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THERMOFORMING OF CLOSED CELL POLYMER FOAM AND ITS RESIDUAL COMPRESSIVE MECHANICAL PROPERTIES

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Summary. This paper aims to investigate the deformation behaviour of a closed cell polymer foam during forming at temperatures above the glass transition temperature of the foam. Further, the residual compressive properties are measured and the results are correlated with measurements on photographs showing the resulting core cell geometry. It is shown that different mechanisms are active for thermoforming in the tensile and compressive directions, but that the resulting mechanical properties seems to be predictable using established models and geometrical expressions.

1 INTRODUCTION

Traditionally, manufacturing of structural sandwich components are limited to simple geometrical shapes or to labour consuming and therefore costly manufacturing processes. For very large structures, this may be difficult to change. However, considering the variety of medium sized applications where structural sandwich components may find its place, from automotive to aeronautical, a demand for more cost efficient production rises. Thermoforming is one potential option.

Thermoforming has been shown to enable efficient manufacturing of complex shaped sandwich structures [1] using polymer foam core. The process utilises that most polymer foams are formable at temperatures above its glass transition temperature, enabling adoption to double curved shapes with high draw ratio. The drawback with this method is however that during forming, the initially isotropic core material changes through alignment with the strain field. The result is a product with different core properties than the virgin core. Before offering this technique to more advanced applications, it is consequently highly desirable to be able to predict this change in core cell structure and the resulting mechanical properties of the foam.

This study aims to investigate the residual compressive mechanical properties of a thermoformed closed cell polymer foam core. Although most forming processes involve both tensile and compressive deformation, these are herein studied separately in order to simplify the evaluation. The change in core cell geometry following thermoforming during tensile and
compressive loading, respectively, is studied using microscopy. Finally, the residual compressive properties are measured and the results are compared to models on the mechanical properties of anisotropic cores.

2 THEORETICAL BACKGROUND

The mechanical properties of polymer foams are largely determined by geometrical features of the material and by the properties of the solid material [2]. Polymer foams are geometrically distinguished as being either open or closed with isotropic or anisotropic mechanical properties. However, considering single cells, their shape are generally not truly spherical, but isotropic core properties are often a result of a randomised distribution of anisotropic core cells. Anisotropy is thus both a matter of cell geometry and its distribution in space inside the core.

In this work, the mechanical compressive properties following thermoforming will be compared to model predictions based on the cubic array assumption, where the cells are considered as cubic arrays of square transverse sections. Adjoining cells are staggered so that their members meet at their midpoints, see eg [2]. The cell wall material is isotropic, so that the anisotropy arises solely from the cell shape. Considering closed cell foams, these models enables capturing deformation mechanisms as extension or compression and bending of the cell walls, where the latter is more pronounced for low density materials [2]. Further, as the cell membranes stretch, the contribution from the axial cell-wall stiffness to the elastic moduli increases.

Based on these assumptions, it has been shown that for isotropic closed cell foam material the following relation between foam compressive modulus, $E$, and the modulus of the solid material, $E_s$, can be derived from (neglecting the gas pressure contribution) [2]:

$$\frac{E}{E_s} = \phi^2 \left( \frac{\rho}{\rho_s} \right)^2 + (1-\phi) \left( \frac{\rho}{\rho_s} \right)$$

(1)

where $\rho$ and $\rho_s$ are the density of the foam and of the solid material, respectively. $\phi$ is the fraction of material in the cell wall membrane. In the same way an expression for the compressive strength, here defined as peak stress during compressive failure, $\sigma^*$ can be determined from the strength of the solid material, $\sigma_s^*$ [2]:

$$\frac{\sigma^*}{\sigma_s^*} = 0.3 \left( \phi \frac{\rho}{\rho_s} \right)^{1.5} + 0.4(1-\phi) \left( \frac{\rho}{\rho_s} \right)$$

(2)

A comprehensive model describing the compressive behavior of anisotropic foam is presented by Huber and Gibson [3] based on the previously described cubic array assumption. The model shows that, given that the rise direction of the cell has dimension $h$ and the square transverse-section, $l$, the cell has anisotropy $R=h/l$ and the compressive modulus ratio can be written
where $E_3$ is the modulus in the core cell rise direction and $E_1$ in the transverse direction. The compressive modulus ratio thus strongly depends on the anisotropy. Since loading in the cell rise direction deflects the shorter cell edges, the stiffness in the cell rise direction is greater than in the plane normal to it.

During thermoforming, the core cells align with the direction of tensile deformation or the direction perpendicular to the compressive deformation for tensile and compressive thermoforming, respectively, see Figure 1. However, note that in this work the components will be tested in the core cell rise direction or transverse direction, respectively, independently of method of deformation.

![Figure 1. Schematic figure showing how the cells deform during tensile and compressive loading, respectively.](image)

Considering thermoforming in the tensile direction, a model describing the foam deformation and load response of the cubic array core have been developed by Akkerman and Pronk [4]. Experiments have show that this model is applicable on the material and process considered in this study if a second relaxation term is added [5]. During thermoforming the load response is clearly viscoelastic showing rate dependence.

The herein presented mechanical models are based on simplified and idealised geometrical models. Today, techniques for generation of more realistic geometries into finite element code exists, which in the future enables more extended modelling, as e.g. [6].

It needs to be remarked that the herein presented models rely on the cell being “perfect”, i.e. free of wrinkles and with even membrane thickness. A number of studies have indicated that imperfections have a large influence on the mechanical properties, however that cell wall wrinkling has the largest impact, e.g. [7], while the influence of thickness variations seems to be significantly smaller. However, during thermoforming in the tensile direction the cell walls and membranes are thinning and eventually yielding. Finding a maximum degree of deformation before weakening the core is one of the aims of this study.
The geometry of cellular foams is commonly determined using Scanning Electron Microscopy (SEM). The anisotropy of cellular foams has previously been determined measuring the distance between core walls along several lines and at different angles [3]. The measurements are then fitted to an elliptical form using least square method. The core anisotropy is consequently equal to some average anisotropy. Since the test samples produced herein do not provide photographs on more than on average 10 core cells, a large statistical base do not exist. In this study each core cell is instead measured and fitted to an ellipsode. The average core anisotropy is calculated as the average anisotropy in the core cell rise direction and transverse direction, respectively. The modulus ratio is thereafter predicted using Equation 3. In order to distinguish these results from compression test results, the resulting modulus ratio will herein be named SEM.

Assuming that the volume is conserved and that all cells are initially spherical (R=1), a theoretical anisotropy \( R_{\text{theory}} \) can be calculated from the known degree of deformation during thermoforming, \( \Delta \), according to

\[
R_{\text{theory}} = \sqrt[3]{(1 + \Delta)^3}
\]

This value will be used for comparison for specimens showing no significant change in density following thermoforming. Using this value for predicting the modulus ratio (Equation 4) a purely theoretical estimation is obtained, herein referred to as “theory”.

3 EXPERIMENTS

3.1 Materials

The material used in the study is a closed cell polymethacrylimide (PMI) foam core Rohacell® WF71 from Röhm Degussa GmbH with a specific density of 78 kg/m\(^3\). In model predictions, the density of the solid material is set to 1200 kg/m\(^3\).

3.2 Preparation of thermoformed samples

Specimens prepared for thermoforming in the tensile direction had a dog bone like geometry with outer dimensions 150*250 mm, thickness 20 mm, see [8] for further details. This geometry was set as a compromise ensuring uniform heat and stress distribution, while producing enough material for further tests.

In order to avoid global buckling, specimens prepared for thermoforming in the compressive direction were cubic with height 30 mm and a transverse sectional area of 20*20 mm.

According to recommendations from the manufacturer [9], the samples should be dried for at least 3h in 130°C prior to thermoforming. Although these recommendations are mainly to avoid humidity in sandwich components in e.g. aeronautical applications, the procedure was followed in order to resemble the real process.

Thermoforming was performed in an Instron 4505 from Instron GmbH, equipped with a hot air heating chamber. The temperature was controlled using an in-built thermocouple.
inside the oven and one either inside the sample (for tensile direction) or inside a dummy placed close to the thermoformed sample (for the much smaller samples in compressive direction).

When the thermocouple inside the specimen (or dummy) showed stable temperature (the set temperature) thermoforming was performed to a predetermined degree of (tensile or compression) deformation. Thereafter the oven was opened and the sample rapidly cooled off at maintained deformation, thereby freezing the deformed structure. When the specimen was cold and thus thermally stable, the Instron was opened and the deformed sample could be removed. Thermoforming was performed at different temperatures (200 and 220°C), to different degrees of elongation/compression (0-55%) and at different deformation speeds (10-300 mm/min). This paper, however, mainly focuses on the results from the base-line deformation at 200°C and deformations speed 10 mm/min. It should be noted that thermoforming in the compressive direction resulted in an even core compaction in the compressive direction and corresponding swelling in the transverse direction without any signs of local crushing of cell layers, as expected for cold compression. To ensure that the thermal properties of the core were not changed by the heating and deformation, the most severely heated samples was tested using Differential Scanning Calamity, DSC [8]. No change or degradation of the polymer material could be detected following thermoforming.

3.3 Compression tests
From the thermoformed samples, specimens for compression test were cut in two directions: the direction of tensile/compression thermoforming and the transverse direction, respectively.

Due to limitations in geometry of thermoformed specimens, the samples from tensile thermoforming were milled to cubes with side length 15 mm and samples from compressive thermoforming to cubes with side length 10 mm. Since the nominal core cell size is small (radius <0.5 mm), also this smaller test geometry was considered to include enough number of cells to consider edge effects negligible.

Compression test were performed in the Instron testing machine according to ASTM standard D1621-00 at compressive strain rate 1.67*10⁻³ s⁻¹, according to standard. Each specific sample was measured prior to testing in order to enable calculating the true stress and strain. Further, each sample was weighed and its density reported.

3.4 SEM
In order to provide specimens for SEM, transverse-sections (about 5*5 mm²), were cut from the middle of the thermoformed specimens. In order to provide a smooth surface with clean-cut cells, the thermoformed specimens were cooled with liquid nitrogen, and broken along the direction of thermoforming or the transverse direction, respectively. The broken surfaces were sputtered (coated) with Au/Pd to obtain the required conductivity using a Denton Vacuum Desk II from Denton Vacuum, USA.

The SEM photographs were analysed using the image software ImageJ [10] from National Institute of Health, USA. In order to determine the shape anisotropy of each cell, the
following procedure was undertaken: The cell diameter was measured at different angles with approximately 15° interval, see Figure 2. The results were read into an in-house written numerical code finding the ellipse that best fit the measurements (least square method). The results are reported in terms of anisotropy (major/minor axis) and the in-plane rotation of the ellipse. The average anisotropy was calculated according to the description in Chapter 2.

![Figure 2. The core cell measurements are fitted to an ellipsoid of anisotropy $R=a_{\text{max}}/b_{\text{max}}$ in the direction $\alpha_{\text{max}}$.](image)

4 RESULTS AND DISCUSSIONS

4.1 Specimens thermoformed in the tensile direction

*Figure 3* shows how the foam compressive modulus and strength, respectively, depends on the degree of tensile deformation during thermoforming. Both are normalised based on the properties of the virgin core material in order to visualise the deviation. Following theory, both stiffness and strength increases in the cell rise direction and decreases in the transverse direction. Considering the modulus this change is more pronounced, with an increase/reduction of up to 50%. The difference in strength is smaller, ±30%. The results show clear trends, but the scatter is large. This is partly explained by the high sensitivity to fluctuations in forming temperatures around the used thermoforming temperature 200 °C. At this temperature, the mechanical properties of the solid material reduce significantly for each degree of increased thermoforming temperature [5].

For specimens thermoformed in the tensile direction, the density seem to remain constant at the level of the virgin core material [8]. *Figure 4* shows a comparison between measured anisotropy and predicted values using *Equation 4*. As can be seen, theoretical prediction and experimental measurements follow a very similar trend up to a deformation level of approximately 40%. As expected, the core cells maintain their isotropic properties transverse to the cell rise direction. Measurements from photographs taken in the transverse direction showed an average anisotropy of $R=1.05 \pm 0.05$. 
Figure 3. Normalised compressive modulus and strength, respectively, as function of tensile deformation during thermoforming.

Figure 4. Comparison between measured core cell anisotropy and theoretical predictions.

Figure 5a shows a SEM photograph of the virgin core material, while Figures 5b-5d show samples thermoformed in the tensile direction, to 23%, 38% and 55% deformation, respectively (please note that figure 4d is 90 degrees tilted).

Figure 6 shows the ratio between compressive modulus in the cell rise direction and transverse direction. The experimental results are compared with estimations from measurements on the cell foam geometry (SEM) as well as theoretical predictions based on the conserved volume principle (theory), Equations 3 and 4. As can be seen, all results follow the same trends. The deviation between the experimentally based values and the theoretical estimation increases at higher degrees of thermoforming deformation.
Figure 5. Samples thermoformed to a. 0% elongation (virgin core), b. 23% elongation, c. 38% deformation, d. 55% deformation (tilted)

Figure 6. Comparison between measured modulus ratio, estimations from SEM photographs and theory for sample thermoformed in tensile direction.

4.2 Specimens thermoformed in the compressive direction

Figure 7 shows how the foam compressive modulus and strength, respectively, depend on the degree of compressive deformation during thermoforming (normalised based on the properties of the virgin core material). As expected, the modulus and strength increases in the core cell rise direction following thermoforming. Further, it is interesting to note that the reduction in modulus in the transverse direction is significant, 80%, but that the compressive strength is only slightly reduced. This is explained by the core densification occurring during forming, see Figure 8. The densification is significant and indicates that the core swelling is negligible compared to the core compaction: a reduction in height with 50% increases the
density with 100%. Since the core material is liquid like during thermoforming, it can be argued that the structure maintains its strength in the transverse direction, but that the stiffness is significantly reduced. In *Figure 7*, theoretical values for the normalised modulus and compressive strength are given based on the measured density of thermoformed samples (*Equations 1 and 2*). As can be seen, for these experiments the predicted values follow the experimental data in the cell rise direction, 3. However, since the theoretical model considers the material as isotropic (same properties in all directions), the thermoformed core materials must be considered somewhat destroyed compared to a virgin core of higher density.

![Figure 7. Normalised compressive modulus and strength, respectively, as function of compressive deformation during thermoforming](image)

Figure 8. Core densification as function of compressive deformation during thermoforming

Figure 9 shows SEM photographs of samples thermoformed in the compressive direction. The average cell anisotropy is measured to: compressive deformation 17% $R=1.2$, deformation 27% $R=1.3$, deformation 40% $R=1.9$, deformation 50% $R=1.9$. In the photographs, cell wall buckling can be detected already at 27% compression.

Figure 10 shows the ratio between compressive modulus in the cell rise and transverse direction for samples thermoformed in the compressive direction. The experimental results are compared with estimations from measurements on the cell foam geometry, as described in Section 2. Since the density is changed following thermoforming, the theoretical approximation, Equation 4, does not hold and is therefore not included in the comparison. The results show poor agreement between measurements and predictions based on the core cell geometry. This is probably due to the excessive reduction in modulus following densification.

The temperature during thermoforming significantly influences the results. It has been shown that when forming at 220°C [11], the core densification after 25% compressive deformation is almost halved compared to at 200°C (i.e. 95 kg/m³ compared to 111 kg/m³). Consequently, further experiments are needed investigating the mechanical properties following thermoforming at higher temperatures.
4 CONCLUSIONS

Thermoforming is a promising method for efficient production of polymer foam core sandwich structures with complex geometry. However, the presented work shows that the compressive mechanical properties changes following thermoforming. Considering the compressive modulus, the properties in the core cell rise direction (tensile direction) increases with 50% for samples thermoformed to 40% elongation. In the transverse direction the trend is opposite, with a reduction of 40%. Corresponding values for the compressive strength is 30% increase/reduction. For the considered thermoforming temperature, excessive elongation (>40%) causes a reduction in the mechanical properties.

Thermoforming in the tensile direction occurs without significant change in density. The study shows that up to the optimal level of maximum tensile deformation, the change in core cell geometry and corresponding mechanical properties can be predicted. The results have been verified by performing measurements from photographs showing the core cell geometry of specimens thermoformed to different degrees of elongation.

For samples thermoformed in the compressive direction densification occurs. At almost 100% increase in density, the compressive modulus increases with 100% in the core cell rise direction and reduces with 80% transversely. However, considering the compressive strength, only a small reduction in the core cell transverse direction can be measured (compared to the virgin core material) and an increase in strength in the core cell rise direction with up to 250%. It has been shown that the trends for the rise direction can be predicted from established models taking the core cell densification into account.
REFERENCES