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Structure-property-relationships for Lightweight Parts Produced via Co-injection Molding and Foam Injection Molding

In this work, foam injection molding is combined with the two-component co-injection molding process to produce hard-soft-combinations with TPS (thermoplastic elastomer based on SEBS) skin and a foamed polypropylene core. Due to the fast solidification of the melt at the cavity wall, an increasing part thickness leads to an increasing foamable melt volume. Increasing the part thickness leads to a higher temperature for a longer time in the center of the part. Thus, for thicker parts, an extended period of time is available for the foaming process, contributing to a further weight reduction. Especially for high blowing agent (N_2) contents of 0.70 %, the finger flow (non-uniform flow of the core melt into the skin melt) is clearly pronounced at the end of the core flow front, due to instabilities of the polymer flow. For the first time the potential for weight reduction of this highly integrated processing technology is analyzed by systematic evaluation of the part thickness and the physical blowing agent content.

Struktur-Eigenschafts-Beziehungen von Leichtbauteilen produziert durch Co-Injektion und Schaumspritzgießen

In dieser Arbeit werden die Prozesse Schaumspritzgießen und Co-Injektion vereint, um Hart-Weich-Verbunde aus TPS (Thermoplastisches Elastomer auf SEBS-Basis) und geschäumtem Polypropylen herzustellen. Da die Randschicht schnell an der Werkzeugwand einfriert, erhält man mit zunehmender Bauteildicke ein größeres Schmelzevolumen im Kern des Bauteils, welches aufgeschäumt werden kann. Die Temperatur in der Mitte des Bauteils liegt daher für einen längeren Zeitraum über der Erstarrungstemperatur. Somit steht bei höheren Bauteildicken ein längeres Zeitfenster für das Schäumen zur Verfügung und die Gewichtsreduktion kann gesteigert werden. Insbesondere bei hohem N_2-Gehalt (0,70 %) ist der Fingerfluss (ungleichmäßiges Fließen der Kernschmelze in die Hautschmelze) am Ende der Kernfließfront deutlich ausgeprägt, was auf Instabilitäten des Polymerschmelzeflusses zurückzuführen ist. Erstmals wird das Potenzial zur Gewichtsreduzierung dieses hochintegrierten Prozesses durch systematische Auswertung des Einflusses von Bauteildicke und Treibmittelgehalt analysiert.

Structure-property-relationships for Lightweight Parts Produced via Co-injection Molding and Foam Injection Molding

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1 INTRODUCTION

Hard-soft combinations are of interest for numerous applications like handles or handholds in the automotive interieur. In this study foam injection molding is combined with co-injection molding to achieve two-component parts with a foamed core and a haptic skin. This highly integrated and efficient processing technology enables the manufacture of products with high potential for lightweight design. In contrast to the overmolding process (realized for example via turning table technology) a complete encapsulation of the core component by the skin component is possible.

As soft component TPS (thermoplastic elastomer based on SEBS) is used in this study, due to its advantages in processability and its high compatibility to PP as core component. By a systematic variation of the skin / core volume ratio in the part, the potential for weight reduction by changing the part thickness is analyzed for the first time. In addition, the influence of the injected melt volume and the blowing agent content was studied. A maximum portion of the foamed core with homogeneous spread in the part as well as a fine-celled homogeneous foam morphology are targeted. As the skin component is a soft-touch material, it plays a minor role for the mechanical properties. For high specific (density-related) bending stiffness mainly the core component with its sandwich structure (foam core surrounded by a compact layer) is relevant.

In the process of foam injection molding, a blowing agent (supercritical fluid) is dissolved in the plastic melt in the plasticizing unit of the injection molding machine. As long as the melt in the cylinder of the injection molding unit is under pressure (up to approx. 200 bar), the blowing agent remains in solution. When the melt is injected into the mold, there is an abrupt drop in pressure to ambient pressure and the gas dissolves from the solution, causing the polymer to foam [1], see Figure 1. Cooling of the melt increases the viscosity of amorphous plastics, and in the case of semi-crystalline plastics, the plastic solidifies by crystallization and the foam cells are stabilized. In the foam injection molding process, the temperature control of ungleichmäßiges Fließen der Kernschmelze in die Hautschmelze the mold and the part thickness are decisive for the stabilization of the cells. The thermal conditions in the cavity lead to a sandwich

structure, shown in Figure 2, consisting of compact outer layers and a large number of foam cells. Thus, with this process, foam injection molded parts with high specific bending stiffness and less material consumption can be produced [2–4]. Depending on the processing technology, raw material and component geometry, up to weight-70 % polymer can be saved [1,5–7].

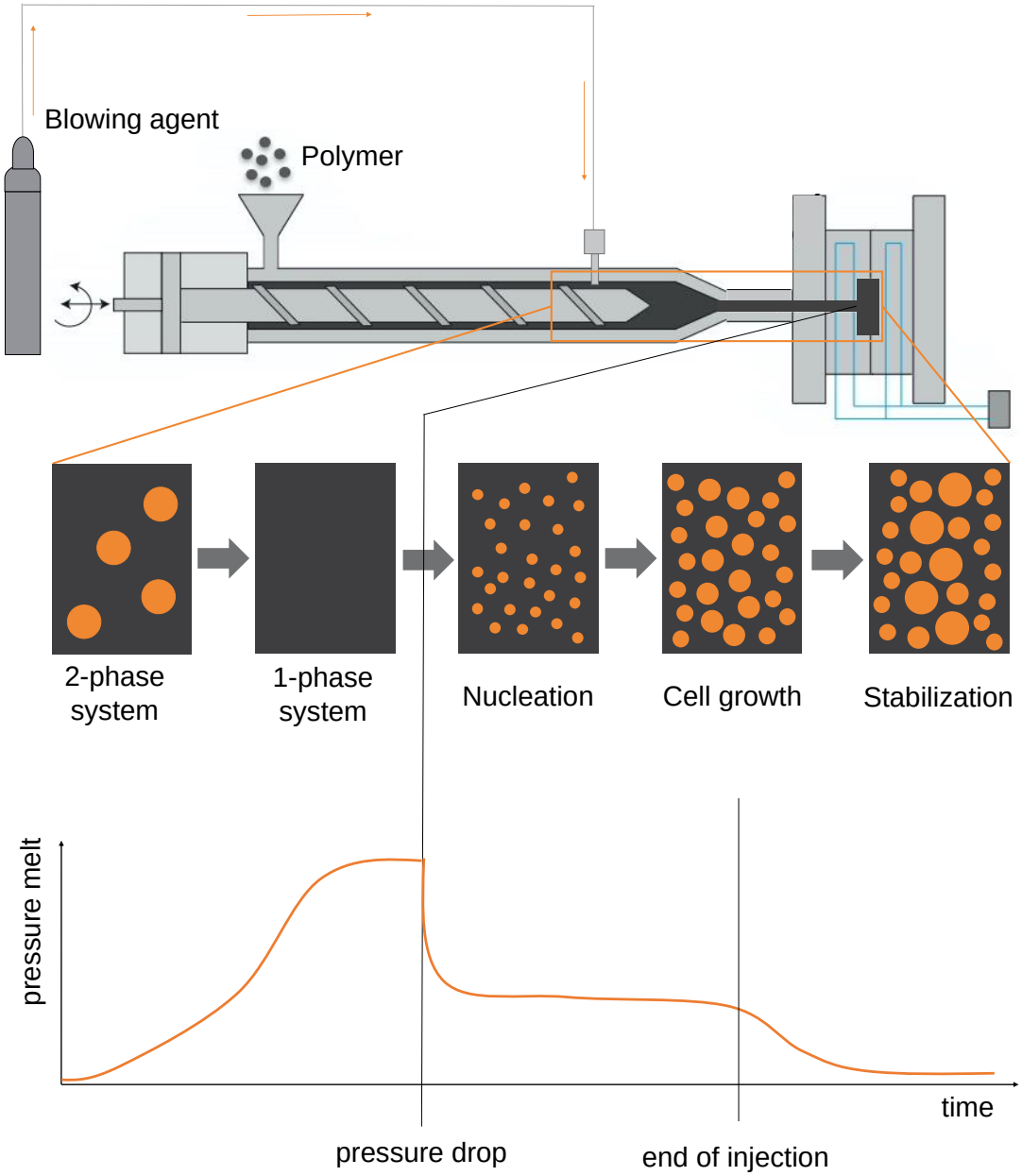

Figure 1: Foam injection molding process

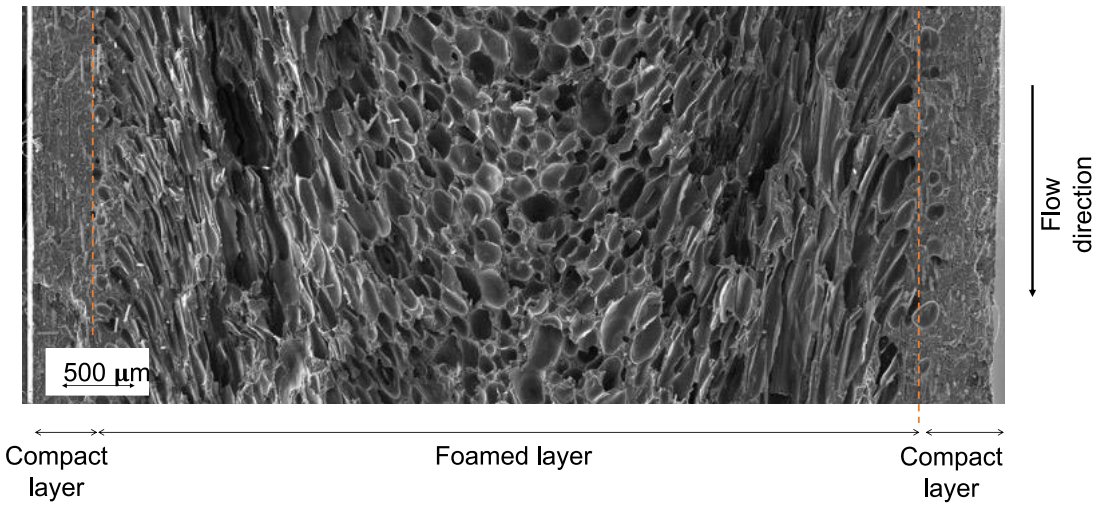

Figure 2: Morphology of foam injection molded part

A major process-specific advantage of foam injection molding is the so-called internal holding pressure which is created by the volume expansion of the foaming melt. This pressure obsoletes the holding pressure applied by the injection molding machine and enables the production of parts with high wall thicknesses without sink marks. On the other hand, the pressure drop at the flow front causes premature outgassing, which leads to the typical surface defects known as silver streaks and swirls [8]. To overcome this obstacle, a second component can be used for coverage: foam injection molding is combined with an overmolding process. By using thermoplastic elastomers as second component, soft-touch properties can be achieved.

An alternative way of producing parts from two thermoplastic components is the co-injection process, which is the focus of this work. In the co-injection molding process, two melts are injected into a mold through the same gate [9].

The co-injection process can be subdivided firstly according to the injection (sequential or simultaneous) and secondly according to the processing technology. In sequential co-injection, the skin component is injected first. Then, the core material is injected into the cavity through the same gate and spreads within the skin component until the entire part is filled. This sub-form of co-injection can be carried out with all processing technologies. In simultaneous co-injection molding, a smooth transition between the skin and core components is realized by controlling shut-off nozzles. When differentiating by processing technology, one should mention co-injection using shut-off nozzles and the mono co-injection molding. The designation "mono" indicates that both melts are injected through only one injection molding cylinder. This means that the materials are always injected one after the other (sequentially) and at the same cylinder temperature. The injection speed, on the other hand, can differ by setting an injection profile in the system control. The co-injection process is much more flexible when co-injection nozzles or co-injection intermediate plates are used,

see Figure 3. In addition to sequential co-injection, simultaneous co-injection with smooth transition between the skin and core components is also possible by controlling the shut-off nozzles. With these two process variants, the process parameters can also be adapted more specifically to the two individual materials, since it is possible, for example, to select different cylinder temperatures for the skin and core components [9].

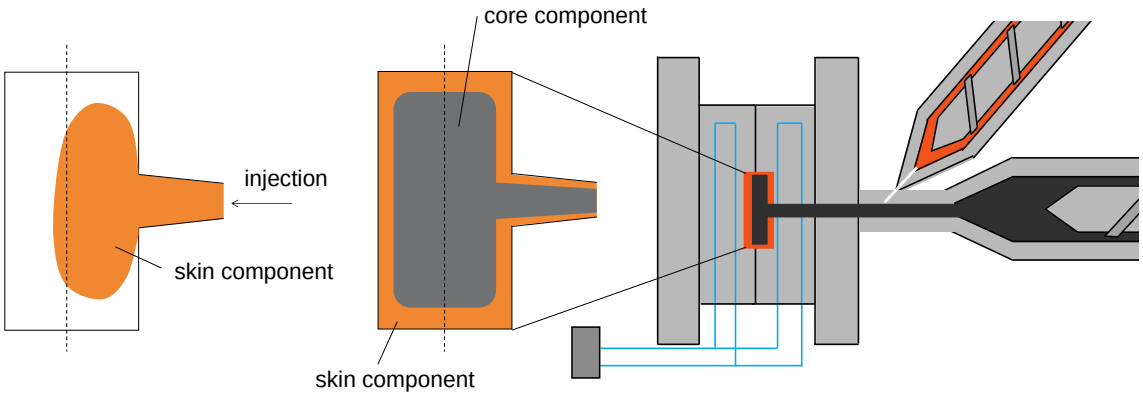

Figure 3: Co-injection molding process

The quality (e.g. optical and mechanical properties) of co-injected parts is usually defined by the distribution of the core component in the skin component, which is directly influenced by the rheological and thermal properties of the melt as well as the compatibility of the individual components and the mold geometry. The most common defects are the breakthrough of the core component at the flow front and the instability of the interface between skin and core (formation of "finger flow") [9,10].

The core content (vol.%) has the greatest influence on the material distribution in the resulting component. For simple geometries, a core content of up to 70% is achievable, while for complex geometries a core content of 30% is desirable [11]. In addition to the volume ratio, the processing parameters of co-injection molding also have a significant influence on the morphological structure of the component [12–14].

The viscosities of the skin and core materials used have a direct effect on the flow behavior and the formation of the skin/core structure [10]: if the shear rate dependant viscosity ratio η_{core}/η_{skin} is too large, the core material remains only in the region close to the gate. If the viscosity ratio is too small, the core material tends to break through the skin material [15,16]. A desired and uniform thickness of the core material can only be achieved with a suitable viscosity ratio (e.g. between 0.5 and 2 [15,16,22]). In this work, co-injection molding is combined with foam injection molding. Relevant literature of this process combination is summarized hereafter.

2 STATE OF THE ART

Table 1 summarizes the available literature about co-injection molding with a foamed core. Skin and core component, as well as type of blowing agent and main findings are listed.

Material		Blowing agent	Main findings	Source, year
Skin	**Core**			
not specified	not specified	chemical	Process feasible under given conditions	[17], 2015
PP	PP	chemical	Higher specific bending stiffness compared to foam injection molded part	[18], 2014
PC/ABS	ABS	physical: N_2	Fine-celled foam morphology (by adding chemical blowing agent as nucleating agent) realizable	[19], 2019
PA	PA			
TPU-GF	TPU			
PP-LGF	PP			
PP	PP			
PP	PP	chemical	Only minor effects of chemical blowing agent on skin/core-structure: longer core flow path when adding blowing agent (compared to compact injection molding). No change in viscosity detectable in online viscosimeter.	[20], 2011
PP	PP	chemical	Optimized surface quality and 13 – 25 % higher tensile strength compared to foamed specimens without skin layer	[2], 2004
PP-GF	PP	physical: N_2	5 % weight reduction (compared to compactly fabricated components of the same materials), part thickness 3 – 5 mm 46.7 % higher surface gloss (compared to foamed PP-GF)	[21], 2017
PS	PS	physical: N_2	6 % density reduction (compared to compact part); thickness 3.5 mm; 84 % warpage reduction (compared to compact part); foamed core penetrates further towards the end of the flow path and produces a more homogeneous skin layer than a compact core	[5], 2004

Table 1: Summary of available literature about foam co-injection molding

L.-S. Turng and H. Kharbas [5] co-injected polystyrene as the skin component and polystyrene with blowing agent (N_2) as the core component. The resulting components have a size of 120 mm x 40 mm x 3.5 mm. A clear edge between the compact skin layer and the foamed core as well as a fine-celled foam morphology are achievable. The density reduction is 6% relative to a compact component made of the same polystyrene. The foamed core penetrates further towards the flow path end and produces a more homogeneous skin layer than a compact core. This is explained by the reduction of the viscosity of polystyrene by the addition of blowing agent. Studies on viscosity reduction are not included in the publication.

Moritzer [20], who uses PP as both skin and core component, investigates the influence of the blowing agent content on the viscosity. He used 0 %, 1 % and 5 % chemical blowing agent of the type Hydrocerol BM 40 from Clariant Masterbatches GmbH, Germany, which has 40 % effective components. However, the influence of this blowing agent on the viscosity of the PP used cannot be detected under the present conditions (shear rates between 10 and 1000 1/s).

The combination of co-injection molding and foam injection molding processes allows the fabrication of visually appealing surfaces [21] with reduced component weight [2,5,21], less warpage [5] and improved mechanical properties [2,18] compared to foamed parts without skin layer. However, no systematical evaluation on the influence of the part thickness on the weight saving potential and the morphology of the parts has been carried out up to now. Besides, the effect of blowing agent content on part's morphology has not yet been investigated. A complex material combination (e.g. hard-soft-combination) has also not yet been addressed.

3 EXPERIMENTAL

3.1 Co-Injection Molding of Test Specimens

The thermoplastic elastomer (ALLRUNA VS 05021808 of Allod Werkstoff GmbH, Burgbernheim, Germany), is used as a soft skin component. It has a density of 0.9 g/cm^3 and a hardness of 83 Shore A. Polypropylene as a homopolymer (Moplen HF 501 N, LyondellBasell, Rotterdam, Netherlands), with a density of 0.9 g/cm^3 is used as the core component. To facilitate the detection of the interface between the skin and the core material, the core component is dyed black with 2 % PE-based masterbatch (Deifel GmbH & Co. KG, Schweinfurt, Germany). In addition, 2 % talc is added to nucleate the foam cells.

The co-injected components are produced on a modified injection molding machine (Engel DUO -1350H-1350M-450, Schwertberg, Austria), which has a

clamping force of 4500 kN. A co-injection plate (A&E Produktionstechnik GmbH, Dresden, Germany) is combined with a plate mold. The geometry of the cavity has a length of 500 mm and a width of 200 mm, see Figure 5. The thickness of the plate is variable. The injection point (conical cold runner) is located in the center of the plate.

To produce the co-injected parts, the main injection unit is used for the core component, see Figure 4. This injection unit has a screw diameter of 60 mm and an L/D ratio of 24. The MuCell process using N_2 is employed for foaming the core component. For the skin component, the injection unit perpendicular to the main injection unit is used (screw diameter: 45 mm, L/D ratio: 20).

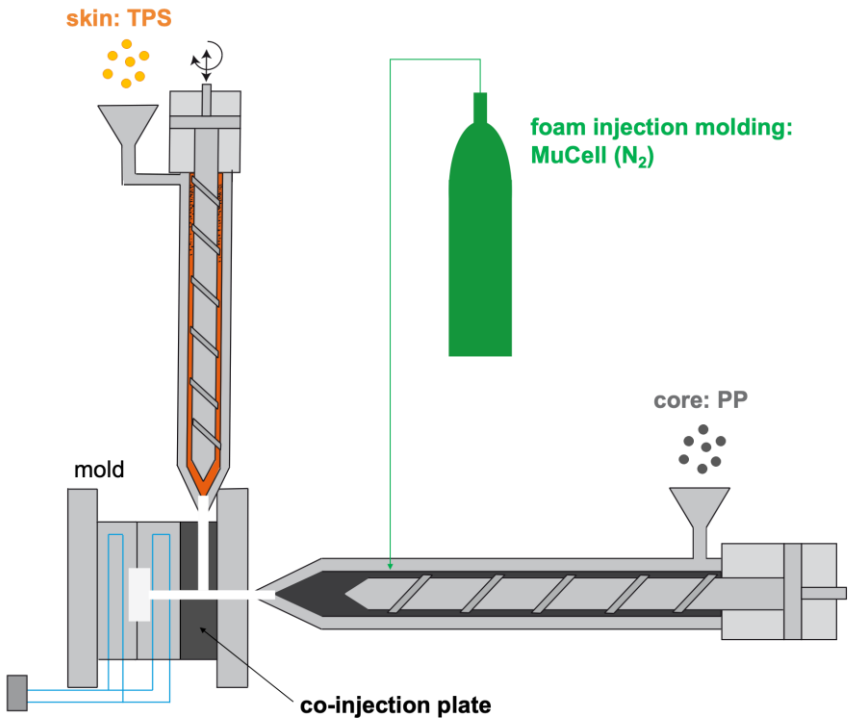

Figure 4: Processing of co-injection molded parts with foamed core

In preliminary trials the processing parameters were optimized: The target value was the maximum achievable core content and its uniform distribution in the skin component. The melt temperature of the skin and core components has been varied in previous studies from 200 to 240 °C in 3 steps (corresponding to the processing temperatures specified by the manufacturers). The injection speed has been studied independently for skin and core component at values between 50 and 150 cm^3/s, and the delay time between the injection of skin and core component was considered between 0 and 6 seconds. The above parameters and other injection molding specific parameters were kept constant. The optimum processing conditions used in this work are listed in Table 2. The delay time of

0 s indicates that the core component is injected directly after the skin component (in sequential injection molding).

Parameter	Core injection unit	Skin injection unit
Melt temperature (max) [°C]	220	220
Injection velocity [cm^3/s]	100	150
Delay time [s]	0	
Cooling time [s]	20	
Mold temperature[°C]	35	

Table 2: Fixed processing parameters for production of co-injection molded parts with foamed core

In addition, the parameters shown in Table 3 are systematically varied to evaluate their influence on the resulting components.

Parameter				
Blowing agent content N_2 [weight-%]	0	0,20	0,45	0,70
Core volume share [%]	30	40	max	
Density reduction [%]	0	5	max	
Part thickness [mm]	2	3	4	5

Table 3: Variable processing parameters for production of co-injection molded parts with foamed core

The core volume share is defined as the quotient of the injected volume of the core component and the total injection volume. When considering the core volume fraction of foamed, co-injected components, a distinction must be made between core volume fraction (i.e. injected ratio of the two components by the injection molding machine) and core area fraction (resulting ratio of the two components in the parts projected area). These two ratios do not match because the core component expands during foaming and therefore it occupies more space. The skin component, on the other hand, remains compact.

The core volume fraction is progressively increased until it is too high and breaks through the core component. The maximum part thickness is limited by the injection volumes of the two injection units.

3.2 Characterization

For the calculation of the projected core area ratio, images of the top view of the manufactured part are taken with a high-resolution camera at first. Then, the area occupied by the core material is evaluated using ImageJ software. The core area fraction is determined by the quotient of the core area and the total area (in top view). All results are based on at least three samples.

For the optical analyzation of the foam morphology, specimens are laser jet cutted and images are acquired with a scanning electron microscope (SEM) (Zeiss EVO MA 15) at 10 kV. The samples are sputtered with an approximately 10 nm thin gold layer. Again, ImageJ software is used to quantitatively evaluate the foam morphology. At least three samples per test series are analyzed. Cell diameter is calculated with the option “particle analyzer” in ImageJ (where cell diameter is calculated from the optimum round particle with same area as the present cell). Cell density *N* is defined as cells per cubic millimeter [3], where n is the cell number of an area A (mm^2) of the micrograph, see equation (1). Location of SEM pictures is shown in Figure 5.

$$N = \left(\frac{n_{cells}}{A}\right)^{\frac{3}{2}} \quad (1)$$

To determine the density of the samples, at least three squared samples with an edge length of 1 cm are prepared from each of the foamed parts using a waterjet cutter. The samples are taken close to the sprue (3 cm from the sprue), in the center (9 cm from the sprue) and far from the sprue (15 cm from the sprue), see Figure 5. The density measurements were carried out with a balance (Kern YDB-03 balance from Kern & Sohn GmbH, Balingen, Germany).

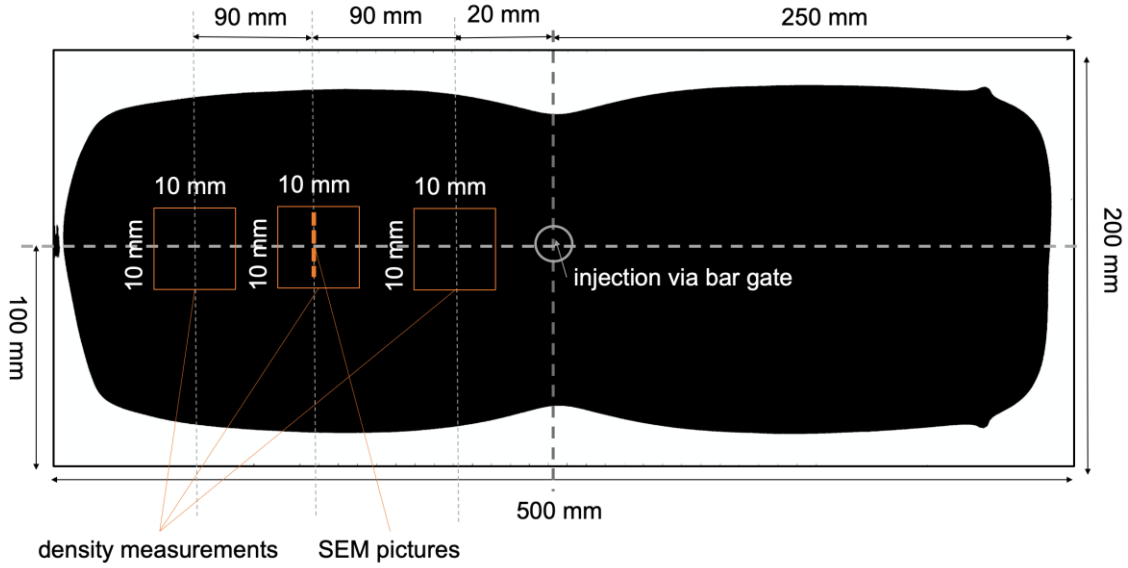

Figure 5: Location of SEM pictures and density measurements

The mass of the manufactured molded parts is determined gravimetrically using a balance (Kern & Sohn GmbH, Modell Kern PCB, Balingen, Germany). The entire component is examined. In order to obtain statistically reliable results, at least three samples are examined for each parameter setting and their average mass with standard deviation is determined.

4 RESULTS AND DISCUSSION

This work focuses on the systematic evaluation of the influence of the part thickness on weight saving potential and the foam morphology. The maximum core injection volume is first determined using a compact core component, see section 4.1. From this starting point, blowing agent is added in rising content. The aim is to fill the same core volume with less material. The skin/core-distribution and microscopical structure are analyzed in section 4.2. The influence of the blowing agent content on part's morphology is enlightened.

4.1 Effects of Processing Conditions

4.1.1 Injected Core Share

First, the core volume fraction of the compact components as a function of part thickness is considered, see Figure 6. The core volume fraction increases with the part thickness. While a maximum core volume fraction of 44 % is achieved with a part thickness of 2 mm, it is maximized to 51 % with a part thickness of 5 mm.

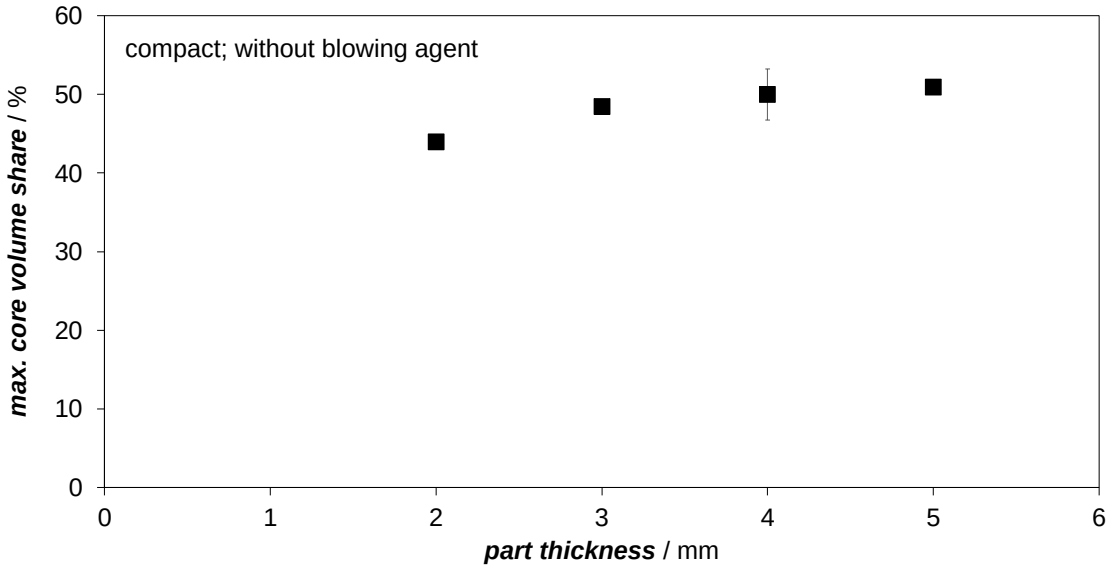

Figure 6: Core volume share as a function of component thickness (compact co-injection molding)

The relationship between maximum core volume fraction and part thickness can be explained by the thermal conditions when the two components are injected into the cavity. For thin-walled components, the distance between the two cavity walls is small and so is the gap in which the hot polymer spreads. When the skin component enters the cavity, it solidifies directly at the metallic mold wall, which is a good conductor of heat. When the core component is injected, a solidified material layer of the skin component has already formed, which can no longer be displaced by the hot, still flowable core melt. This limits the available space and thus the maximum core volume fraction. If the part thickness and thus the distance between the two thermally conductive cavity walls is increased, more space remains for the core component and the core volume fraction can be increased.

The only minor effect can be explained by the high length (500 mm) and width (200 mm) of the part. For smaller plates a higher influence is expected. It can be concluded that, particularly in the case of thick-walled components, there is a high potential for weight reduction through foaming of the core component.

Gomes et al [11] did not investigate the influence of the component thickness on the achievable maximum core fraction, the authors only considered molded parts with a thickness of 2 mm. They achieved a core fraction (PP) of 55 %, while the skin fraction (PS) was 45 %. This is higher than the maximum core fraction of 44 % presented here, but the lateral expansion of the parts was with 150 mm x 40 mm significantly lower than the parts presented here (500 mm x 200 mm). Since in the case of Gomes et al. a gate is considered at the edge of the plate, the maximum flow length is 150 mm. In the case presented here, 250 mm of flow path length must be overcome.

In the work of Seldén at al [9], the 100 mm x 100 mm plate with film gate used has an even a smaller maximum flow path length of 100 mm with a thickness of 3 mm. Here, the maximum achievable core (PBTB) volume fraction is 48 %, while the PA6-skin fills 52 % of the mold. In the present work, a core volume fraction of 48 % (at 3 mm part thickness) is also achieved. However, the maximum flow path length is more than twice as large in the present work. Parsons and Toyoda [22] co-injected various thermoplastic materials with a maximum flow path length of 100 mm. A core volume fraction of 55 % led to a constant core thickness in the square test plate (100 mm x 100 mm x 3 mm). Eigl demonstrated in [14] that a maximum core volume fraction of 60 % could be realized for a component thickness of 3 mm and a flow path length of 130 mm (component width: 75 mm; film gate) for parts with PP both, as skin and core component.

The maximum flow path / wall thickness ratio in this work is more than twice as large than the values considered in literature. At lower flow path / wall thickness ratios (in this work 250 mm / 2 mm), the values for the maximum core volume fraction are in the same range as the values reported in literature.

4.1.2 Maximum Achievable Weight Reduction

Based on the maximum core volume fraction determined in the previous section, the core volume is foamed in this section. Figure 7 shows the weight reduction of the part (based on the weight of the compact part of the same thickness) as a function of the part thickness. Three different blowing agent contents (from 0.20 weight-% to 0.70 weight-%) are used for foaming.

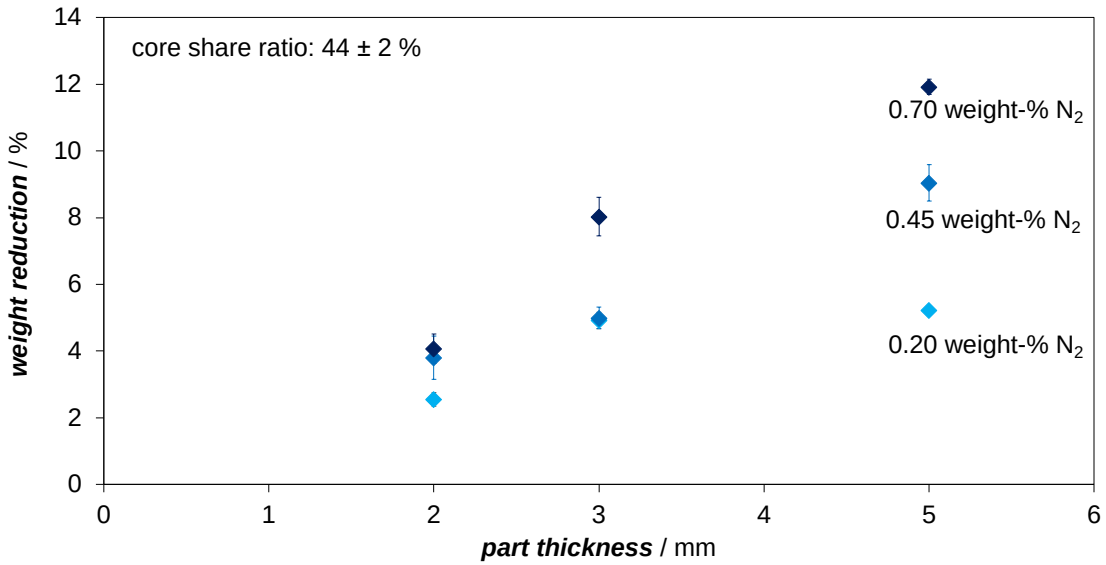

Figure 7: Total weight reduction as a function of component thickness

The maximum weight reduction increases with increasing part thickness for 0.70 and 0.45 weight-% blowing agent content. Increasing part thickness leads to larger material quantities, which have to be cooled over approximately the same cavity area. The width and length of the part (200 mm x 500 mm) remains the same, only the area of end faces increases by the respective difference in part thickness. Furthermore, the heat in the center of the part has to be transferred through a larger amount of low-heat-conductive polymer with rising part thickness. Therefore, the core component is in a hotter state for a longer time, the crystallization temperature is reached later, the polymer is foaming for a longer time and a higher weight reduction can be achieved. This effect has been investigated in [23]. At a blowing agent content of 0.20 weight-% the maximum weight reduction remains constant for part thickness of 3 and 5 mm. This can be explained by an insufficient foaming pressure at low gas loading.

With a part thickness of 2 mm, 4.0 ± 0.4 % weight can be saved. If the part thickness is increased to 5 mm, a weight saving of 11.9 ± 0.2 % can be achieved. It can be concluded from the present considerations that, especially for parts which already have a high wall thickness, the use of the co-injection molding process with a foamed core is economically and ecologically target-oriented.

The state of the art [2,19,21,24,25] also shows a trend towards higher weight reductions with increasing part thicknesses. While in literature much smaller parts (in some cases tensile bars) are used where mold filling is completed after a short time, the parts in the present work (with 500 mm x 200 mm) have a longer flow path and a longer filling time. A large proportion of the foam cells grow only after the injection is completed (injection pressure has stopped), until the material has solidified. This time period can be much shorter for components with a longer flow path, which is why a smaller weight reduction (for the same part thickness) can be achieved [1]. In addition, the injection pressure is usually higher with a larger flow path/wall thickness ratio and the foam cells nucleate later (only when the pressure falls below the critical pressure).

4.2 Effects on the internal structure of the part

4.2.1 Skin/Core-Distribution

In addition to the maximum core content and the maximum weight reduction, the structure of the parts is decisive for its properties. In the present section, the influence of the blowing agent content on the skin/core distribution is investigated. Figure 8 shows the skin-core distribution of co-injected components with different blowing agent content and core volume share. The weight reduction of the foamed components remains constant at 5 % and the part thickness is 3 mm. The blowing agent content increases from left to right and the core volume share of the parts increases from top to bottom.

An increase in core volume share leads to an increase in core area ratio as also shown in the literature on (compact) co-injection molding [11–14]. While an injected core volume share of 30 % leads to a core area ratio of 52 %, 40 % lead to 67 % and 45 % to 83 %, respectively. For each of the three different core volume ratios shown, no influence of the N_2 content on the core area ratio can be seen. The influence of the gas content on the viscosity of the core component plays a minor role here.

The flow front of the core material is significantly shorter at low (and no) gas loading, while a longer, thinner core appears with increasing gas content, due to decreasing viscosity for increasing gas content. A similar behavior is observed by Gomes et al [11] when the melt temperature of their (compact) core material is increased and thus the viscosity decreased. L.-S. Turng and H. Kharbas [5] also observe a longer and thinner core when using the foam injection molding process compared to compact core material.

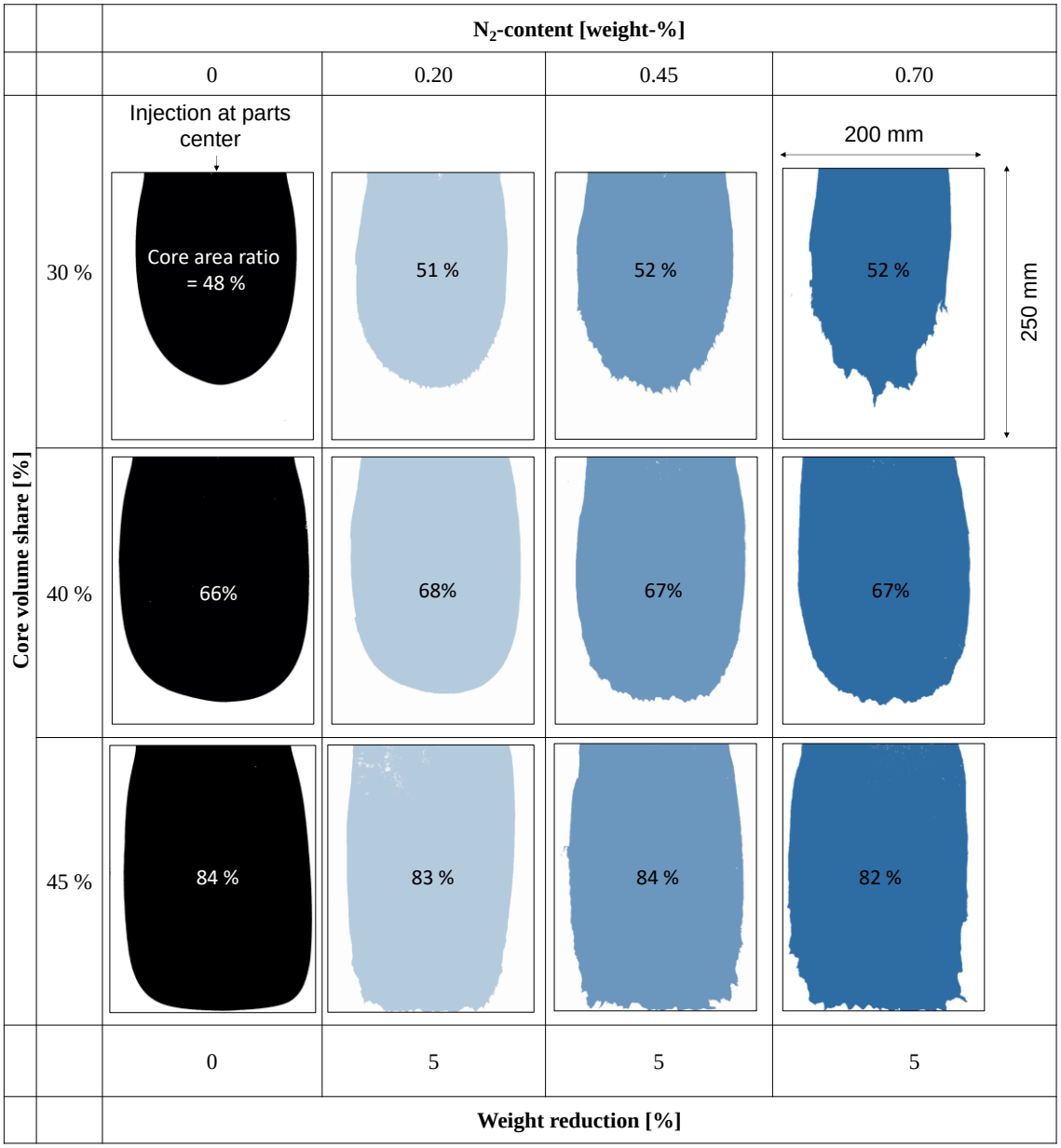

Figure 8: Skin-core distribution of co-injected components with different blowing agent content and core volume share (part thickness 3 mm, weight reduction of foamed parts 5%)

Especially at the end of the flow path, there is a low pressure (final mold filling is achieved by the gas-loaded core by means of foaming [1,8,26]) and pressure falls under the critical pressure, causing outgassing of the blowing agent. For high gas contents the amount of out-gassing N_2 is high and thus, the finger flow is clearly pronounced at the end of the core flow front as the gas content increases.

4.2.2 Foam Morphology

In addition to the distribution of the core component in the skin component, the cell size distribution is enlightened in this work. Therefore, the influence of the component thickness on the cell size distribution is considered first, Fig. 9: An increase of component thickness leads to a broader cell size distribution with larger cell sizes. While the most frequent cell diameter in a part of 2 mm thickness is 0.02 mm with a frequency of 67 %, a part of 4 mm thickness depicts a most frequent cell size of 0.03 mm with a frequency of only 20 %. This is explained by the change in thermal conditions in the part [23], as already discussed.

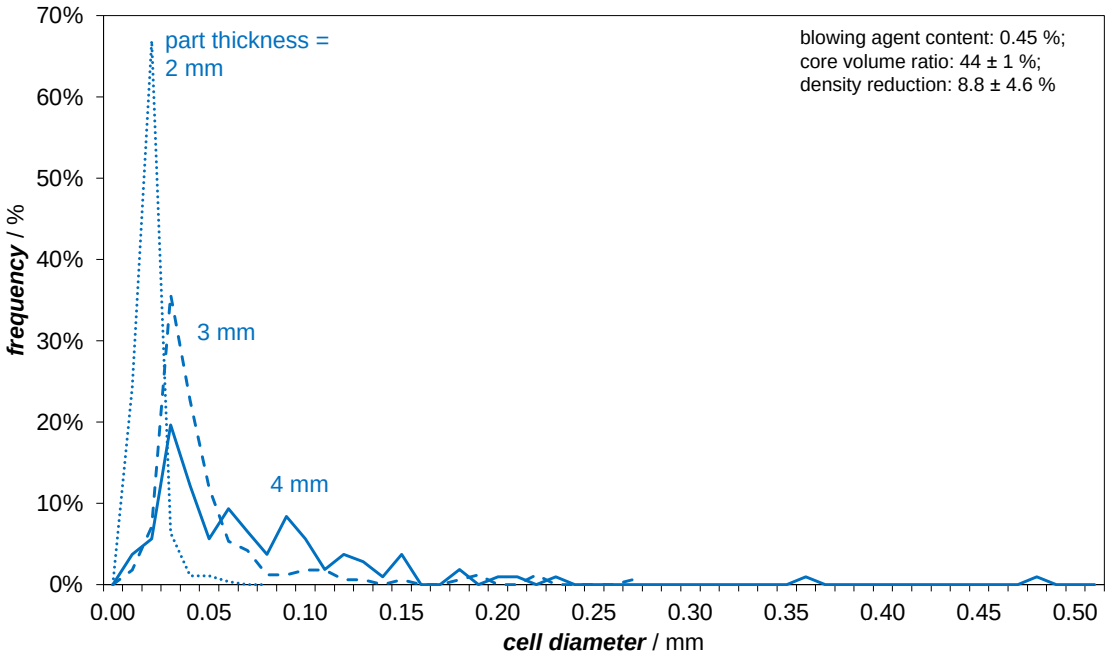

Figure 9: Frequency of cell diameter versus cell diameter of co-injection molded parts with foamed core at different part thicknesses

This also explains the significantly lower cell density (see Figure 10) of 285 /mm^2 on average for a part thickness of 4 mm compared to 6688 /mm^2 for a part thickness of 2 mm: the cells are stabilized later during the cooling period therefore they have more time to coalesce in the case of higher part thicknesses. The SEM images of the specimens, see Figure 12, also confirm these explanations: bigger part thicknesses lead to larger foam cells, especially in the center of the specimens.

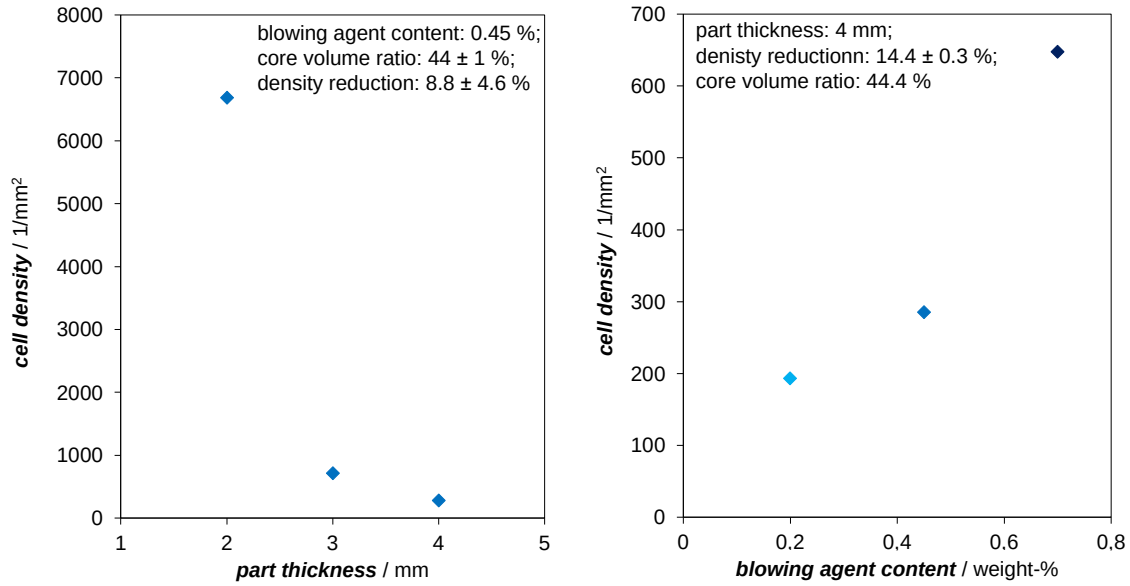

Figure 10: Left: Cell density versus part thickness of co-injection molded parts with foamed core.
Right: Cell density versus blowing agent content of co-injection molded parts with foamed core.
(Error bars are smaller than data points)

The influence of the N_2 content on the cell size distribution, Figure 11, is less pronounced than the influence of part thickness. Nevertheless, an increasing N_2 content leads to a narrowed cell size distribution. While the most frequent cell size of 0.20 % blowing agent content is 0.10 mm (frequency 11 %), 52 % of the cells at a blowing agent content of 0.70 % show a size between 0.04 and 0.06 %. Although a blowing agent content of 0.45 % shows the highest frequency of 20 % at 0.03 mm, the cell size distribution is wider compared to a blowing agent content of 0.70 %. The cell density, see Figure 10, increases with increasing blowing agent content.

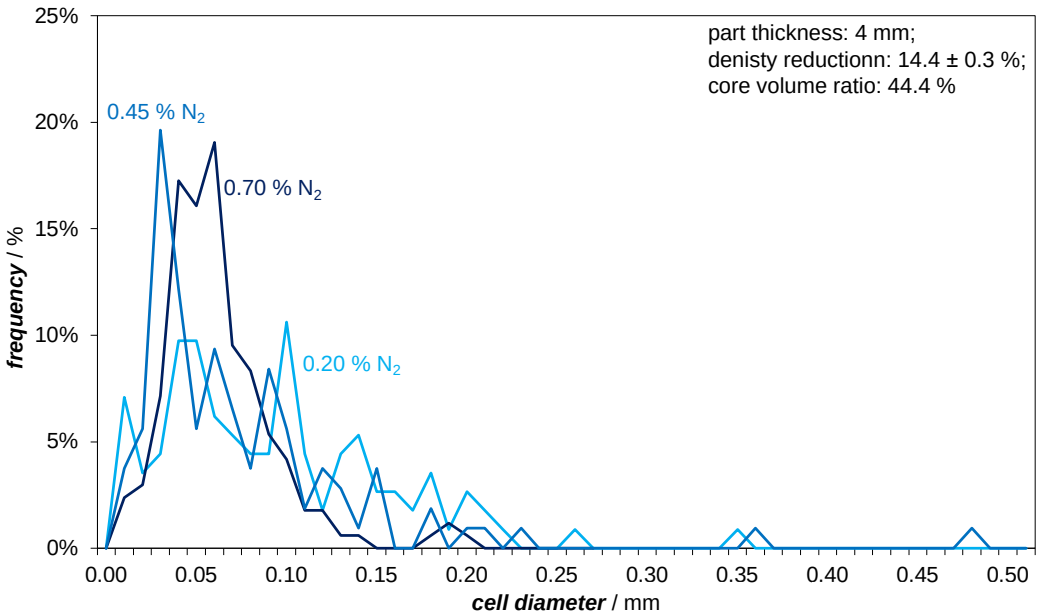

Figure 11: Frequency of cell diameter versus cell diameter of co-injection molded parts with foamed core at different blowing agent contents.

In literature [19], cell diameters up to a maximum of 0.2 mm are achieved in co-injection molded parts with PP core, too. However, a systematic elucidation of the influence of the component thickness and the blowing agent content on the cell morphology has not yet been published.

The literature values from the single-component foam injection molding of Kotzev [27] and Gomez-Monterde [28], which investigate thermoplastic foams from PP, show cell diameters that are higher than the present ([27]: 400 to 500 µm; [28]: 3 - 288 µm) but the cell densities are in the same range ([28]: 3.30 to 8000 /mm^2).

Figure 12 shows the SEM images of the parts with different thicknesses and blowing agent contents. The N_2 content of the parts increases from left to right and the thickness of the parts increases from top to bottom. All samples show a distinct foam structure, as desired. While at 2 mm the foam cells are small and evenly distributed in-between the compact layers, the typical integral foam structure (small cells at the edge and large cells in the center) becomes more pronounced as the part thickness increases. The influence of blowing agent content is also shown in the SEM images: The cell density increases with increasing blowing agent content.

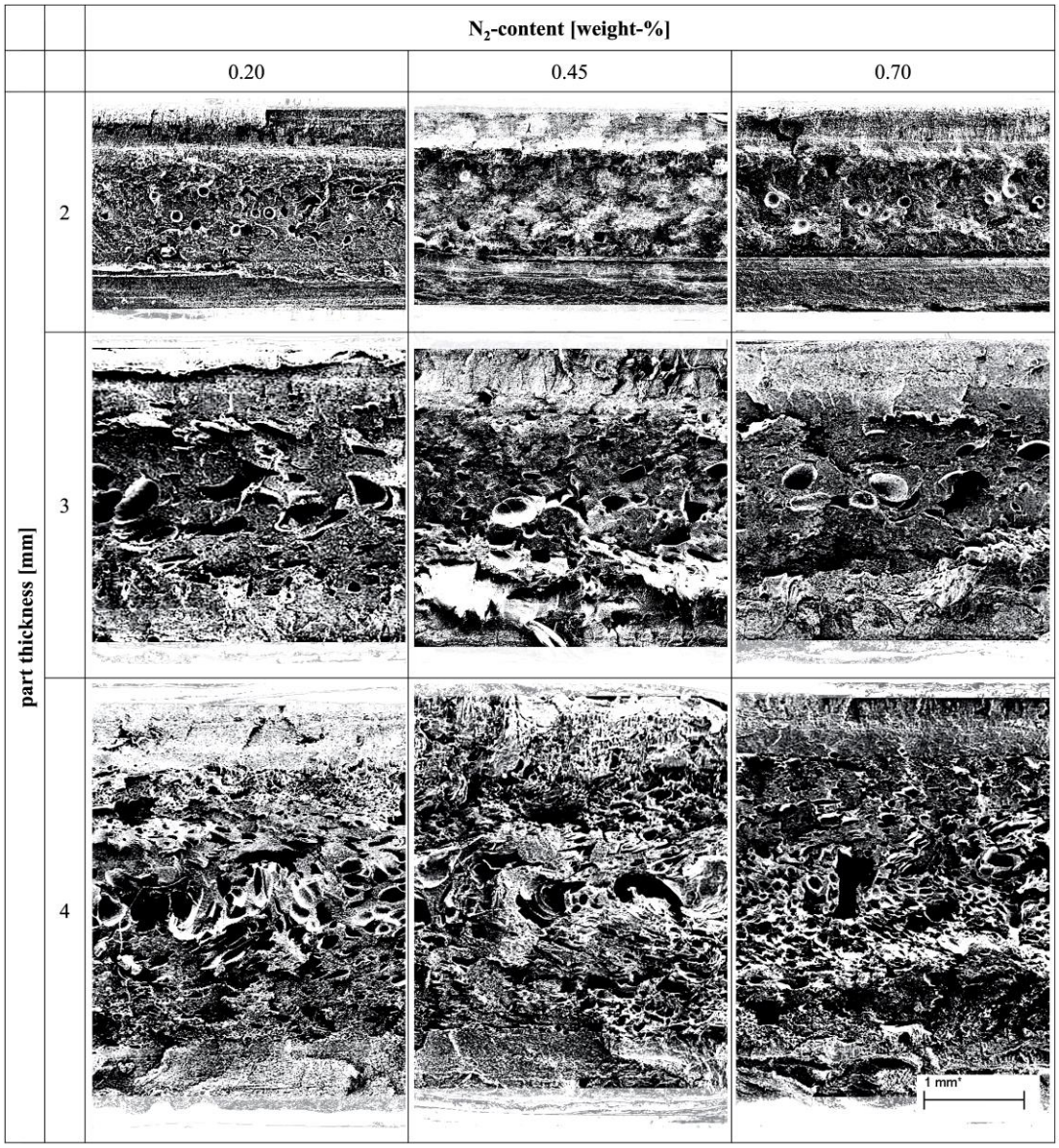

Figure 12: SEM images of co-injected components with foamed core at different blowing agent content and component thickness.

5 CONCLUSION AND OUTLOOK

In summary, increasing part thickness leads to a higher maximum core volume in the part. While with our sample geometry a part thickness of 2 mm leads to a maximum core volume fraction of 44 %, the fraction is increased to 51 % with a part thickness of 5 mm. This can be explained by the change of thermal conditions, when increasing the distance between the mold walls, leading to more remaining space for the core component between the frozen skin component.

Even if the maximum flow path / wall thickness ratio in this work is more than twice as large than the values considered in the literature [9,11,14,22], comparable core volume fractions are achievable.

Also, the maximum weight reduction increases with increasing part thickness. Increasing part thickness leads to larger material quantities, which have to be cooled over approximately the same cavity area. Due to the low heat-conductivity of the polymer melt, the melt exhibits a higher temperature for a longer time in the center of the part. Thus, a longer time frame for foaming is available for higher part thicknesses.

While the maximum weight reduction increases with the part thickness for 0.45 and 0.70 weight-% N_2, it remains constant for a blowing agent content of 0.20 weight-% for part thickness of 3 and 5 mm. This can be explained by an insufficient foaming pressure at low gas loading. Especially when comparatively high blowing agent contents of 0.70 weight-% N_2 are used, large part thicknesses (5 mm) can save up to 12 % of the total weight compared to an compact co-injection molded part. The weight savings can be further maximized by increasing the component thickness. However, due to the comparatively large amount of thermal energy that needs to be dissipated, high component thicknesses lead to large foam cells, especially in the center of the core component. This needs to be critically examined when applying the process to mechanically loaded components.

An increase in core volume share leads to an increase in the core area ratio as also shown in the literature on (compact) co-injection molding [11–14]. The N_2 content plays a minor role for skin/core-distribution. Especially for high N_2 contents (0.70 %) the finger flow is clearly pronounced at the end of the flow front of the core polymer, due to instabilities of the polymer melt flow (out-gassing of the N_2 after pressure drop).

In further investigations, the mechanical properties as well as the warpage of co-injection molded parts with TPS skin component and foamed PP core component will be examined for different part thicknesses and thus part morphologies. Furthermore the influence of flow path length on achievable core fraction will be investigated.

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