Numerical simulation with experimental validation of the structural reaction injection moulding of 3D continuous fibre reinforced polyurethane foam

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Abstract
Sandwich composite materials are established in the industry. Polyurethane foam reinforced with spacer fabric represents an innovative solution for a core in this field. It is manufactured in the Structural Reaction Injection Moulding (SRIM). This paper describes new investigations that provide the base for component and process design when using this Interpenetrating Phase Composite (IPC). Filling studies were carried out for this purpose in three moulding tools with and without spacer fabric. It is shown that the PUR foam expansion and the foam bulk density are clearly influenced by the sprue type, cavity design and spacer fabric. Simulations are necessary to investigate all process-structure-property relationships in detail and to enable a user-friendly and efficient design of material and process. Adequate mathematical models to simulate the transport of mass, heat and momentum in the SRIM are presented in this paper. The resistance to the expansion process caused by the porous structures in the domain were taken into account. The transport of momentum in the mould is described with the Navier–Stokes-Brinkman equations which in the limit of the permeability tensor reduces to the Navier–Stokes equation. The model equations are solved numerically and the results show reasonable agreement with the experimental data.

1. Introduction and state of the art
Sandwich design is well established in the aviation, automotive, railway and shipping industries [1]. Low component masses in combination with excellent mechanical properties can be achieved by the use of it. Limitations are related to the strength of the component transition area between the facings and the core as well as to the mechanical properties of the core itself [2]. Polyurethane (PUR) foam is the most common core material [3]. Reinforcing fibres are used to increase its mechanical properties especially under pressure and shear loads. These transmit the forces through the structure according to their orientation [4]. The bulk density should not be significantly increased by the use of fibres.

The efficient and reproducible production of PUR foam as a moulding is carried out by Reaction Injection Moulding (RIM). The two chemicals di/polyisocyanate and a polyol formulation are processed to a reaction mixture by a mixing and dispensing machine which feeds it into a closed mould [5, 6]. The process is established in the industry since the 1970s for the production of body panels and fascia [7]. It also has been extensively investigated. Kabakci et al showed for example that the structure and properties of moulded PUR foams are
strongly depending on the following process parameters: mould temperature, amount of charge, working pressure, polyol temperature, flow rate and curing time [8].

Particles, short or long fibres are carried along in the PUR reaction mixture in Reinforced Reaction Injection Moulding (RRIM) for reinforcing moulded parts [9]. Kamal et al investigated short glass fibres in this process [10]. It was shown that a large reaction mass and a low nucleation level reduce the average pore size and increase the pore homogeneity and mechanical properties. Chen et al processed long glass fibres and investigated the bending properties of the manufactured mouldings [11]. High fibre volume contents and lengths did not lead to good results because of non-uniform distribution. An optimum was determined at 15% and 25 mm. It also could be shown that the processing temperature of the chemicals and the demould time had a great influence on the results. Cao et al investigated long fibres of glass, jute and carbon in the RRIM and tested the impact properties of the mouldings [12]. This paper confirms that the uniform distribution of the fibres is essential for high mechanical properties. A fibre volume content of 10% and a fibre length of 12.5 mm were determined as an optimum in this study.

Reinforcing materials are positioned in the cavity of the mould during Structural Reaction Injection Moulding (SRIM) to impregnate them with the reaction mixture [13]. The continuous fibre reinforcement through complete PUR components can only be realised with the SRIM. Wirth described the parametrisation of this process while processing glass fibre mats in two different moulds with pressure sensors. The objectives were acceptable cavity pressure, no core shifting and crushing, no reinforcement compaction and complete impregnation [14]. Makey et al investigated glass fibre mats with different grammages in the SRIM and also varied the foam bulk density. The flexural modulus of the mouldings and the impact energy determined in the falling dart test increased with increasing values [15]. Li et al manufactured PUR foam reinforced with flax knits in the SRIM and demonstrated the reinforcement effect in a tensile test [16].

Spacer fabrics are suitable for the 3D continuous fibre reinforcement of PUR foam in the SRIM. They consist of two fabric surfaces which are kept at a defined distance by spacer threads [17]. Schäfer et al described their processing in the SRIM and demonstrated the reinforcement effect using two different variants in a rigid and a flexible foam under pressure and bending load [18, 19]. Chen et al reinforced a flexible PUR foam with six scientifically comparable spacer fabrics [20, 21]. The highest compression stresses were achieved with a closed surface structure, coarse spacer threads and a large spacer thread inclination angle. Pan et al reinforced the surfaces of a warp-knitted spacer fabric with two nonwovens each made of a mixture of PET and Kevlar fibres and an additional carbon or glass textile between them [22, 23]. The semi-finished product was completely impregnated with a PUR foam in the SRIM. The textile 3D-reinforcement of PUR foams differs in the process control from all common types of RIM. New investigations are necessary to design appropriate components and plan the processes. The work required for this is very labour-intensive. This makes it impossible to investigate all relationships comprehensively. The development of simulations based on the experimental data is necessary therefore. These allows a user-friendly and efficient design of material and process in addition.

The simulation of expanding PUR foam systems is an area of active research. Trends have shown a systematic development ranging from tracking the temporal evolution of the PUR foam density and temperature [24, 25] to simulating the spatio-temporal evolution of associated flow properties such as temperature, propagation of foam front, viscosity as well as the reacting species [26–37]. Lefebvre et al developed a two-dimensional numerical framework to predict the evolution of the macroscopic velocity, temperature, stresses and species concentration fields in the flow of a reacting polymer system [26]. Seo et al similarly predicted the flow field, the distribution of foam density, the thermal conductivity and the progression of the foam front in mould filling processes of PUR foam numerically using a theoretical 3D model which accounts for the chemical reactions in the system and assumes empirical relationships for density and viscosity [27]. A model by Mitani et al accounts for the initial shape and rate of foam expansion without emphasis on chemical reactions or temperature changes. The flow pattern of expanding PUR foam in a mould was predicted in this way [28]. However, the morphology of expanding PUR foams is strongly influenced by the interplay between chemical reactions, temperature generation and evolution of the foam rheology [29]. Geier et al expanded the ideas in [24, 26, 27] for a systemic analysis of the early stage of product development and presented a workflow for simulating the foaming process in the manufacturing of a refrigerator [30, 31]. Rao et al adopted in addition an empirical time and temperature dependent density model to simulate the expansion process of foams in a physically blown reactive PUR foam setup [32]. The resulting models reasonably predicted the foam propagation, viscosity and temperature distribution in a closed complex geometry. An improvement of the model framework is presented in a followup study [33]. It was shown that the applied homogenised continuum models can adequately predict the density distribution and the filling profiles of the PUR foam in a closed mould.

The authors of this paper derived equations in previous studies which govern the complex dynamics of expanding PUR foam influenced by the reaction temperature, the degree of conversion and the chemoviscosity [38]. The Kamali model is used to describe the chemical reactions during the PUR foam processing [39]. The equations were solved numerically for the spatio-temporal analysis of the flow properties. The results showed
good agreement with filling study experiments where volume expansion and reaction temperature (up to 160 °C) were measured. A mathematical model accounting for the non-uniformity in the expansion process of PUR foams was derived in further work [40]. This was solved and also validated by experiments. The rheology of expanding PUR foam also has been studied in detail by the authors of this paper to improve the own mathematical structure for modelling [41].

There are also reports in the literature about attempts to couple micro- and macro-scale activities in the simulation of expanding PUR foam. Geier et al. presented a multiscale modelling approach, which combined atomistic molecular dynamics simulations with CFD (Computational Fluid Dynamics) models using a surrogate equation [31]. The associated model equations were used to predict the expansion process of physically blown PUR foam systems. The results showed reasonable agreement with experiments.

The mathematical modelling and simulation of the expansion of PUR foam through porous networks has not yet been extensively explored. This paper presents an approach to the topic. The evolution of the rheology and associated flow parameters of PUR foam introduces additional difficulty in modelling their expansion through porous media. The presence of such fibrous structure induces some resistance to the expansion process as well as heat transport within the mould [18, 19]. Intricate properties such as the permeability of the porous fibre material, degree of polymerisation, heat generation, evolving rheology of the fluid, gas creation and foam growth should be accounted for in developing 3D mathematical framework for SRIM process of PUR foams. Kim and Macosko described the thermal transport and pressure rise in the mould for a SRIM system with PUR using the Darcy law and Kozeny’s equation in this regard [13]. The presence of porous structures in SRIM process prompts the use of the Navier–Stokes-Brinkman equations in regions occupied by the fibre and the Navier–Stokes equation in the fibre free parts. Corresponding studies were carried out and described in this paper. The system of coupled non-linear partial differential equations governing the foam expansion process in the mould containing the fibre networks are solved using finite volume techniques and the results are validated with experimental data.

2. Experimental work

2.1. Materials
A reactive two component foam system from Covestro AG (Leverkusen, Germany) was used for the filling studies. This produces a rigid PUR foam with a free foam bulk density of approx. 40 kg m\(^{-3}\) and primarily closed cells. The polyol formulation BAYDUR 43-101 contains polyether polyol (OH number 330 mg KOH g\(^{-1}\)) and all necessary additives for the polyaddition reaction and CO\(_2\) formation. The polyisocyanate Desmodur 44V20 LF (NCO content 30.5%/wt.–32.5%/wt.) is aromatic. The two components are processed in a mass ratio of 67 polyol formulation to 100 polyisocyanate. The relationship between the volume of the PUR reaction mass and the resulting PUR foam is 1 to 30 in the case of free expansion. The system has a starting time of 50 s and a tack-free time of 15 min, which determines the demoulding time.

Two warp-knitted spacer fabrics were used for the investigations to reinforce moulding areas with a thickness of approx. 20 mm and 40 mm. These were produced by the Spiga GmbH (Flöha, Germany) on a high distance raschel machine with a needle gauge of E12 from the Karl Mayer Textilmaschinenfabrik GmbH (Obertshausen, Germany). They are both made of polyester. The spacer yarns are monofilaments and have an IXI course. The surfaces were made of multifilaments as fillets. Fringe and tricot were used for spacer fabric 1 (SF 1) and tricot exclusively for spacer fabric 2 (SF 2). Both variants mainly differ in the thickness and the thread density (figure 1). SF 2 has a 3.7 times higher stitch and spacer thread density compared to SF 1 (table 1).
2.2. Manufacturing process

The filling studies were carried out in three moulding tools with completely different cavities. They all consisted of the aluminium alloy AlMg4.5Mn. With the first one a plate can be manufactured with a surface of 150 mm × 150 mm and a thickness of 20 mm (Figure 2). This corresponds to a volume of 450 cm³. The PUR reaction mass is distributed from the injection point through a 0.6 mm thick fan sprue. It is finally injected into the cavity at a height of 5 mm over a complete side.

The moulding tool 2 has a beam as cavity with a length of 500 mm, a width of 50 mm and a height of 40 mm. This corresponds to a volume of 1,000 cm³ (Figure 3). It has a 4-part, 0.6 mm thick duct sprue, which introduces the PUR reaction mass into the cavity over the full length at a height of 15 mm.

The third one is used to manufacture a complex formed wave (Figure 4). This has a length of 490 mm and a width of 100 mm. The thickness widens from 1.6 mm to 24.0 mm and tapers again to 1.6 mm. The volume amounts to 540 cm³. The PUR reaction mass is injected over a length of 180 mm by a fan sprue in the widened area of the moulding. This also has a thickness of 0.6 mm.

The moulding tools were heated externally with plates from the Heidolph Instruments GmbH & CO. KG (Schwabach, Germany) at a temperature setting of 55 °C. This results in a temperature of approx. 42 °C in the
sprues and at the cavity walls. The release agent MP-4066 from the Münch Chemie International GmbH (Weinheim, Germany) was used to demould the PUR foams. A two-component mixing and dispensing low-pressure system from Unipre GmbH (Werl, Germany) was used to mix the chemicals. The feed into the moulding tools was carried out with an output rate of 600 g min\(^{-1}\).

The filling studies in mould 1 were carried out with SF 1 in the dimensions of the cavity. SF 2 was used for the beam. The dimensions also corresponded to the cavity. The wave was reinforced with SF 1 in the largest possible area, which fitted into the cavity without compression. This was 100 mm \(\times\) 150 mm. The spacer fabrics were cut to size using the USM-G electric circular knife from the Hoogs Cutting Systems GmbH & Co. KG (Bonn, Germany). The longer side of the cuttings (X-direction see figures 1–4) corresponded to the working direction during the production of the spacer fabrics. They were inserted shortly before the mould was closed and the PUR reaction mass was injected. The spacer fabrics therefore had room temperature of about 23 °C when they were subjected to the flow. No fixing was necessary to prevent displacement. The PUR reaction mass was fed in without pressure and the foam expansion continued successively through the chemical reactions and the resulting blowing agent CO\(_2\).

2.3. Characterisation

The two spacer fabrics SF 1 and SF 2 are geometrically characterised using micro-tomographic imaging. The 3D images were scanned at the special \(\mu\)CT at Fraunhofer ITWM (Kaiserslautern, Germany) with an x-ray emission tube (Feinfocus FXE 22), a maximum acceleration voltage of 225 kV and a maximum power of about 20 W. A PerkinElmer detector with 2048 \(\times\) 2048 pixels for high energy images (usable from 100 kV to 225 kV) acceleration voltage and a Thales detector with 3072 \(\times\) 3072 pixels for low energies (usable from 40 kV to 160 kV) were also employed. The resolution for both spacer fabrics was chosen to 27 \(\mu\)m to resolve accurately the monofilament and to be able to scan a sample with a size of 50 \(\times\) 50 mm.

The segmented 3D images could be directly used to calculate the full anisotropic permeability tensor \(K\) of the spacer material by simulating the fluid flow through the spacer fabric geometry based on the Stokes equation. The digital material laboratory software tool GeoDict\textsuperscript{®} of the Math 2 Market GmbH (Kaiserslautern, Germany) was used to import the \(\mu\)CT-data, to cut out a representative periodic area of the spacer fabric and to calculate the flow through the spacer fabric in all three coordinate directions voxel grid. The permeability tensor was automatically calculated in GeoDict\textsuperscript{®} by averaging the flow filed data.

The sprue of the foam mouldings was removed for the determination of the mould filling levels and the foam bulk densities in relation to the mass of the feed. The volume of the samples of the filling studies was set in relation to the volume of the cavity to determine the mould filling level. The volume of the mouldings was determined by discrete measurement. They were divided into 10 mm wide segments in X-direction (see figures 2–4) to measure the expansion in Y-direction. The segments of the samples of the beam filling studies were again divided into four parts in Z-direction at a distance of 10 mm, because of the strongly varying expansion in the height. The measured expansion was multiplied by the segment width and height to determine the segment volumes of the samples of the plate and the beam. The volumes of the complete segments of the complex formed wave were determined in the computer-aided design (CAD) model. The filled volume of this segments is calculated subsequently by dividing the measured foam expansion by the cavity width multiplied by the complete volume of the segment. The total volume of a sample is calculated by adding the segment volumes. The bulk density of the foam of a sample is given by the ratio of its mass to its volume. The mouldings and spacer
fabrics were weighed before impregnation to calculate this. The foam mass of the reinforced foams is obtained by subtracting the mass of the spacer fabric from the total mass of the sample. The mass of the sprues was also determined. The true mass of the feed from the machine into the moulding tools and therefore the deviation from the setting can be determined by this together with the foam mass of the mouldings.

3. Mathematical modeling

The geometries described in section 2.2 were investigated numerically in this study. The specified spacer fabrics were considered by the prescribed permeability $K$. Simulations were carried out with and without these textiles in the cavity and with the same PUR reaction masses from the experiments. The foaming mixture is assumed to be a pseudohomogeneous incompressible chemorheological fluid and the expansion process is considered to be driven by an adequately modified expansion source term $S(T, \varphi_g)$ depending on temperature ($T$) and gas fraction ($\varphi_g$) which allows for non-uniform expansion of the reacting PUR in the mould. These assumptions correspond to the previous work of the authors, which is described in section 1. The flow in the porous region within the domain is assumed to satisfy Darcy law. The Navier–Stokes–Brinkman equations therefore governing the mass conservation and momentum transport as follows.

$$\nabla \cdot \vec{v} = S(T, \varphi_g)$$  \hspace{1cm} (1)

$$\frac{\partial \rho \vec{v}}{\partial t} + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot \sigma - \mu_m \hat{K}^{-1} \vec{v} + \rho g$$  \hspace{1cm} (2)

The flow velocity is $\vec{v}$, the density is $\rho$, the bulk gravitational force is $g$, pressure is $p$ and the chemoviscosity model for the reacting PU foam mixture is $\mu_m$ adopted directly from the previous work of the authors (see section 1). $\sigma = \mu_m \gamma$ is a stress tensor with $\gamma = 0.5(\nabla \vec{v} + \nabla \vec{v}^T)$. The second order permeability tensor $\hat{K}^{-1}$ is defined in piecewise form by equation (3).

$$\hat{K}^{-1} = \begin{cases} K^{-1}, \text{for flow in the porous region} \\ 0, \text{for flow in the non porous region} \end{cases}$$  \hspace{1cm} (3)

The energy balance in the presence of the porous structure with void fraction $\phi$ within the mould is described according to Kim and Macosko with equation (4).

$$\phi \rho C_p \left( \frac{\partial T}{\partial t} + \vec{v} \cdot \nabla T \right) = \nabla \cdot \left( \kappa_{eff} \nabla T \right) - (1 - \phi) \rho_f C_p \frac{dT}{dt} + \phi \left( \mu_m \gamma + \rho H_f \frac{d\alpha}{dt} \right)$$  \hspace{1cm} (4)

The density $\rho_f$ and specific heat capacity $C_p$ of the solid fibre constitute the pore network. The thermal conductivity, density and specific heat capacity of the foam-gas mixture are respectively $\kappa$, $\rho$ and $C_p$. The heat of reaction for the exothermic system is $H_f$, which is described in detail in the previous work of the authors (see section 1). The effective thermal conductivity ($\kappa_{eff}$) follows Kim and Macosko according to equation (5), where $\kappa_f$ and $\kappa_i$ are respectively the thermal conductivities of the expanding foam and the solid fibers.

$$\frac{1}{\kappa_{eff}} = \frac{\phi}{\kappa_f} + \frac{1 - \phi}{\kappa_i}$$  \hspace{1cm} (5)

The degree of conversion follows the Kamal law described with equation (6).

$$\frac{d\alpha}{dt} = \frac{\partial \alpha}{\partial t} + \vec{v} \cdot \nabla \alpha = (k_1 + k_2 \alpha^m)(1 - \alpha)^n$$  \hspace{1cm} (6)

The reaction parameters $k_1$, $k_2$, $m$ and $n$ describing the kinetics and the order of the reactions. The models and equations governing the liquid and gas volume fractions $\varphi_l$ and $\varphi_g$ as well as the mixture density and other relevant state parameters were directly adopted from the previous work of the authors (see section 1). The resulting governing equations are solved with respect to the physical conditions of the experiments.

4. Results and discussion

4.1. Computer tomographic reconstructions

The computer tomographic reconstructions of the two spacer fabrics exactly reproduce their real textile structures and illustrate their differences (figures 5 and 6). SF 1 has very open surfaces with oval omissions. The surfaces of SF 2 are largely closed in contrast, which is only interrupted by narrow, parallel omissions. These gaps can also be identified in the spacing area in the X-Y plane, because the spacer threads are integrated in the
surfaces. The slices in this plane also visualise for both spacer fabrics the low fibre volume content at high thread density in the spacer area. The larger monofilament diameter of SF 1 compared to SF 2 is also noticeable. The spacer threads are arranged one after the other in the X-Z plane. Their curvature between the surfaces is
therefore visible in this slice. The crossing of the spacer threads in the IXI course can be detected in the Y-Z plane. No continuous spacer threads can be detected through the curvature in this slice however. Both spacer fabrics have similar spacer thread courses. A considerably lower thread density is visible for SF 1 compared to SF 2. The permeability tensors of SF 1 \( (K_{SF1}) \) and SF 2 \( (K_{SF2}) \) given in the equations (7) and (8) were derived from the computer tomographic reconstructions. SF 1 has a 2.4 times higher permeability compared to SF 2 accordingly.

\[
K_{SF1} = 10^{-7} \begin{bmatrix}
4.07 & 0 & 0 \\
0 & 4.83 & 0 \\
0 & 0 & 5.57
\end{bmatrix}
\]

\[
K_{SF2} = 10^{-7} \begin{bmatrix}
1.68 & 0 & 0 \\
0 & 1.71 & 0 \\
0 & 0 & 2.70
\end{bmatrix}
\]

4.2. Flow fronts

The PUR foam expansion is convex half-elliptical in Y-direction during the manufacturing of the plate (figure 7). The flow front takes up the full cavity height in the Z-direction with a slight convex curve. The simulation results show very good agreement with the observed experimental flow profile. Even the flatter flow front in the Y- and Z-direction is visible when using a spacer fabric compared to the foam expansion in the empty cavity. This behaviour is attributed to the interplay between the flow resistivity because of the chemoviscosity of the expanding foam and the obstructions induced by the porous media within the domain. There is only one difference between experiment and simulation in moulding tool 1 for the manufacturing of the plate, when a spacer fabric is used. The curvature of the spacer threads is directed away from one side wall of the cavity. This forms a flow channel with lower flow resistance. The PUR foam prefers this in the experiment, which results in a flow front advance. The simulation is not able to take this into account because the spacer fabric is considered as a homogeneous flow resistance.

The flow front of the PUR foam is divided into four half-elliptical parts in the Y-direction by the four-part sprue of the moulding tool 2 for manufacturing the beam (figure 8). The expansion in the Z-direction is irregular because of the greater cavity height compared to the plate. The flow resistance in the Y-direction is higher compared to the Z-direction when using spacer fabrics, which results in a faster expansion of the foam upwards. The foam touches the top of the cavity already with 30 g, which is earlier in comparison to the expansion without spacer fabric. The flow front of the foam in Y-direction advances without spacer fabric at the bottom where it reaches the opposite cavity wall. The corner above is filled afterwards. All these observations about the expansion
in the moulding tool 2 for manufacturing the beam are exactly reproduced by the simulation. There are some differences when using a spacer fabric in this tool, however. A convex curve in the Z-direction is formed in the experiment, because the foam adheres to the fibres immediately after emerging from the sprue at a height of 15 mm. The foam reaches the opposite cavity wall at a medium height therefore and then fills the corners above and below. The simulations do not reproduce this. An advance of the foam front at the bottom is found instead. The reason for this is that the spacer fabric is only considered as flow resistance in the simulation and adhesion is not taken into account.

The maximum cavity height of the moulding tool 3 for manufacturing the wave is comparable to the plate. This is therefore completely taken up with a slight convex curve during the whole PUR expansion. The foam initially expands convex half-elliptical in Y direction without spacer fabric, which is also comparable to the manufacturing of the plate (figure 9). This is based on the comparable sprue. The spacer fabric in the partial area of the cavity causes the PUR foam to preferably occupy the free areas next to the insert. This leads to an expansion in three convex half-elliptical parts. The opposite cavity wall is reached in this way and the thick part of the wave mould is completely filled. The long and very thin areas of the cavity are filled afterwards. The reason for this is the feed into the widened cavity area and the greater space for expansion there. The thin areas are filled with a flow front along the Y-direction in positive and negative X-direction. The agreement of the flow front between experiment and simulation is exact in this mould.

**4.3. Filling level**

The average deviation of the two-component mixing and dispensing low-pressure system from the set feed masses over all tests was 1.4 g. The maximum was 4.9 g. The complete filling of the empty cavity of moulding tool 1 for the manufacturing of the plate requires 45% less PUR reaction mass compared to moulding tool 3 for the manufacturing of the wave, although the cavity volumes and the sprue are comparable. The reason for this is the different complexity of the form of the mouldings. The moulding tool 2 for manufacturing the beam has a two times larger cavity than the other two moulding tools and therefore requires the largest PUR reaction mass for a complete filling. This is about 140% more compared to the plate and about 30% more compared to the wave.

The sprue mass in the filling studies to manufacture the plate was constant at 1.7 g. The infiltration of SF 1 required additional 15% PUR reaction mass compared to the complete filling of the empty cavity (figure 10). The expansion ratios of the volumes of the PUR reaction mass and the resulting PUR foam in this mould were 1
to 19.7 without and 1 to 16.8 with spacer fabric. The sprue mass in moulding tool 2 for manufacturing the beam was constant at 3.5 g. Additional 40% PUR reaction mass was required in comparison to the empty cavity to achieve a complete filling with SF 2 inserted (figure 11). The expansion ratio without spacer fabric was 1 to 18.4 and with 1 to 13.1. A constant sprue mass of 2.5 g was found in the filling studies of the wave. An additional PUR reaction mass of 10% was sufficient to manufacture the complete reinforced moulding compared to the empty cavity (figure 12), because the spacer fabric was only partially integrated. The expansion ratios were 1 to 12.7 without and 1 to 11.6 with spacer fabric.

Figure 9. Comparison between real and simulated filling studies for the manufacturing of (a) unreinforced and (b) 3D continuous fibre reinforced polyurethane foam in the moulding tool 3 for waves.

Figure 10. Comparison between real and simulated filling levels of the foam in the manufacturing of unreinforced and 3D continuous fibre reinforced polyurethane foams with the moulding tool 1 for plates.
The PUR foam expanded linearly in all three moulding tools up to a filling level of 90\% (figures 10–12). The curves then behave degressively. The need for increased PUR reaction masses for a complete cavity filling when using spacer fabrics was also demonstrated for all three moulding tools, although the textiles already occupy up to 4.4\% of the cavity volume. The reduced expansion caused by spacer fabrics occurs only at later filling levels (figures 10–12). In the case of the plate this can be noticed from about 70\%, in the case of the beam from about 80\% and in the case of the wave from about 99\%. The last percentage corresponds completely to the thin area of the wave with a thickness of 1.6 mm, which despite its length of 125 mm only accounts for this small volume portion of the moulding (see figure 4).
The simulations show very good quantitative agreement for the filling levels in mould 1 for manufacturing the plate with and without spacer fabric (figure 10). This is also the case for the manufacturing of the beam without textile insert (figure 11). Differences occur in the infiltration of the spacer fabric in moulding tool 2. The simulation predicts a complete filling of the cavity with PUR foam at slightly over 60 g. A minimum of 85 g is required in the experiment in contrast. The degressive filling behaviour of the foam observed in the experiment between 50 g and 85 g could not be reproduced in the simulation. A reason for this discrepancy could be related to the increasing pressure build-up in the cavity caused by the gas generation as the injection mass increases. This is not well captured in the current models because the mathematical framework does not include the dependence of the expansion on the pressure within the system. The pressure rise in the mould is usually above the atmospheric pressure. This increase in pressure would result in lower foam expansion because of pressure induced counter forces, which act against the motion of the expanding foam. The pressure in the simulation is currently set at atmospheric pressure (see section 1). This is also the reason for differences between simulation and experiment in moulding tool 3 for the manufacturing of the wave (figure 12). The complete wave is manufactured using 50 g without and 55 g with spacer fabric. Inconsistent in this respect are the results of the simulation where in both cases 35 g is sufficient for a complete cavity filling. A massive pressure increase in the cavity can be assumed when filling the thin areas. This results from the long flow path, which leads to an increased viscosity of the reaction mass because of the progressed chemical reactions. An excessive amount of reaction mass is required for moving the material to a complete cavity filling therefore, which generates pressure in the system.

4.4. Bulk density
Differences between the non-reinforced mouldings can also be found when considering the bulk density after the cavities have been completely filled. The beam had a 10% and the wave a 60% higher foam bulk density compared to the plate. The spacer fabrics also compact the PUR foam in the plate by 20%, in the beam by 50% and in the wave by 15% (figures 13–15). The PUR foam first expands continuously in all three moulds during the cavity filling process with a bulk density of 50 kg m\(^{-3}\) to 60 kg m\(^{-3}\). The compaction of the PUR foam begins progressively at the point of degressive drop in expansion at 90% filling level. Foam compaction by the spacer fabrics begins at the same time as the reduced expansion through them begins in the respective mould.

The simulated bulk densities of the PUR foam generally show good agreement with all experiments carried out (figures 13–15). The continuous foam expansion at the beginning with 50 kg m\(^{-3}\) to 60 kg m\(^{-3}\) is correctly predicted just like the varying rises of the bulk density at the end depending on the moulding tool. However, the final bulk density in the manufacturing of the beam with spacer fabric and the wave in general only agrees with the experiments when considering the same PUR reaction masses and not the points where the cavities are completely filled. About 20 g less PUR reaction mass is required in the simulations in these three constellations.
compared to the experiments (see section 4.3). The foam bulk density has also not increased in the simulations of these experiments when the cavity is completely filled. A good agreement of the final bulk density is achieved when the simulations are carried out with the PUR reaction mass, which leads to a complete filling of the cavity in the experiments.

5. Conclusion

The SRIM with PUR foam and spacer fabrics was investigated in this work. Experimental and computational filling studies were carried out in three moulds with different cavities with and without textile inserts. It was
shown that PUR foam expansion is significantly influenced by the sprue type, cavity design and spacer fabric. The level of cavity filling and the bulk density in relation to the PUR reaction mass are directly linked. If the filling level runs linearly, the bulk density is constant. However, if the filling level runs degressively, the foam is compressed and the bulk density develops progressively.

The sprue takes up a considerable part of the flow path of the PUR foam in the process. Longer flow paths result in higher foam bulk densities, as the viscosity of the PUR reaction mixture increases over time (see literature of section 1). The design of the sprue therefore has a significant influence on the expansion in the cavity. The foam bulk density of the manufactured beams was 10% higher in comparison to the plate, because the corresponding moulding tool had a sprue with a double volume. The influence of a complex cavity design was investigated using the example of a wave as a moulding. A 60% higher foam bulk density was determined in comparison to the beam, because the PUR reaction mass was compacted at narrow areas. For all three moulds was proven that the foam expansion is hindered by spacer fabrics as inserts. Increased reaction masses for complete cavity filling become necessary because of their use. SF 1 compacted the foam by 20% in the manufacturing of the plate and by 15% in the wave. SF 2 with a 3.7 times higher stitch and spacer thread density compressed the PUR foam in the moulding tool of the beam by 50%.

This foam compaction only starts from a high cavity filling level of at least 70%, which became clear in the comparison with the filling studies without spacer fabric. On the one hand, this is based on the continuous dissipation of the temperature of the PUR formation by the spacer fabrics. Up to 160 °C are generated in the exothermic polyaddition reaction (see section 1), while the spacer fabrics in the process were at room temperature. On the other hand, the threads of the spacer fabrics cut the pores of the foam. The forming CO₂ cannot be contained in the plastic mass and flows out of it. But as blowing agent it is essential for a complete cavity filling with low foam bulk density. This is not critical at the beginning of the process, because continuously more PUR reaction mass is fed, which forms new CO₂. The significant increase in foam bulk density begins, when the feed is stopped and the reaction temperature is decreased.

The results from the simulation compared favourably with the experimental observations for the flow fronts, filling levels and bulk densities. Excellent was the agreement in the manufacturing of the plate. Minor discrepancies are caused in some cases when an obvious pressure build-up occurs in the moulding tool like in the manufacturing of the beam or the wave. The pressure rise within large cavities induces a resisting force because of the generated gas, which opposes the expansion of the foam. This is for example the case in the manufacturing of the beam. The effect is currently not well captured because the model is based on incompressibility of the expanding foam and constant atmospheric pressure in the free space of the cavity. The discrepancies to the experimental results are therefore created. The interplay between the chemoviscosity of the foam and the pressure at geometric constrictions is also not well captured in the model. This explains the observed differences in the manufacturing of the wave. The approach for further investigations is based on these observations and the need to adequately incorporate pressure effects into the models.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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