

THERMOFORMING OF FOAM SHEET

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Introduction

Thermoforming is a widely used process for the manufacture of foam sheet products. Polystyrene foam food trays for instance can be produced by first heating the thermoplastic foam sheet, causing the gas contained to build up pressure and expand, after which a vacuum pressure can be applied to draw the sheet in the required form on the mould. This production method appears to be a very sensitive process with respect to e.g. the sheet temperature, the pressures applied and the cooling time. More problems can be foreseen when for environmental reasons the blowing agent will be adapted (for instance replaced by a gas with a lower molecular weight).

To gain more insight in the occurring phenomena the large deformations of a foam structure have been analysed using finite element modelling. To this end a constitutive model has to be defined. Starting from the basic theory given by Gibson & Ashby [1], the behaviour of a closed cubic cell has been elaborated for large strains. The total stiffness is then the sum of the contributions of the edges and faces of the cell and the gas contained in it. The large deformations cause anisotropy of the cells [2], which influences their tangential stiffness. The constitutive model developed here includes the effects of internal gas pressure and the evolving anisotropy.

Theory

The constitutive model [3] is based on the response of a cubic cell (fig.1). The total stress is modelled here as the sum of the stresses arising from:

- bending of the cell edges (stretching is neglected)
- shearing, stretching and isotropic inflation of the cell faces
- compression/extension of the gas contained in the cell

Thus, for instance, straining in x -direction leads to bending of the edges and stretching of the faces, with stiffnesses

$$E_x^{bending} = \mathbf{f}^2 \left(\frac{\mathbf{r}^*}{\mathbf{r}_s} \right)^2 E_s \frac{L_0^4 \cdot L_x}{2 \cdot L_y \cdot L_z} \left(\frac{1}{L_y^3} + \frac{1}{L_z^3} \right), \quad E_x^{stretch} = (1 - \mathbf{f}) \frac{\mathbf{r}^*}{\mathbf{r}_s} E_s \frac{L_0 (L_y + L_z)}{2 \cdot L_y \cdot L_z},$$

where $L_{x,y,z}$ are the principal cell dimensions, L_0 is the initial cell size, \mathbf{r}_s and E_s are the density and stiffness respectively of the solid material, whereas \mathbf{r}^* is the density of the foam, and \mathbf{f} is the part of solid material in the cell edges. Changing the cell face area leads to an additional volumetric stress contribution from the cells with stiffness

$$E^{inflation} = E_s (1 - \mathbf{f}) \frac{\mathbf{r}^*}{\mathbf{r}_s},$$

whereas the response of the gas is described by the universal gas law. Most parameters can be measured directly, only the relative part of the material in the cell edges (\mathbf{f}) is determined by fitting stress-strain curves from tensile tests on the foam at elevated temperature.

As the stiffness of the solid is explicitly present in this formulation, it enables a straightforward extension to temperature or time dependent stiffnesses. At this stage we only consider the short time span of vacuum forming (less than 0.5 s), which is assumed to be isothermal. Physical nonlinearities such as yielding are neglected: only the geometric effects on the evolving stiffness are taken into account.

Results & Discussion

Experiments and simulations have been performed on different conical axisymmetric cups. Planar isotropy has been assumed, although the extruded foam sheet does show different average cell sizes in different directions. Much of this anisotropy vanishes when the sheet is heated before vacuum forming. This is confirmed by simulations of heating orthotropic foam structures (the modulus of the solid drops and the gas expands, leading to a more or less isotropic cell structure).

An example of a moulded tray is given in fig.2. The grid has been used to measure the in plane strains and cross sections have been taken in order to measure the thickness distribution. The constitutive model has been implemented in the finite element package Dieka, developed at the University of Twente, e.g. for deep drawing simulations [4]. A representative mesh of axisymmetric quadrilaterals is depicted in fig.3. Contact elements are located between the mould and the foam sheet.

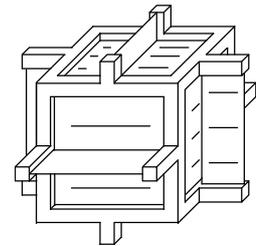


Figure 1 Cubic cell

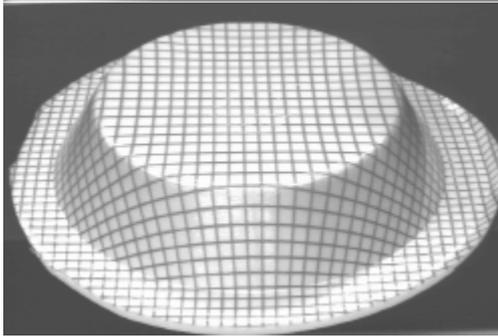


Figure 2 Truncated 60° cone

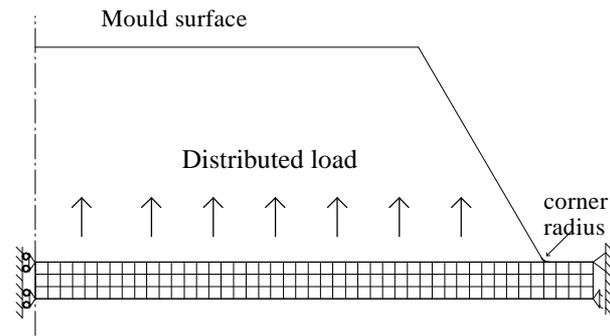


Figure 3 Finite element discretisation

Changing the applied vacuum pressure has little influence on the thickness distribution. Increasing the sheet temperature leads to an overall greater thickness of the products, due to further expansion of the gas. This greater thickness results in a greater bending stiffness of the final product.

For higher cones a bad surface quality can be found. Wrinkles appear on the outside radius of a tray. These are attributed to a spring-back phenomenon, which originates from a low cell pressure and a low cell stiffness. These, in turn, are a result of the local deformations and temperatures of the foam structure. Effective cooling improves the surface quality as this increases the cell stiffness.

Predicting the stresses and strains by finite element analysis and subsequently comparing these to the compressive strength of the material enables a prediction of the occurrence of wrinkles. A comparison of the measurements and the first simulation results is given in fig.4.

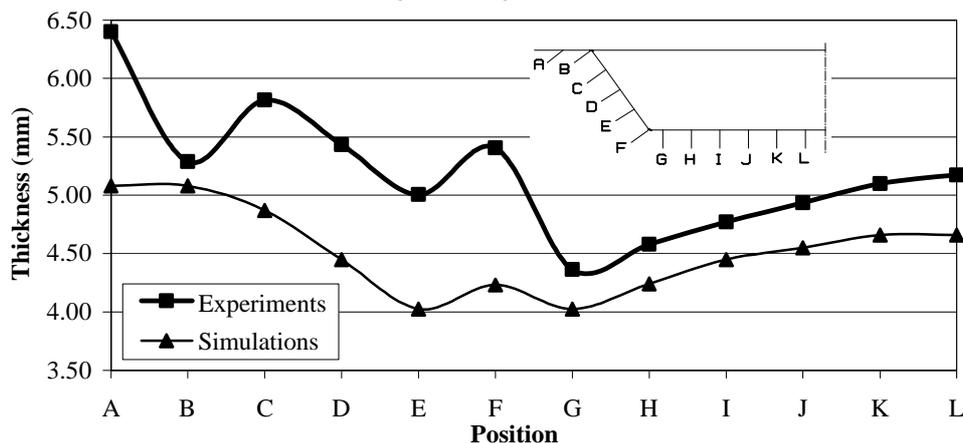


Figure 4 Thickness distribution of the 60° truncated cone

The overall thickness is predicted too low, caused by a low estimate of the initial thickness of the foam sheet after heating. The global trend is followed reasonably. At top corner B the simulation used a smooth radius (for reasons of convergence of the algorithm), which does not result in the decrease of thickness that was measured. At lower corner F the simulated tray did not touch the mould, again resulting in a smoother thickness distribution than was measured. The model can be refined further.

Acknowledgement

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References

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