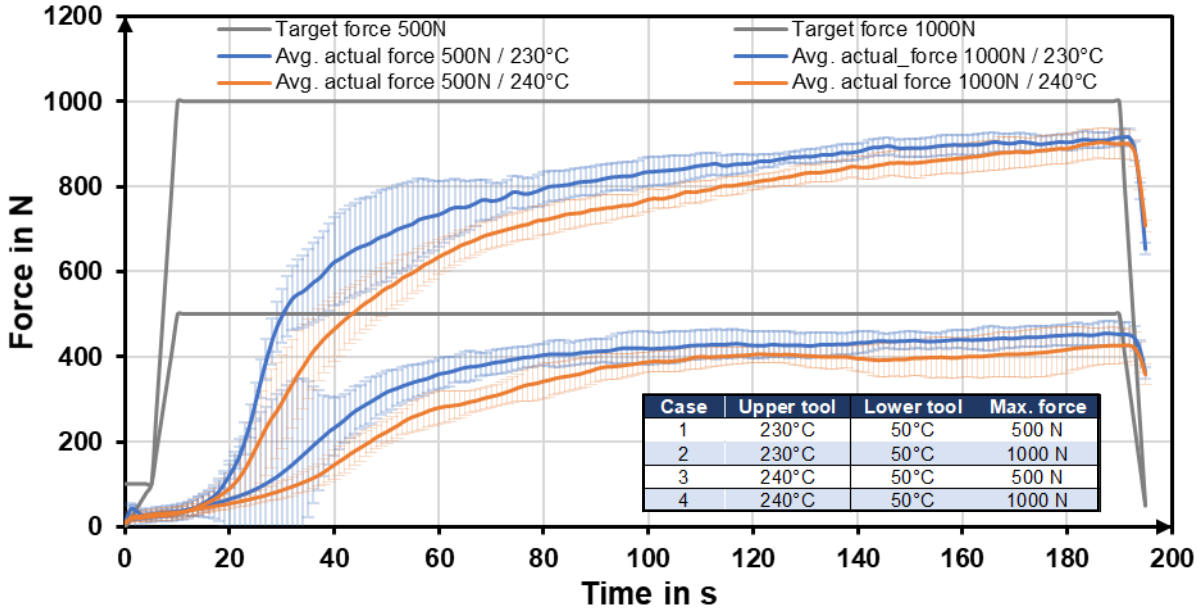


*Fig. 10: Comparison of the nominal and actual force in the non-isothermal hot pressing process.*

However, using the target force profile as the input in the simulations results in a force progression during compaction which follows exactly the specified force, since this is controlled by a very small simulation time step. This leads to a significantly increased compaction of the foam in the simulation compared to the experiments, which can be seen in Fig. 11 and Fig. 12. Here, the foam thickness profile during the process in the simulation and in the test at 230°C for a 500 N or 1000 N maximum force respectively for the Divinycell F50 is shown. The diagrams show the upper tool travel starting at the initial foam thickness of 5 mm on the primary axis and the force progression on the secondary axis. The lower final thickness of the foam in the simulation (in shown by the thick blue line) compared to the individual tests (colored, thin lines) can be clearly seen. At a maximum force of 500 N, the final thickness of the foam is underestimated by 14.6 %, and at the larger force of 1000 N by 76 %, which is not satisfactory. In both the experiential and simulation results, a graded reduction of the foam thickness can be seen, which can be explained by the sudden collapse of individual rows of foam cells.

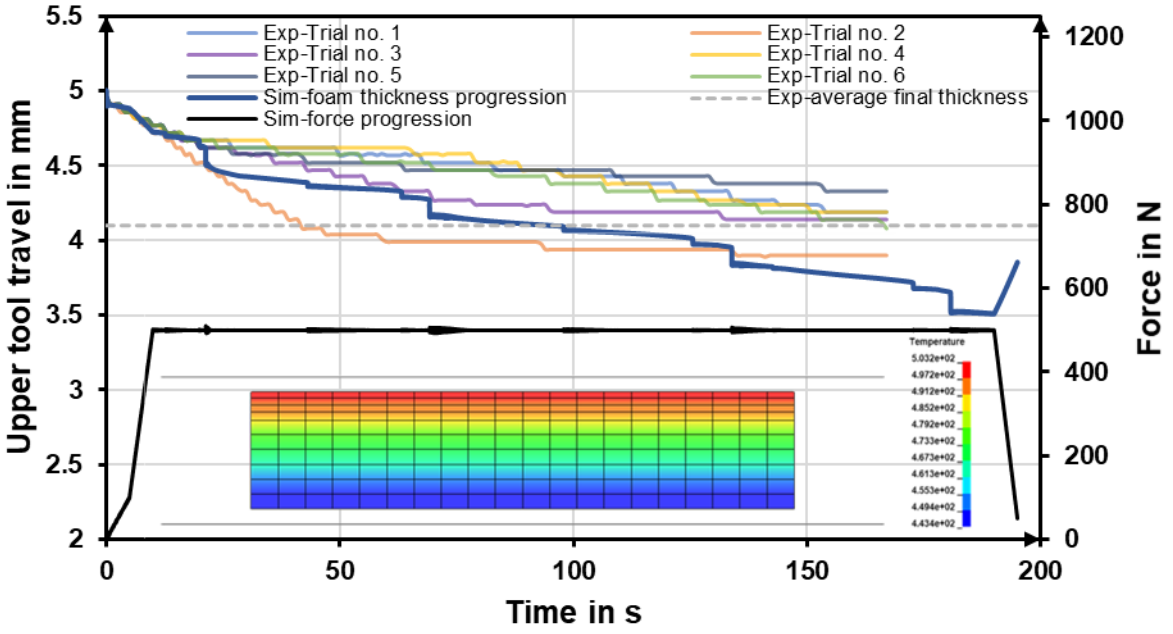


*Fig. 11: Comparison of foam thickness progression during the hot pressing process between simulation and experiment at 230°C and 500 N maximum force for Divinycell F50.*

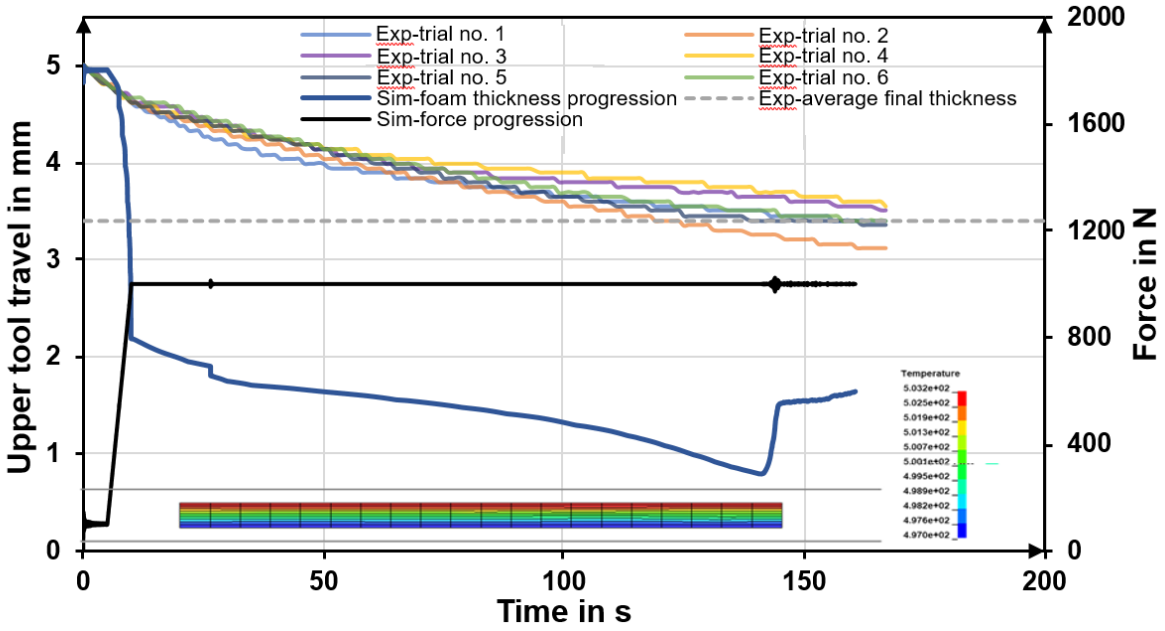


*Fig. 12: Comparison of foam thickness progression during the hot pressing process between simulation and test at 230°C and 1000 N maximum force for Divinycell F50.*

Significant improvements in the results are achieved when the measured force curve from the tests is used as simulation input. Fig. *13* and Fig. *14* show the results after this adjustment has been carried out. At a maximum force of 500 N (Fig. *13*) the final thickness of the foam is now only overestimated by about 9 %, whereas the thickness at 1000 N maximum force (Fig. *14*) is now underestimated by approx. 19 %. The gradual thickness decrease at 500 N is now clearly less pronounced, since fewer foam cells collapse.

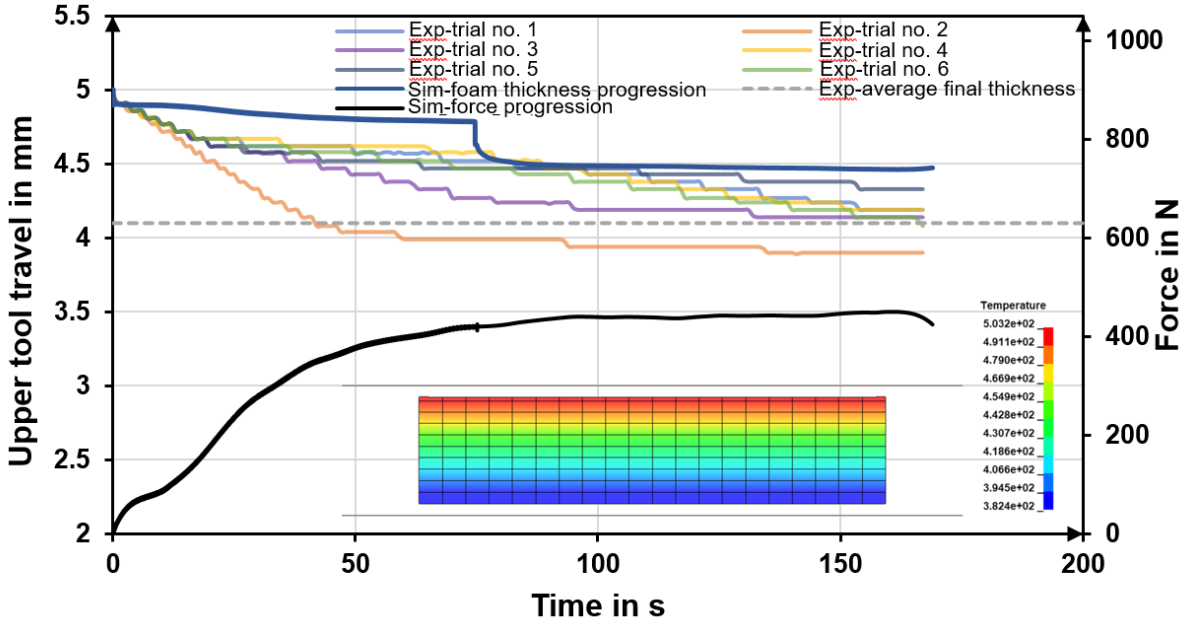


*Fig. 13: Comparison of foam thickness progression during the hot pressing process between simulation and test at 230°C and 500 N maximum force for Divinycell F50 after adjustment of the force input*.

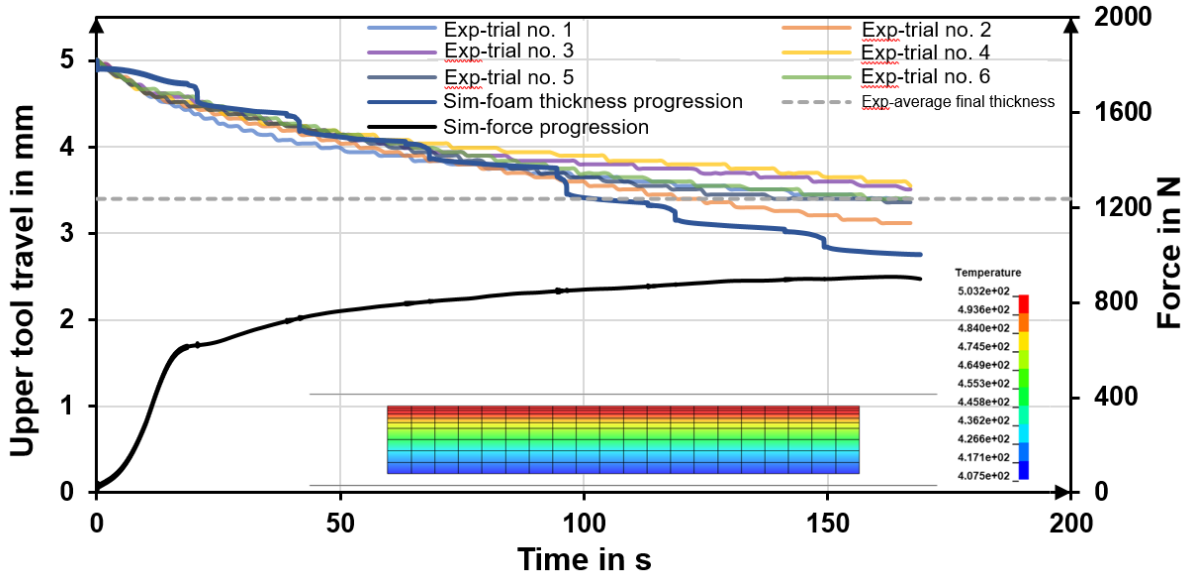


*Fig. 14 Comparison of foam thickness progression during the hot pressing process between simulation and test at 230°C and 1000 N maximum force for Divinycell F50 after adjustment of the force input*.

## 7 Summary and potential for improvements

An efficient method for the simulation of the hot press process used to transform commercially available thermoplastic foams into structural foams has been presented in this work. The approach employs shell element modeling combined with a standard LS-DYNA® material model ***MAT_188_THERMO_ELASTO_VISCOPLASTIC_CREEP** in order to simulate the complex, temperature dependent compaction behavior of thermoplastic foams. The method is capable of accurately replicating the isothermal compaction experiments carried out during material characterization, while there is still room for improvement when simulating the non-isothermal hot press process.

The results presented in Section 6 showed that using the target force curve as an input for the simulation results in an underestimation of the final foam thickness. Here, using the measured effective (and lower) force curves helped improve accuracy. However, using the measured force curves as simulation input leads to increased experimental effort, which is not purposeful. Implementing the controller behavior of the hot press equipment into the simulation model using PIDCTL via ***DEFINE_CURVE_FUNCTION** will help achieve a more realistic force progression in the process and therefore a more accurate simulation of the compaction of the foam under the target force conditions.

While this work did not focus on the investigation of the thermal conductivity of the thermoplastic foam, a detailed investigation of the thermal conductivity is considered to be necessary in order to be able to make reliable statements about the final thickness of the foam. It can be assumed that in reality that there is a mutual dependency and influence between thermal conductivity and the degree of foam compaction. A compaction dependent thermal conductivity could potentially also be modeled by implementing ***MAT_THERMAL_USER_DEFINED.**

Further improvements could also be achieved by introducing additional data points in the material model between room temperature (23°C) and 215°C rather than just assuming dimensional stability of the foam up to 180°C. Here, additional isothermal compression tests at the lower temperatures, e.g. 50°C, 100°C and 150°C could provide a better representation of the real foam behavior and thus lead to more accurate results. Furthermore, the strain rates experienced by the foam during the hot press process are not constant. Therefore, the implementation of strain rate dependency in the material model would also support a further increase in model accuracy.

## 8 Acknowledgement

The project “SOPHIA – Smart Processes and Optimized Designs for High Production Cadences” was funded by the Federal Ministry of Economic Affairs and Energy within the scope of the aeronautical research programme V-3 on the basis of a decision by the German Bundestag (funding reference 20-X1715D).

## 9 Literature

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