Bending properties of structural foams manufactured in a hot press process

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ABSTRACT
Thermoplastic foams allow manufacturing of lightweight parts with good thermal and acoustic insulation properties. To increase the mechanical properties without changing the part weight, these foams can be transformed into structural foams by a newly developed two-step isochoric and isothermal hot press process. Structural foams consist of a low-density foam core and two high-density polymer skins. The production of a polymer skin on the surface of a foam was realized in a hot press process by heating one tool half to process temperatures above glass transition temperature of the amorphous polymer. To manufacture polymer skins on both sides of the foam, it is necessary to turn the foam upside down and repeat the procedure. Structural foams were manufactured with two different polymer foams with different cell structures and densities. Optical analysis of microsections was used to investigate the formation of the polymer skins and the change in foam structure. This study investigates the applicability of an empirical relationship between part densities and bending properties. It was found, that knowledge about the part density alone is not sufficient for the prediction of the bending properties, because the foam structure (e.g. open or closed foam cells) has a considerable impact on the foam properties.

Keywords: Thermoplastic foams; amorphous polymer; structural foams; bending properties; hot press process; Divinycell F; Ultem XP; open cell foams; closed cell foams

Introduction
Global challenges such as reduction of energy consumption and emission of carbon dioxide demand sustainable lightweight structures and parts for automotive and public transport application. Especially with public transport vehicles, materials for structural parts must comply with fire safety regulations [1–3]. While end-of-life parts made with thermoset polymers can be recycled through various approaches, e.g. mechanical recycling and reuse as...
filler material, these processes are often associated with a downgrage in material properties. Composites made with thermoplastic polymers allow a circular economy and the reduction of end-of-life waste, without considerable downgrading of the polymer. Thermoplastic polymers also come with a variety of advantages such as the use of semifinished products with unlimited shelf life and part manufacturing with short cycle times. Processes to produce thermoplastic parts can be designed by efficient continuous compression molding techniques for flat semifinished products. Transformation into final part geometry can be achieved in thermoforming processes with short-cycle times [4].

Polyethersulfone (PES) and Polyetherimide (PEI) are excellent candidates for application in structural parts for public transport due to inherent flame retardant properties and good thermal stability [3].

Polymeric foams are cellular materials with a three dimensional structure, that may contain open or closed cells and can be manufactured to relative densities as low as 3% of the polymer density. They are excellent engineering materials regarding thermal and acoustic insulation, but due to reduced densities, their mechanical properties are low [5].

Structural foams have a sandwich-like structure with a low-density foam core and high-density polymer skin at their part surfaces. Due to this density gradient across the part thickness, they can achieve higher stifferness than uniform density foams at the same overall density. Compared to monolithic material, they can achieve the same stiffness at lower part weights. State of the art processes to produce structural foams are carried out by chemical or physical foaming techniques in injection molding processes and are applied for manufacturing of final part geometries [6–11].

This study discusses a novel process to manufacture flat structural foam and the impact on part structure and bending properties. The process allows the transformation of commercially available thermoplastic foams, based on amorphous polymers into structural foam sheets. Compared to conventional processes for the manufacturing of structural foam parts, the method allows production of flat parts with a defined thickness and a defined density distribution within the part. Additionally, thermoforming of these flat semifinished parts facilitates the production of more complex, shell-like components.

Uniform density thermoplastic foams have been transformed into structural foams with relative densities between 4% and 20%. The polymer skins produced on the part surface have been analyzed using microsections. The change in bending properties was investigated in three-point-bending tests. The first objective of this study is to discuss an approach that has been applied to determine the thickness of the produced polymer skins in open and closed cell foams. Since established scientific models for the prediction of bending properties require an in-depth knowledge of the foam structure, the second objective of this study is to investigate the applicability of an empirical relationship between the part density and the bending properties.

### State of the art

**Relationship of foam properties and mechanical properties**

The relationship between the density and the mechanical properties for uniform density foams and structural foams has been the focus of many publications. Prediction of the properties has been considered by a variety of approaches, but have been met with limited success. While sophisticated modeling approaches allow good prediction of the mechanical properties, the parameters necessary for these predictions demand exhaustive examination of the materials structure. Surprisingly, rather simple empirical approaches provide a prediction of mechanical properties based on foam densities [7, 12–19].

A foam part has a volume $V_{\text{part}}$ and a density $\rho_{\text{part}}$ and is considered to be a composite material made of a polymer volume $V_{\text{polymer}}$ and the density $\rho_{\text{polymer}}$ with air filling the residual volume $V_{\text{air}}$ with the density $\rho_{\text{air}}$. The part weight can then be described by the linear law of mixtures (Eq. (1)):

$$V_{\text{part}} \cdot \rho_{\text{part}} = V_{\text{polymer}} \cdot \rho_{\text{polymer}} + V_{\text{air}} \cdot \rho_{\text{air}}$$  \hspace{1cm} (1)

which can be rearranged to Eq. (2).

$$\rho_{\text{part}} = \frac{V_{\text{polymer}}}{V_{\text{foam}}} + \frac{V_{\text{air}}}{V_{\text{foam}}} \cdot \frac{\rho_{\text{air}}}{\rho_{\text{polymer}}}$$  \hspace{1cm} (2)

The density of air $\rho_{\text{air}}$ can be considered to be much smaller than the density of the polymer $\rho_{\text{polymer}}$. Therefore, Eq. (3) describes a simplified version of Eq. (2), a simple relation between part volumes and part densities, the relative part density $\phi$:

$$\frac{\rho_{\text{foam}}}{\rho_{\text{polymer}}} = \frac{V_{\text{polymer}}}{V_{\text{foam}}} = \phi$$  \hspace{1cm} (3)

This ratio $\phi$ is considered a key property within the published literature [5]. A commonly assumed relationship between a mechanical property, e.g. the Young’s modulus $E$, and the relative density $\phi$ can again be described using the linear law of mixtures (Eq. (4)):
urethane foams and found varying values for the exponent $n$ for different properties between $1.1 < n < 1.8$ [18]. Iida et al. found a relation for $n = 1.91$ [19].

Based on the findings of these reports, it should be possible to describe the relationship between relative mechanical properties and relative density of foamed material with the empirical equation (Eq. (8)):

$$\frac{E_{\text{foam}}}{E_{\text{polymer}}} = \left(\frac{\rho_{\text{foam}}}{\rho_{\text{polymer}}}\right)^n = \varphi^n \quad (8)$$

In the presented literature, values $1 < n < 2$ are given for the exponent $n$ for the empirical approach described in Eq. (8).

**Figure 1** shows the relationship between relative bending modulus and relative part density for different exponents $n$. This equation can be rearranged into Eq. (5):

$$\frac{E_{\text{foam}}}{E_{\text{polymer}}} = \frac{V_{\text{polymer}}}{V_{\text{foam}}} + \frac{V_{\text{Air}}}{V_{\text{foam}}} \frac{E_{\text{Air}}}{E_{\text{polymer}}} \quad (5)$$

Considering that $E_{\text{Air}}$ is much smaller than $E_{\text{polymer}}$ the relation can be described by Eq. (6):

$$\frac{E_{\text{foam}}}{E_{\text{polymer}}} = \frac{V_{\text{polymer}}}{V_{\text{foam}}} = \frac{\rho_{\text{foam}}}{\rho_{\text{polymer}}} = \varphi \quad (6)$$

Equation (6) describes a linear relationship between the relative density $\varphi$ and the relative modulus. The applicability of this relation for selected mechanical properties has been confirmed by several authors [5, 7, 13, 14].

Moore, Couzens and Iremonger compared different modelling approaches with experimental values for shear, tensile and compression moduli. In their report, it is described that comparison of the measured moduli to the density of the material are inadequate. The properties must be related to the properties of the unfoamed material. As a result of comparing five theoretical models, they found best agreement of experimental values with an empirical square-law relation (Eq. (7)) between the relative modulus, the ratio of foam modulus to the modulus of the solid polymer and the relative part density, ratio of part density to polymer density [12]:

$$\frac{E_{\text{foam}}}{E_{\text{polymer}}} = \left(\frac{\rho_{\text{foam}}}{\rho_{\text{polymer}}}\right)^2 \quad (7)$$

Although the authors were not able to explain this correlation, its applicability has been confirmed by several authors [14–17].

Iremonger and Lawler presented finite element analysis models of ‘circular hole in square plate’ and ‘spherical hole in solid cube’ and found better agreement with this square-law relation (Eq. (7)) than with previous theoretical models [17].

Traeger investigated the relationship between part properties and part densities for polyester based
thickness or the density within the polymer skin. However, to use an existing model, or even develop a new approach to correlate the density distribution within a structural foam with its mechanical properties, it must be considered at first how the foam structure is changed by the presented process.

**Material distribution in polymer foams**

Foams are cellular materials, a three-dimensional cluster of cells that may be open or closed. Open cell foams can be described as a network of struts, while closed cell foams additionally have membranes spanning between the struts. Material distribution in open and closed cells can be calculated with Eqs. (10) and (11). In closed cell foams the relative density $\varphi$ scales linearly with the ratio of edge thickness $t_e$ to its length $l_e$. In open cell foams $\varphi$ scales with the square of this ratio. The constants of proportionality $C_1$ and $C_2$ can be approximated as being close to $C_1 = 1$ and $C_2 = 1.5$.

$$\varphi = C_1 \frac{t_e}{l_e}$$

$$\varphi = C_2 \left(\frac{t_e}{l_e}\right)^2$$

**Compressive behavior of polymer foams**

Compressive deformation of cellular materials can be divided into three distinct sections: elastic and plastic deformation as well as densification, see Figure 2. When the foam is loaded with a compressive force, the cell walls start to buckle. When the force exceeds the compressive strength, cell walls start to break continuously. The compressive stress–strain curve shows a plateau for a wide range of deformation. The last section describes the densification. During densification, the stress shows a steep increase due to opposing cell walls being pressed together.

The compressive behavior of foams is mainly influenced by their structure that is divided into open or closed cells. Figure 3 shows cubic cell models for open and closed cell foams as well as the manner in which plastic deformation occurs. The figures are an excerpt from Cellular Solids: Structure and Properties by Gibson and Ashby. In open cell foams, the mechanisms of deformation can be described by cell wall bending as well as axial deformation. Contained fluid can flow between the cells. Deformation in closed cell foams on the other hand can be described as a combination of cell wall bending, edge contraction and membrane stretching. Compressive linear elasticity is mainly impacted by cell wall bending, in both open and closed cell foams. While membranes in closed cell foams do have a bending stiffness, their impact on the overall bending behavior of the cell is rather small; usually these membranes are very thin.

**Thermomechanical behavior of thermoplastic polymers and foams**

The mechanical properties of foams depend on the mechanical properties of the material within the cell walls. Figure 4 shows the temperature dependent Young’s modulus for amorphous thermoplastic polymers. Since the mechanical properties of thermoplastic polymers decrease with increasing temperature, the mechanical properties of thermoplastic foams must decrease as well. The most important temperature for amorphous polymers is their glass transition temperature $T_G$.

With regard to compressive behavior at increasing temperature, the compressive modulus and strength decrease. In the elastic-plastic state ($T \approx 0.9 T_G$) the polymer becomes more ductile and cells can be deformed more easily. When the temperature is raised above $T_G$, the compressive behavior declines even further. At temperatures above $T_p$, the behavior enters a rubbery regime ($T \approx 1.2 T_G$) and eventually can be described as a viscous flow ($T \approx 1.4 T_G$). However, the most important characteristic of foamed materials is their thermal insulation behavior. Conductive heating through the polymer is reduced due to the low density of foams and the biggest contribution to heat flux through a foam is the conduction through the gas within the cells.

**Theoretical considerations**

**Polymer skin production**

This combination of reduced compressive strength at high temperatures and low thermal conductivity through the foam thickness could be exploited to change the structure of polymer foams made from amorphous thermoplastic polymers. Structural foams discussed in this study are manufactured...
from uniform density foams with an initial thickness \( t_0 \). To produce polymer skins on both sides of the foam, its cells are compacted at temperatures above \( T_G \) \((T > T_g)\) to a defined thickness \( t_{\text{part}} \) in two process steps. Figure 5 shows a schematic drawing of the cross section of a uniform density foam that is transformed into a structural foam. The polymer skins are the result of the compaction of foam cells. The part thickness \( t_{\text{part}} \) of a structural foam can be described with Eq. (12) as the sum of the skin thicknesses \( t_{\text{skin}} \) and the thickness of the residual foam core \( t_{2-\text{core}} \):

\[
t_{\text{part}} = 2*t_{\text{skin}} + t_{2-\text{core}}
\]  

(12)

The compaction \( t_{\text{comp}} \) describes the foam thickness that is compacted into the polymer skin. It is calculated as the difference between the initial foam thickness \( t_0 \) and the thickness of the residual foam core \( t_{2-\text{core}} \) with Eq. (13(a-c)):

\[
t_{\text{comp}} = t_0 - t_{2-\text{core}}
\]  

(13a)

\[
t_{\text{comp}} = t_0 - (t_{\text{part}} - 2*t_{\text{skin-theo}})
\]  

(13b)

\[
t_{\text{comp}} = t_0 - t_{\text{part}} + 2*t_{\text{skin-theo}}
\]  

(13c)

The relative density \( \varphi_0 \) describes the ratio of the density of the uniform density thermoplastic foam and the solid polymer (Eq. (14)).

\[
\varphi_0 = \frac{\rho_0}{\rho_{\text{polymer}}}
\]  

(14)

In the presented process, the polymer skin is produced through local compaction of foam cells, and therefore, through an increase in material density. However, material density can only be increased until the polymer density is reached; the skin thickness, thus, reaches a minimum when the polymer density is reached. To describe skin formation through compaction of foam cells, the cubic cell models shown in Figure 3 have to be considered. When open cell foams are fully compressed, the material can be described as a porous cluster of struts, while closed cell foams can be described as a more homogeneous package with membranes filling the spaces between the struts. Using the relative foam density \( \varphi_0 \) (Eq. (14)), the skin thickness can be calculated for each compaction \( t_{\text{comp}} \) of foam cells (Eq. (15)).

The minimal theoretical skin thickness \( t_{\text{skin-theo}} \) can be determined by the ratio \( \varphi_0 \) that describes the initial density \( \rho_0 \) of the thermoplastic foam and the density of the solid polymer \( \rho_{\text{polymer}} \).
Table 1. Properties of semifinished materials [23–25].

| Material       | Polymer | Cell structure | Density (kg/m³) | Initial thickness (mm) |
|----------------|---------|----------------|----------------|------------------------|
| Divinycell F40 | PES     | Closed         | 40             | 9.7                    |
| Divinycell F50 | PES     | Closed         | 50             | 5                      |
| Ultem XP50     | PEI     | Open           | 50             | 5                      |
| Ultem XP110    | PEI     | Open           | 110            | 5                      |

Theoretical skin thickness can be calculated with Eq. (15a):

\[
t_{\text{skin-theo}} = \frac{1}{2} \phi_0 \cdot t_{\text{comp}}
\]

Relative skin density can be calculated with Eq. (15b):

\[
\phi_0 = \frac{1}{2} \cdot \phi_0 \cdot \left( t_0 - t_{\text{part}} + 2 \cdot t_{\text{skin-theo}} \right)
\]

Relative deviated skin thickness can be calculated with Eq. (15c):

\[
\phi_0 = \frac{1}{2} \cdot \phi_0 \cdot \left( t_0 - t_{\text{part}} \right)
\]

To evaluate the compaction of foam cells based on the measurements from optical analysis of polymer skin areas, their density could be estimated with Eq. (16), using the relative skin density \( \tau \), the ratio between the theoretical skin thickness \( t_{\text{skin-theo}} \) and the measured skin thickness:

\[
\tau = \frac{t_{\text{skin-theo}}}{t_{\text{skin-measured}}}
\]

Considering the inaccuracies while measuring the involved factors, the relative propagated error \( \frac{\delta \tau}{\tau} \) for the relative skin density \( \tau \) can be calculated with Eq. (17). The initial density of the polymer foam \( \rho_0 \) will be regarded as being constant for this calculation; the remaining variable factors are the relative deviation for compaction \( \frac{\delta(t_0 - t_{\text{part}})}{t_0 - t_{\text{part}}} \) and the relative deviation for the measured skin thickness \( \frac{\delta(t_{\text{skin-measured}})}{t_{\text{skin-measured}}} \):

\[
\frac{\delta \tau}{\tau} = \sqrt{\left( \frac{\delta(t_0 - t_{\text{part}})}{t_0 - t_{\text{part}}} \right)^2 + \left( \frac{\delta(t_{\text{skin-measured}})}{t_{\text{skin-measured}}} \right)^2}
\]

The overall density of the manufactured structural foam can be calculated with Eq. (18) using the initial density of the polymer foam \( \rho_0 \) together with the initial thickness and the part thickness:

\[
\rho_{\text{part}} = \rho_0 \cdot \frac{t_0}{t_{\text{part}}}
\]

### Manufacturing of structural foams

The hot press process for manufacturing structural foams presented in this study was designed as a two-step isothermal and isochoric process on a hot press. To control the compaction of foam cells only the upper tool was heated to process temperature above glass transition temperature \( T_g \) of the polymer. To achieve compaction to defined part thicknesses, the cavity height between the top and bottom tool of the hot press was limited by steel spacers. Since this process design only allows production of polymer skin on one side, it was necessary to turn the foam upside down after the first process step. The general approach to manufacturing structural foams described in this study is shown in Figure 6.

The manufacturing of thermoplastic structural foams using varithermal and isothermal hot press processes and the effect on different part properties is described in Refs. [28–30].

Structural foam sheets with surfaces of 100 \( \times \) 100 mm² were manufactured on a hydraulic laboratory press Collin P 300 P/M in two subsequent hot press processes to produce polymer skins on both sides. The surface of the top and bottom tools of the laboratory hot press was 300 \( \times \) 300 mm². In combination with the casing of the hot press and the steel spacers as a barrier, this much larger tool surface prevented convective cooling of the much smaller surface of the structural foam sheet of 100 \( \times \) 100 mm². After reaching the process temperature in the top tool, a waiting period of 10 min allowed a homogeneous temperature distribution on the tool surface. During manufacturing of structural foam sheets, the temperature was controlled using thermocouples. The compaction was equal for both process steps. The process pressure was set below the compressive strength of the foam material and was applied for 180 s. The temperatures used for manufacturing are given in Table 3.

For each parameter set, consisting of material and final part thickness, five structural foam sheets were produced. The properties of the structural foam sheets manufactured in this study are summarized in Table 4.

Microsections for the analysis of skin thicknesses and test specimens for testing of the bending properties have been cut from these structural foam sheets. The position within the structural foam sheet...
as well as the viewing direction for the microsection is shown in Figure 7.

**Analysis of polymer skins**

The polymer skins manufactured in the hot press process were analyzed via microsections using a Leica DM6000M microscope with the associated software tool. The method to define the skin thickness is outlined in Figure 8. A microsection with a width of 20 mm was prepared for each produced structural foam sheet (Figure 8a). To measure skin thicknesses, the microsection was further divided into five individual sections along its width (Figure 8b). This procedure was necessary to obtain images of each individual section with a sufficient resolution for analysis. The skin thickness was determined by the use of two parallel bars. The first bar was placed on the surface of the sample. The second bar was placed on the core-side to determine. The skin thickness was then defined as the smallest thickness between the part surface and the foam core. Skin thicknesses in these individual sections were determined for upper and lower skins (Figure 8c). The average skin thickness and the standard deviation for one structural foam sheet has been determined as the mean value of five thicknesses each for upper and lower skins. The average skin thickness and standard deviation for one test series, a combination of material and final part thickness, was determined as the mean value across all five structural foam sheets.

**Mechanical testing of structural foams**

Mechanical properties of the structural foams were determined in three-point-bending tests according to DIN EN ISO 178. The setup for this test is shown in Figure 9.

The test specimen were of dimensions $(l_{\text{part}} \times b)$ of $80 \times 10\ \text{mm}^2$ with different thicknesses between 2 and 9.7 mm. Testing speed was 2 mm/min. Support length for bending tests are given in Table 5. To compensate for inhomogeneities within the manufactured structural foams sheets three samples were tested per produced structural foam sheet.

The characteristic property of bending strength can be calculated with Eq. (19) as the maximum value of bending stress $\sigma_b$ during testing [31]:

$$\sigma_b = \frac{3 \times F + L}{2 \times b \times t_{\text{part}}^2}$$  \quad \text{(19)}

The bending strain $\epsilon_b$ is calculated with Eq. (20) by the deflection $s$ of the part as [31]

$$\epsilon_b = \frac{6 \times s \times l_{\text{part}}}{L^2}$$  \quad \text{(20)}

Bending modulus $E_b$ is calculated with Eq. (21) as the secant gradient for bending stress for bending strains between 0.05% and 0.25%. Using both the bending stress $\sigma_b$ and the bending strain $\epsilon_b$ the bending modulus of the part is calculated as [31]:

$$E_b = \frac{\sigma(\epsilon = 0.25\%) - \sigma(\epsilon = 0.05\%)}{0.25\% - 0.05\%}$$  \quad \text{(21)}

**Results**

**Manufacturing of polymer skins**

The cross sections of two integral foams manufactured from Divinycell F50 and Ultem XP50 are
presented in Figure 10. Here the closed cell structure of Divinycell F and the open cell structure of Ultem XP are visible. While for XP50 the skin and core are distinguishable, this depiction does not allow a proper examination of the structure for F50. A comparison of structural foams of different thicknesses made with F50 and XP50 is shown in Figure 11. The contrast in these microsections between the polymer skin (bright) and the low-density foam core (dark) allowed good differentiation between both sections within the foam. In this comparison, the difference in skin formation between the closed cell structure of F50 and the open cell structure of XP50 is recognizable. Figure 12 shows cross-sections of structural foams made with F50 and XP50. The depicted cross-sections of the samples span across more than one individual section to portray the deviation of skin thickness along the entire specimen width. In structural foams made with Divinycell F foams, the polymer skins are thinner than those in structural foams made with Ultem XP foams. Even though the foams that were used to manufacture the foam had similar densities, both 50 kg/m³ and initial thicknesses of 5 mm, the skin thickness varies significantly. This could be explained by differences in skin formation for closed (F50) and open (XP50) cell foams based on the mechanisms during compression and material distribution within the foam cells. To evaluate the compaction and estimate the density in the produced skin, the measured skin thicknesses will be compared to minimal theoretical skin thickness, as

| Material | Initial thickness (mm) | Compaction in each step (mm) | Part thickness (mm) and density (kg/m³) |
|----------|------------------------|----------------------------|----------------------------------------|
| F40      | 9.7                    | 1.85                       | 6                                      |
|          |                        | 2.85                       | 4                                      |
|          |                        | 3.85                       | 2                                      |
| F50      | 4.9                    | 0.4                        | 4.1                                    |
|          |                        | 0.92                       | 3.1                                    |
|          |                        | 1.37                       | 2.2                                    |
| XP50     | 5.2                    | 0.65                       | 3.9                                    |
|          |                        | 1.05                       | 3.1                                    |
|          |                        | 1.60                       | 2                                      |
|          |                        | 0.48                       | 3.9                                    |
|          |                        | 0.89                       | 3.1                                    |
|          |                        | 1.43                       | 2                                      |
| XP110    | 4.9                    | 0.48                       | 3.9                                    |
|          |                        | 0.89                       | 3.1                                    |
|          |                        | 1.43                       | 2                                      |

Figure 7. Structural foam sheet with positions for extraction of microsection and test specimen for three-point-bending tests.

Figure 8. Sampling of microsections and individual sections for skin thickness analysis.

Figure 9. Schematic for three-point-bending tests [31].

Table 5. Support length for different part thicknesses.

| Thickness t_{part} (mm) | Support distance (mm) |
|-------------------------|-----------------------|
| 2                       | 32                    |
| 3                       | 48                    |
| 4                       | 64                    |
| 5                       | 64                    |
| 6                       | 64                    |
| 9.7                     | 64                    |
described in Eq. (15). This comparison is shown in Figures 13–18.

In Figures 13 and 14, the measured skin thickness of structural foams made with F50 and XP50 are shown for part thicknesses of 2.2 mm and 2 mm, respectively. The data points are differentiated by the structural foam sheet number within the test series and by measured values for the upper or lower skin. Structural foams made with F50 (Figure 13) show small deviations within the microsections, between upper and lower skin thickness, as well as between microsections from different structural foam sheets. The average skin thickness for these microsections was determined to be 61 μm with a standard deviation of 6.7 μm. With theoretical skin thickness of 52 μm the relative skin density $\tau$ is 86% compared to that of the solid polymer. In contrast to this, Figure 14 shows measured values for structural foam sheets made with XP50. Here, deviation between different structural foam sheets and between upper and lower skin is more distinct. The mean values were determined to be 120 μm with a standard deviation of 25 μm. In comparison to a theoretical skin thickness of 65 μm, the measured values indicate that the relative skin density $\tau$ in this area is 55%. The

![Figure 10. Cross section of integral foams manufactured from F50 and XP50.](image1)

![Figure 11. Cross section of structural foams made with F50 (left) and XP50 (right) with different part thicknesses.](image2)

![Figure 12. Microsections of structural foams made with F50 and XP50 with measurements of skin thickness.](image3)
comparison of skin thicknesses for the test series with different compaction and density shows that the skin thicknesses measured for structural foam sheets manufactured with Divinycell F foams (closed cell foam) match the theoretical values quite well, see Figure 15. However, it seems that the difference between the measured values and theoretical values decreases for increasing compaction. The theoretical skin density \( s \) can be calculated as the ratio between theoretical and measured skin thickness for each individual specimen. It seems, that for sufficient compaction, the manufactured skin thickness can be estimated by the approach described in Eq. (15), see Figure 16. On the other hand, measured skin thicknesses in structural foams made with Ultem XP (open cell foam) are at a similar level, regardless of the initial density of the thermoplastic foam and the compaction applied in the process, see Figure 17. Even though the relative skin density \( \tau \) seems to increase for increasing compaction (Figure 18), an actual relation for these foams cannot be described with the proposed model. Since the foam structure, open cell or closed cell, is a main difference, it can be said that the foam structure plays an important role in skin formation.

To evaluate the validity of the calculated relative skin density \( \tau \) it is necessary to consider the error propagated by inaccuracies during measurement of the involved factors by Eq. (17). The values are presented in Figure 19 in relation to the compaction that was applied during the skin production. Since the method to determine the skin thickness is associated with inaccuracies, the presented values should be regarded as a lower boundary for possible errors, rather than absolute values. Nevertheless, an average error between 10% and 15% does not change the previously made statements.

To evaluate the suitability of this method for measuring skin thicknesses and calculation of the theoretical densities, several conditions and simplifications have to be considered:
The first simplification for the model is that foam cells are compacted only in the immediate vicinity of the hot tool. This does not consider the possibility of the foam being plastically deformed by force beyond its compressive strength. For the application of this method, process force must not exceed compressive strength of the material at room temperature.

The second simplification is that a homogeneous bar of polymer skin would be the result of the compaction. The microsections of the structural foams clearly show that the skin production is supported by cell walls and struts. Because of this, the boundary between skin and foam core is inhomogeneous. For structural foams made with open cell Ultem XP foams display this behavior even more so than structural foams made with closed cell Divinycell F foams.

The third simplification is the method itself that was used to determine the skin thickness. The skin thickness was defined as the smallest thickness between the part surface and the foam core, as demonstrated in Figures 8 and 12. The measurement of this thickness was complicated due to the inhomogeneous formation of the skin described in the previous section. Reproducibility and reliability of the values for modelling approaches have to be confirmed in future studies with different independent examiners. The method needs to be compared to other means of optical analysis, e.g. grey-value analysis of areas with defined thicknesses.

The last simplification is that compaction of foam cells at temperatures above $T_g$ occurs in a similar way, regardless of cell structure (closed vs. open), and thus, the distribution of material (membranes vs. struts). These mechanisms have to be evaluated further to optimize the measurement.

Due to the challenges described in the previous paragraphs as well as the uncertainties considering the values determined for skin thicknesses, only a qualitative comparison of the difference in structure can be applied.

Consideration of material distribution in polymer foams

Although this study cannot offer a definite measurement of skin thicknesses for the manufactured structural foam sheets, differences for open and closed cell foams have been identified. The material distribution within the foam has to be considered to identify, why the models proposed in Eq. (15) can be used to predict skin thickness in closed cell foams examined in this study.

In open cell foams, material is mainly located within the cell edges. Polymer skins can only be produced at points within the network, where these cell edges overlap and are heated. In closed cell foams, the material for production of polymer skins is located within the cell edges, but also within membranes spanning between these edges. The membranes can be described as being thin skins, and therefore, facilitate skin production.

Figure 20 compares the theoretical ratio of cell edge thickness $t_e$ to its length $l_e$ for the examined thermoplastic foams. The values are calculated with $C = 1$ and standard deviation is calculated with $0.8 < C < 1.2$. Each foam is considered to only contain closed or open cells. The comparison of F50 and XP50 shows the significant difference in material that is located within the cell edges. Approximately five times more material would be located within the cell edges of XP50 compared to F50. This means, that the remaining material in F50 would be distributed within the membranes, providing a better foundation for skin production, and therefore, allows a prediction with Eq. (15).

Figure 21 shows the cubic cell models described by Gibson and Ashby together with a simplified two-dimensional cross section model for the material distribution in open and closed cell foams and considers the deformation within both foam types. It also shows µ-CT scans of XP50 and F50. The polymer skin in XP50 appears to be of lower density than the skin in F50.

Bending properties of structural foams

Three-point-bending tests according to DIN EN ISO 178 were conducted to investigate the change in
mechanical properties. The change in stress–strain curves for structural foams made with F50 is shown in Figure 22. Compared to the raw material, a uniform density foam, the transformation into structural foams allows the part to tolerate higher bending stresses at lower part thicknesses but equal part weights. However, the structural foams display a more brittle behavior and distinct break occurs at smaller bending strain.

Figure 23 shows the change in bending modulus for structural foams with different thicknesses that were made with F50. Every test series contained five structural foam sheets manufactured to the same part thickness. Three test specimen, out of each of these structural foam sheets were tested to compensate for inhomogeneities. In general, the compaction of foam cells and thus the production of polymer skins has a positive impact on the bending modulus and bending strength. However, the scatter between the properties of samples made from the same foam with similar part thicknesses increases with increasing compaction. This has to be investigated further and connected to the process parameters in future studies.

Figures 24 and 25 show the bending properties of structural foams made with F50 and XP50. Bending modulus and bending strength increase with increasing compaction for both materials. While bending properties in structural foams made with F50 seem to increase linearly, the bending properties for structural foams made with XP50 increase nonlinearly. Figures 24 and 25 show that the bending modulus and strength increase with increasing compaction, i.e. increasing part density, of the structural foam.

To allow comparison of the change in bending properties across the different test series, the properties will be compared by the relative bending modulus (ratio of part modulus to polymer modulus) in relation to the relative part density (ratio of part density to polymer density), see Figures 26 and 27. Different authors proposed that the boundaries for comparisons of mechanical properties as a function of foam densities could be set by the linear law of mixtures (Eq. (6)) as an upper boundary and the square-law relation (Eq. (7)) as a lower boundary. The following figures also include additional curves as a means of comparison, representing a relation between relative modulus and relative density with different exponent $1 < n < 2$. However, if the change in bending modulus is compared to the courses for ratios with equal $n$, it is shown that not only the modulus increases with increasing density, but also the exponent $n$ seems to decrease (Figure 26). Through the transformation of uniform density foams into structural foams, the exponent for calculation of bending properties approaches $n = 1$, the linear law of mixture. Based on the results of the tests, this can be confirmed for structural foams made with Divinycell F as well as Ultem XP.
However, the comparison of different curves of these changes shows that the foams made with Divinycell F display a more digressive curve – a steep increase in bending modulus for small changes in density – while the foams made with Ultem XP display a linear increase with increasing density (Figure 27).

Figure 28 shows the exponent $n$ for bending modulus for all of the manufactured structural foams. The course of the exponent $n$ overlaps quite well for foams made with Divinycell F40 and F50 foams despite difference in initial thickness. A comparison of foams made with ULTEM XP is rather difficult.

The comparison of the change in exponent $n$ for bending strengths for F50 and XP50 shows that the impact of the foam structure becomes more pronounced, see Figure 30. There is a considerable difference between the first (raw material) and second (structural foam) data points for F50 and XP50 foams. While the exponent $n$ seems to stagnate in foams made with XP50 at 1.63, it changes from 1.63 to 1.43 in foams made with F50.
In Figure 31, the change for the exponent $n$ is plotted over the relative part density for all of the manufactured structural foams. We find again, that the change in Divinycell F foams overlaps quite well and that comparisons between Ultem XP foams is rather difficult due to the difference in initial density, as it could be seen in Figure 29.

**Discussion and outlook**

Structural foams were manufactured in a two-step isochoric and isothermal hot press process. Polymer skins were produced on the part surface through the compaction of foam cells at temperatures above glass transition temperature of the polymer. This transformation was examined for semifinished foams Divinycell F (PES – closed cell foam) and Ultem XP (PEI – open cell foam) for different densities. An overview of the determined properties is given in Table 6. The produced polymer skins were
analyzed using microsections. The analysis showed, that the polymer skin produced with Divinycell F foams are rather thin and their thickness can be approximated quite well using a linear relationship between the relative foam density $\rho$ and the applied compaction $t_{\text{comp}}$, see Eq. (15). However, this relation could not be confirmed for polymer skins produced with Ultem XP open cell foams. One explanation why skin formation in closed cell foams can be predicted with Eq. (15) is their cell structure. Due to the mass distribution between the cell edges and the membrane surfaces, a homogeneous polymer layer is produced as a skin by compacting under the influence of temperature. In open cell foams, the mass is concentrated in the cell edges. If these are compacted under the influence of temperature, the result is a compacted rod structure with a significantly higher pore content, which is why Eq. (15) cannot be used.

The transformation into structural foams has a significant effect on the bending properties of the foam parts. The change in bending properties was compared to empirical relationships between part density and bending properties. It was found, that not only the increase in part density is responsible for the increase in bending properties but also the change in the part structure also has a considerable impact. While this impact is less pronounced for the relation between relative bending modulus and relative part density, its impact becomes more recognizable when the bending strengths are compared. Even though the method used to determine the skin thickness is not without flaws, the general change in foam structure could be compared to the change in exponent $n$. The thin polymer skins, with a higher presumed density that were produced with closed cell Divinycell F foams resulted in a steeper change in exponent $n$, than for thicker polymer skins with a presumed lower density produced with open cell Ultem XP foams. With increasing compaction, this effect becomes less pronounced. A possible explanation as to why closed cell foams achieve steeper increase in bending properties might be that even at low compactions the material to produce the skin is available in a more homogeneous manner, thus creating a better-defined polymer skin.

Future investigations into the manufacturing of flat structural foam parts need to look at a larger selection of semifinished products as a starting point (e.g. combinations of initial density and initial thickness), to fully understand the relationship between the mechanical properties and the foam structure. The investigations need to be extended for the manufacturing of parts with relative densities that cover a wider range between initial densities, as low as 3% and polymer densities, up to 100%. In doing so, it should be possible to compare the properties of parts with equal relative density, but different core densities and skin-to-part density ratios. Another interesting objective would be further development of the process into a continuous compression molding process. The flat structural foam parts could be transformed into a final part geometry in thermoforming processes. Through an adjustment of the press tools, it should also be possible to manufacture structural foam parts with complex part thickness and geometries; thus resulting in varying skin thicknesses. These investigations could be conducted in a static or continuous hot press process.

Conclusion

This study discussed the impact of a novel process for manufacturing of structural foams on foam structures and their bending properties. Polymer skins produced in this process were analyzed using microsections. The measured skin thicknesses were compared to theoretical values to evaluate the density inside the produced polymer skin. It was found that skin production in closed and open cell foams does not take place in a similar manner. The change in bending properties was investigated in three-point-bending tests. Significant increase in bending properties was observed for increasing part densities. However, it was found that part density is not the only parameter that needs to be considered to predict part properties. The foam structure itself has a considerable impact on the foam properties.

Nomenclature

| Symbol | Description |
|--------|-------------|
| PEI    | polyetherimide |
| PES    | polyethersulfone |
| V      | volume |
| $P$    | density |
| $\Phi$ | relative density |
| $E$    | Young’s Modulus |
| $n$    | exponent of the empirical relationship |
| $C$    | constant for calculation of relative foam density with regards to cell edge thickness to length ratio |
| $\log$ | logarithmic function |
| F40    | Divinycell F40 |
| F50    | Divinycell F50 |
| XP50   | Sabic Ultem XP50 |
| XP110  | Sabic Ultem XP110 |

Symbols

| Symbol | Description |
|--------|-------------|
| $V_{\text{foam}}$ | volume of the part |
| $V_{\text{polymer}}$ | volume of the polymer |
| $V_{\text{air}}$ | volume of air within the foam |
| $\rho_{\text{part}}$ | density of the part |
| $\rho_{\text{air}}$ | density of air |
| $\rho_{\text{foam}}$ | density of the foam |
| $\rho_{\text{polymer}}$ | density of the unfoamed polymer |
| $\rho$ | relative density of the foam |
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Data availability

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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