EXPERIMENTAL AND NUMERICAL INVESTIGATIONS OF THE FORMING OF THERMOPLASTIC SANDWICHES

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SUMMARY: Sandwich panels have been used extensively in the transportation industry. However, as geometric complexity increases, the manufacturing techniques require longer cycle times and significant manual labour. Press forming of initially flat thermoplastic sandwich panels is a new, potentially cost-effective route to obtain a complex part in a one-step process. Nonetheless the heterogeneous nature of the sandwich panels requires accurate control of the heating stage and the complex geometry of the final part can lead to wrinkling of the faces and local collapse of the core during forming. Thus, the potential for complex shape forming of thermoplastic sandwiches, based on a polyetherimide (PEI) foam core combined with PEI warp-knitted reinforced skins, has been investigated. An experimental approach associated with numerical simulations was used to define appropriate processing windows in terms of forming temperatures and to determine sandwich deformations during forming.

KEYWORDS: Deformation map, drapability, explicit FEM code, inverse method, processing window, sandwich, stamp forming, thermoplastic, knits.

INTRODUCTION

Thermoforming offers the potential to shorten cycle times, a key factor for large scale production. This technique is, however, seldom used to manufacture sandwich parts [1]. Studies have been published recently on thermoformed sandwiches made with a 3D-knitted core [2], with a honeycomb core [3] or with hybrid thermoplastic sandwiches made of two thermoplastic matrices [4, 5]. The literature is, however, limited as to how to treat the thermoforming of sandwiches based on the same thermoplastic matrix for the face sheets and the core.

For this sandwich, two opposing requirements must be satisfied in order to obtain optimal temperature conditions prior to forming. The face sheets should be heated to temperatures above that of the softening point of the matrix, whereas the foam core should be heated to temperatures below that of the glass transition of the matrix in order to avoid the collapse of the closed foam cells [6]. Furthermore, the small skin and interface thicknesses make the measurement of the in-situ through-thickness temperature difficult. Since an accurate control of the temperature gradient is required, a numerical tool to study the influence of the

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processing parameters on the final temperature profile through the sandwich thickness was developed.
A second challenge comes from the occurrence of folds and wrinkles in the face sheets during stamping. Therefore, investigations on drapability were carried out for glass fibre textiles. A double warp-knitted bar knit was selected from among more than ten drapable fabrics due to its high drapability, and was then impregnated with polyetherimide thermoplastic matrix (PEI) [7, 8]. Pressforming technology for thermoplastic sandwiches is still relatively untested and "trial-and-error" can be costly, inefficient and may result in insufficient understanding of the forming process. Numerical simulation can, on the contrary, help to avoid tedious experimentation and to predict the occurrence of skin instabilities or foam collapse. Consequently, a forming model was required to optimise the processing.
Both the heating and forming models are presented separately below.

HEATING MODEL

Heating technique and boundary conditions

Pre-heating experiments were conducted using one heating step. The sandwich structure was heated from room temperature to forming temperature between two hot plates. The recorded temperatures showed that this heating procedure was not suitable to obtain the required temperature profile. Suitable face sheet temperatures were, in fact, induced but the temperature of the foam was too elevated in the vicinity of the interface and too low at the midplane.
By heating in two steps, however, the heat resistance between the skins and the foam can help to fulfil the thermal requirements. The whole sandwich structure is first heated between two hot plates at the lower forming temperature of the foam. Once thermal equilibrium is achieved the sandwich is transferred to a second set of plates which are held at a temperature comprised within the process window temperature of the skins. During this second heating step the skins are preferentially heated. This heating procedure ensures that the foam is at least at its minimum forming temperature.
The thermal properties of the sandwich and the boundary conditions controlling the heating of the sandwich by contact and the cooling in the air, were determined using an inverse method [9]. The principle is to reproduce measured temperature curves with a finite element thermal model by adjusting the missing properties. The quadratic error between the two was decreased by iterative calculations.
For the modelling of the two-step heating technique, investigations were focused on the second stage where the determination of the processing parameters is crucial. Parameters such as the transportation times between the two heating devices and between the hot plates and the mould were set to 2 seconds, as is possible in practise. The determination of the optimum holding time and hot plate temperature were performed using a systematic approach [10].

Results and discussion

An example of the determination of the thermal properties using the inverse method during the heating of a thick foam panel is given in Figure 1. The calculated curves described the experimental points very well. When convergence was reached, the quadratic error found between measured and predicted data was always lower than 1°C. The same type of experiment was conducted in order to determine the thermo-physical properties of the face sheets and the interfacial heat conductance.

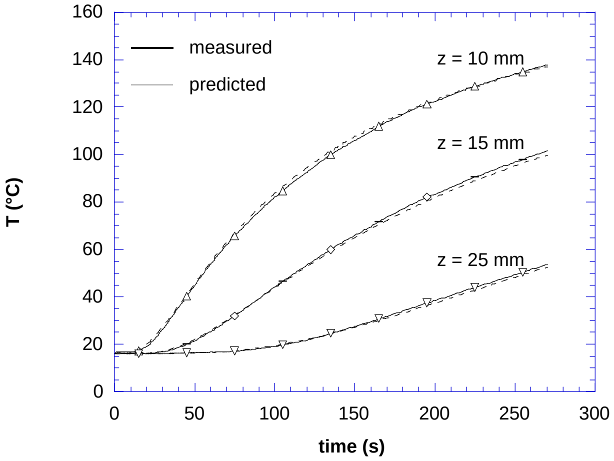


Figure 1: Measured and predicted temperature profiles at 10, 15 and 25 mm from the surface of 50 mm thick PEI foam panel. The sample was placed on a hot plate at a constant temperature of 205°C. Continuous and dashed lines represent measured and predicted data, respectively.

The influence of the hot plate temperature on the temperature profiles is plotted in Figure 2 for a constant holding time of five seconds. It can be observed that the final temperature of the skins was greatly influenced by the heating temperature while the final temperature of the foam is affected to a much lesser degree than that of the skins, even in the vicinity of the interface. On the contrary, the influence of the variation of the holding time for a constant temperature had more importance on the foam temperature and almost none on the final skin temperature.

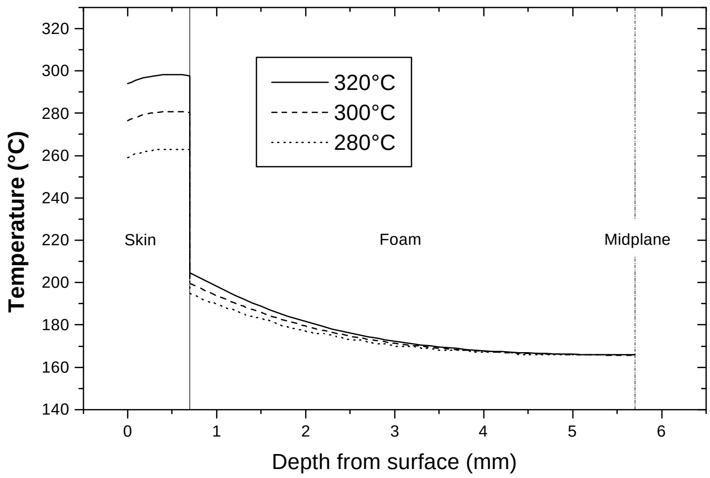


Figure 2: Influence of the hot plate temperature on the knitted sandwich temperature profile at a constant heating time of 5 seconds.

The influence of the hot plate temperature and the holding time on the final temperature profile is explained by the thinness of the skins in comparison to the foam. The higher conductivity of the skins and the heat resistivity of the interface enhance the occurrence of a temperature gradient between the skins and the foam. Consequently, a high plate temperature should be used to keep the skins above their minimum forming temperature, and a short holding time would keep the foam below its maximum forming temperature. The temperature evolution at various locations within the skins and the foam are plotted in Figure 3. Using a holding time of five seconds and a hot plate temperature of 320°C, the required thermal gradient is achieved. Consequently, the thermoforming of PEI woven and knitted sandwiches is conceptually possible, with respect to temperature and process times. A heating device which allows fast and precise heating cycles is currently under construction.

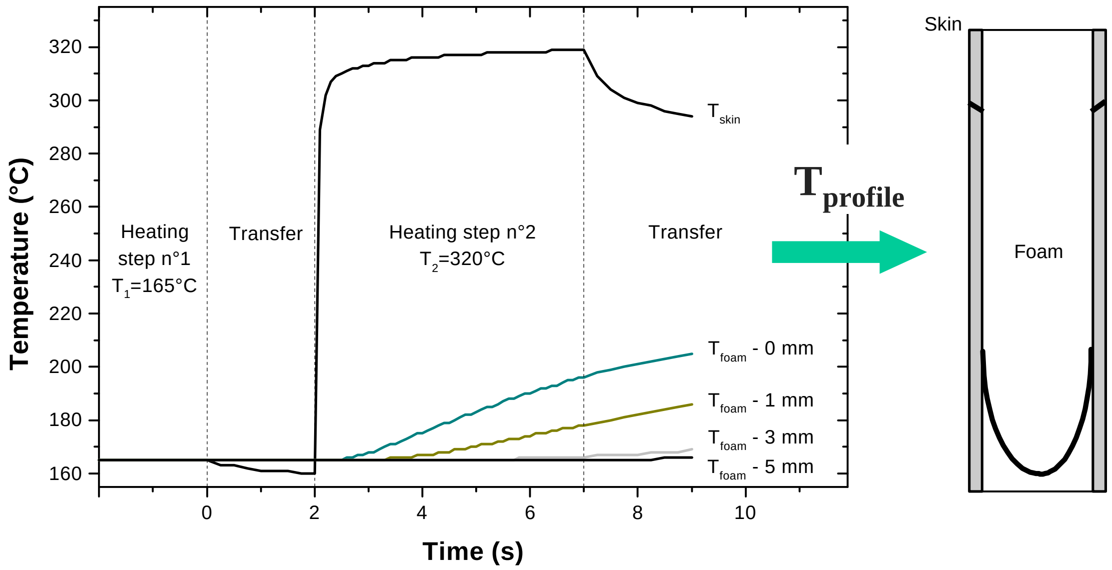


Figure 3: Calculated temperature profile evolution for a PEI knitted sandwich with a 10mm thick core. The thermal gradient required for thermoforming is achieved using the optimal processing parameters.

FORMING MODEL

Materials, meshing and implementation

Shell finite elements were used to represent the mould halves and clamping device. The face sheets were modelled using shell elements with a given thickness while the foam core was described with volume elements [11]. A bottom view of the set-up and sandwich panel meshed with FEMAP® is given in Figure 4.

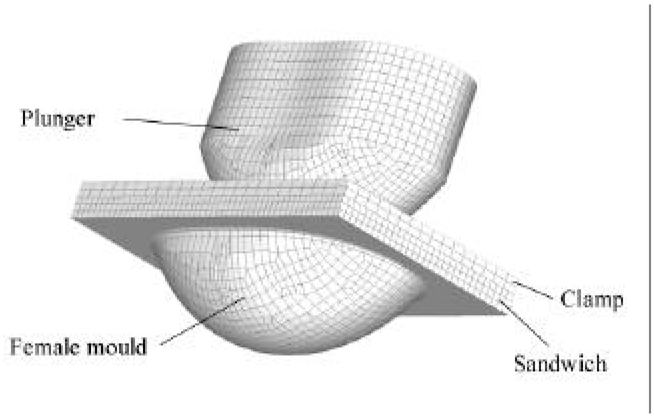


Figure 4: Meshed forming set-up before forming. The negative and positive moulds, the clamp device and the sandwich structure are represented.

Mechanical tests were performed at high temperatures on the face sheets and on the foam core [12]. The mechanical performance of the foam obtained for the normal and transverse planes indicated an isotropic behaviour. The face sheets reinforced with the selected knitted fabric exhibited a high stretchability with strains up to 60% and showed isotropic properties at forming temperatures upon 280°C (Figure 5).

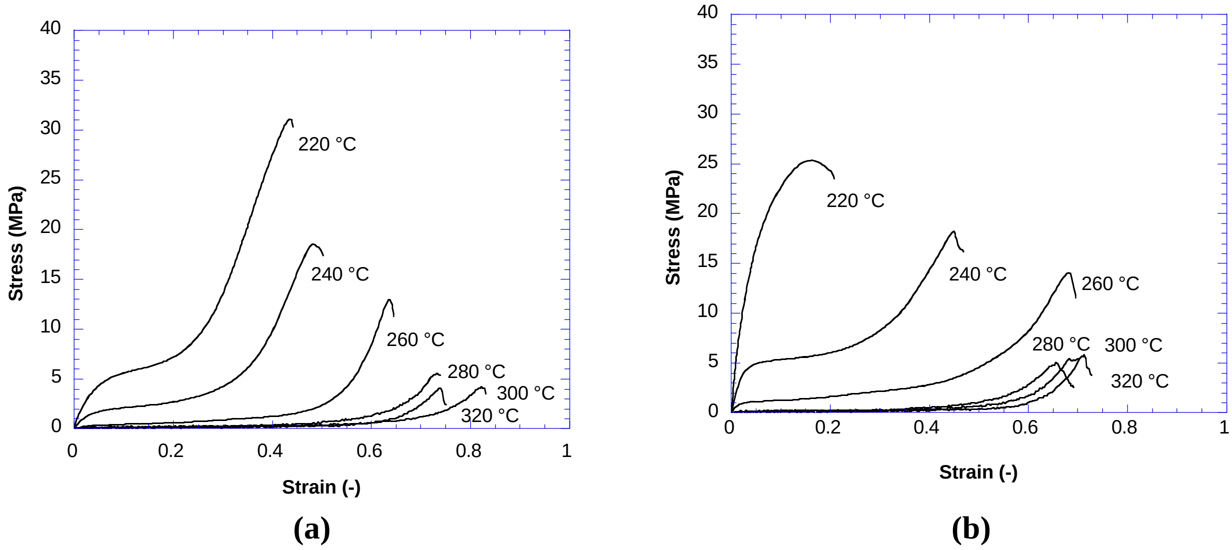


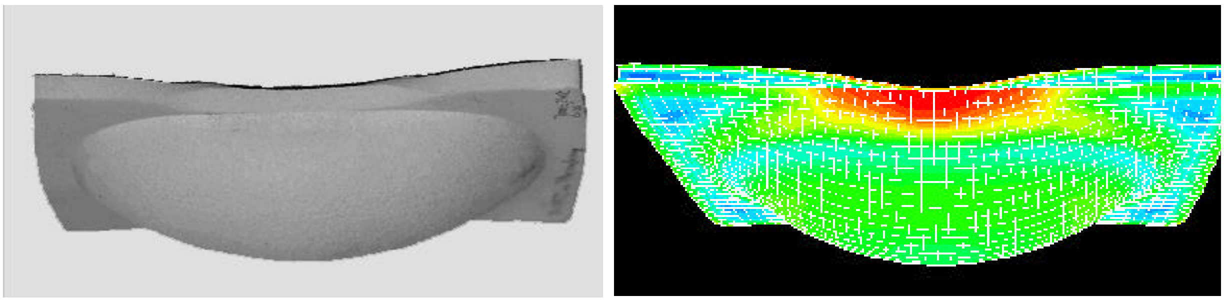
Figure 5: Stress / strain curves of PEI knitted reinforced laminates at high temperatures at 0° (a) and 45° (b).

Consequently, these results were implemented in a bilinear isotropic material model which was used to describe the sandwich. A commercial explicit finite element solver, LS-DYNA(™), was used for its ability to solve highly non-linear dynamic problems. The treatment of the contact along the interface was handled using a penalty method. The clamping force required during processing was reproduced and frictional forces were experimentally measured and accounted for.

Finally, thermoforming experiments on the foam core, the face sheets and the thermoplastic sandwiches were conducted. Initially flat preforms were pressed into a mould with double constant curvature. The experimental displacements of the shaped parts were measured by a Moiré technique to validate the forming model. Two procedures were used to generate the fringe patterns. For out-of-plane displacements, a grating was projected onto the foam shaped parts while for in-plane displacements, a grid with parallel lines of the same width and pitch was printed onto the flat specimens prior to forming. The resulting pattern obtained from the overlapping of the pictures taken before and after deformation, contained information on displacements.

Results and discussion

Results from the forming experiments and from the simulation are given in Figure 6a -b for the foam core.



(a) **(b)**

Figure 6: a) Thermoformed PEI foam; b) Predicted effective plastic strains in the foam.

The visual correlation between the experimental and numerical results is good. The model describes the fact that the edges were slightly pulled inwards from the side with the strongest curvature well. The calculated geometry is close to the experimental shape and the areas of high deformation are clearly identified.

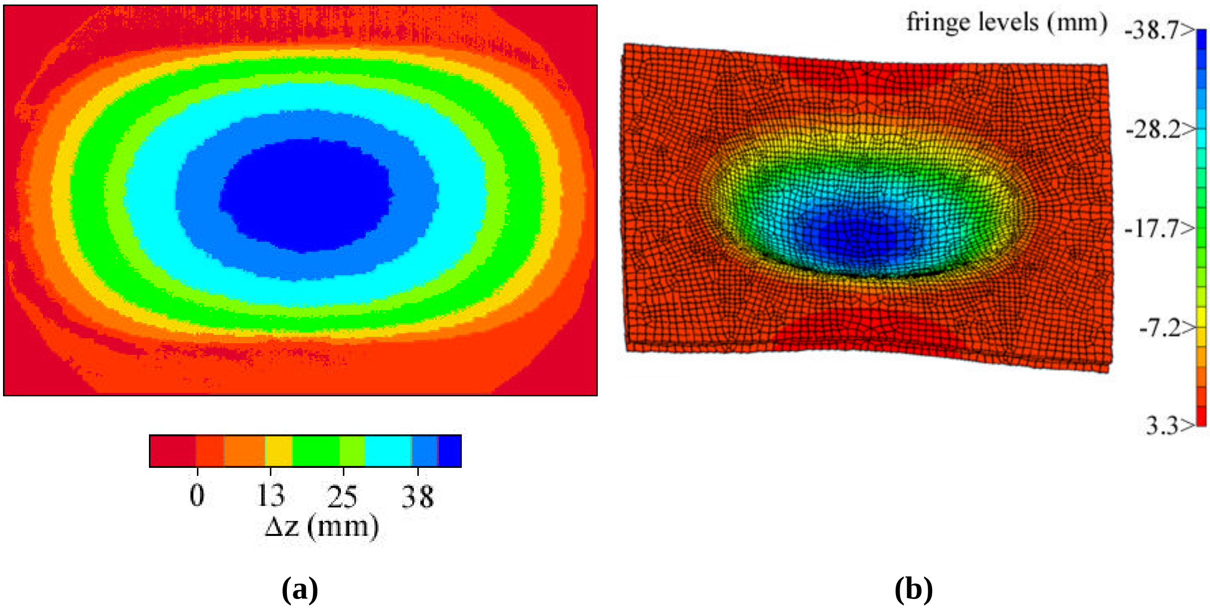


Figure 7: Out-of plane displacements of a shaped specimen made of foam. The results were obtained by Moiré analysis (a) and by simulation (b).

The results of the out-of-plane analysis performed by the Moiré technique and predicted by the model are shown in Figure 7a-b. The areas presenting high and low vertical displacements are identified. The same displacement values were found with the model and a good correlation is observed between experiments and predictions.

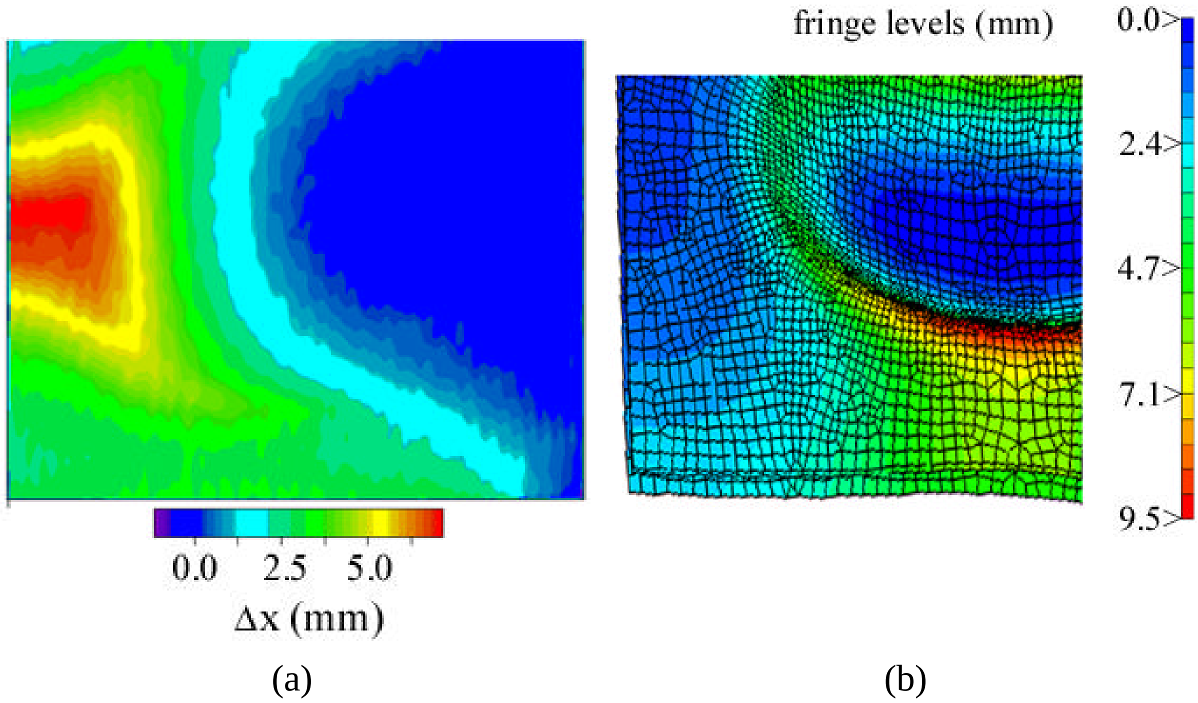


Figure 8: In-plane displacements measured by Moiré (a) and calculated by simulation (b) for one quarter of a thermoformed foam part.

The in-plane displacements along the part length (X axis) obtained by the Moiré analysis made on one quarter of a shaped foam part are represented in Figure 8a. The reference point was arbitrarily fixed on the centre of the part. The displacements are more severe along the symmetry axis of the shape. The areas where high deformations are predicted (Figure 8b) correspond to the high displacements measured by the Moiré technique. Consequently, good qualitative (shape) and quantitative (values of displacements) agreements were found between the predictions and the experiments.

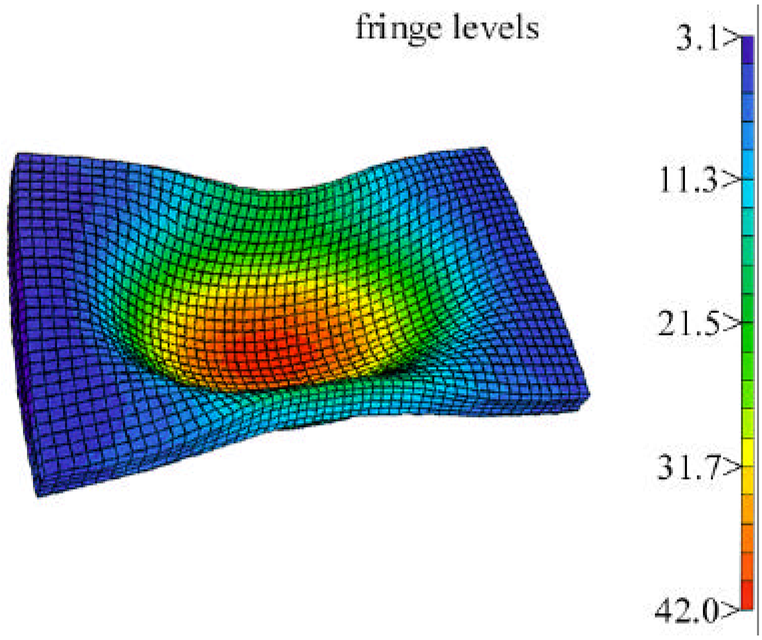


Figure 9: Plastic strains calculated during the thermoforming of an initially flat thermoplastic sandwich into a complex shape.

Finally the same approach was applied to the forming of the complete sandwich. The predicted plastic deformations for a thermoformed sandwich part are presented in Figure 9. Deformations ranging from 10% to 42% occur within the curved area and no failure of skin or foam was observed.

CONCLUSIONS

The thermoforming of PEI sandwich preforms was studied. Two models were developed for the heating and the forming of the sandwich. The thermal model demonstrated that a two-step heating procedure is required to achieve the required thermal gradient between the skins and the foam. Furthermore, the heating temperature preferentially influences the temperature of the foam while the holding time essentially controls the temperature of the skins. The forming model predicted the sandwich deformation during the thermoforming process. The calculated displacements correlate well with the experimental results provided by the Moiré technique which was applied to the processed parts. The thermal and forming models are useful engineering tools for the manufacture of a sandwich structure of increased complexity.

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