FEA Simulations of Thermoforming – Using Hyperelastic Material Properties

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Abstract

A common misconception in the thermoforming community is that, prior to conducting a thermoforming simulation, significant material testing must be completed to develop a complex visco-elastic material model. Published research reports over the last twenty years, as well as work by the author of this white paper, show that for the vast majority of thermoformable polymers a very simple hyperelastic (rubber-like) material model will work sufficiently well. Spending considerable time and expense on experimental work to develop a visco-elastic material model for a polymer, while not incorrect, is usually unnecessary.

Background: Thermoforming Using Vacuum or Pressure (Not Plug Assisted)

With just a few exceptions, thermoformable polymers will exhibit similar material behavior during the forming process, if they are uniformly heated to within their forming temperature window. Nearly all of the thermoformable polymers will stretch and thin in a very similar manner. As a result, different polymers will produce nearly identical material distributions, if the thermoforming process uses only vacuum and or pressure (not plug assisted). (Note: how to efficiently deal with the simulation of plug assisted thermoforming is covered in another white paper entitled “Optimizing the Plug Assist Geometry Using Simulations”). An additional assumption is that the polymer stays at a relatively uniform temperature within its forming temperature window until it contacts the mold surface and where it is quickly cooled below its forming temperature and stretching and thinning stop.

One of the first reports of similar material behavior (stretching and thinning) during thermoforming was in a 1989 ANTEC paper (1), that summarized research work done at GE Plastics. In that study, three different polymers, polycarbonate-polybutylene terephthalate (PC-PBT), polycarbonate (PC) and polyetherimide (PEI), each having different forming temperature windows, produced nearly identical material distributions when formed in the same mold (see Figure 1). The GE researchers also conducted a FEA simulation of the thermoforming process using a “rubber-like” material model. The simulation results (PITA) are also shown on Figure 1 and are close to the experimental values.

Throne, one of the leading experts in thermoforming, concluded in his 2000 ANTEC paper (2) that “elaborate viscoelastic modeling of polymers for FEA is probably unwarranted, since thermoforming is for the most part, a geometry-driven process, not a material property-driven process”.

For many years, a thermoforming analysis scheme called Geometric Analysis was used to predict thickness distributions in thermoformed parts. Mold geometry was broken into simple geometric shapes such as wedges or cones from which the material thickness distribution was calculated, without specific knowledge of the material properties. Geometric Analysis would not have been effective in predicting material thickness distribution if every thermoformed polymer behaved differently.

The reason that thermoforming can be considered a geometry-driven process is because nearly all polymers that are thermoformed follow a hyperelastic material model during the forming process. Hyperelastic materials are rubber-like, in that they retain their initial volume throughout the forming process until they are cooled below the forming temperature window. Thus, as the polymer is stretched during forming it will also thin in order to maintain the original volume of material. Due to the inherent hyperelastic material behavior, final material distribution in a thermoformed product (that uses only vacuum or pressure for forming) is not significantly changed by any of the other process conditions, as long as the sheet is uniformly heated within its forming temperature window. The only exception may be the amount of sheet sag when forming a large part.

While it is not incorrect to develop a viscoelastic material model for a polymer at forming temperature, it is usually not necessary. For the very limited number of polymers that do not follow a hyperelastic material model, a viscoelastic material model would need to be developed in order to accurately simulate the forming process and predict the final product wall thickness.

During forming, the typical polymer behaves hyperelastically until it touches the mold and cools below the forming temperature and stretching and thinning are stopped. Areas of the polymer that are not in contact with the mold continue to stretch and thin hyperelastically. Thus, the last areas of the polymer to touch the mold, such as corners, are usually the thinnest.

FEA Simulations of Thermoforming (Not Plug Assisted)

Similar material behavior for different polymers during forming allows a wide range of hyperelastic material property models to be used as input to a FEA simulation of the thermoforming process. A range of hyperelastic material models will produce results with about the same final material distribution. Thus, there is no need to develop the exact stress-strain curves at the forming temperature for every polymer prior to running a simulation. However, if one needs to know the vacuum or pressure levels required to form a part, which is almost never the case, the exact stress-strain curve at the forming temperature would be required as input.

In the FEA simulations, when the polymer touches the mold a relatively high coefficient-of-friction value is used between the polymer and mold, which effectively stops the polymer from further stretching.

The degree of difficulty in simulation of the thermoforming process without a plug assist is much lower than when including the plug assist. As a result, simulation of vacuum or pressure forming without a plug assist and can be conducted using a number of commercial non-linear FEA programs. The field of reliable and efficient FEA programs decreases significantly when a plug assist is added to the process. FEA programs that handle contact issues well will be the most efficient at solving thermoforming problems with complex shapes and plug assists. The non-linear FEA program, Abaqus Explicit, was used in the examples described in this paper.

Simulation Examples

Figure 2 shows a thermoforming simulation of a box with an undercut, conducted by the author, that is the same mold as that used by the GE Plastics researchers. The example uses a general hyperelastic material model, but without exact knowledge of the material characteristics. Figure 2 includes color contour plots of stages in the forming process, showing thick and thin areas. There is also a plot of thickness versus location along the middle of the box. The simulation and experimental values are very similar.

Figure 3 shows another thermoforming simulation of a cylindrical product, conducted by the author. Again, this example uses a general hyperelastic material model, but without exact knowledge of the material characteristics. Figure 3 includes color contour plots of stages in the forming process, showing thick and thin areas. There is also a plot of thickness versus location along the centerline of the product. There is very good correlation between the simulation results and the measured thickness.

Conclusions

A general hyperelastic material model can be used in a FEA simulation of thermoforming (vacuum and or pressure forming only) to accurately predict the wall thickness distribution in a product. The development of a visco-elastic material model is, in general, not necessary. The use of a plug assist requires some additional simulation measures to be adopted, and will be covered in another white paper entitled “Optimizing the Plug Assist Geometry Using Simulations”.

If properly set-up, finite element analysis (FEA) simulations of the thermoforming process will accurately predict the final material thickness distribution in a product. The purpose of simulations in the product design process is to identify potential problem areas prior to making the first prototypes. Also, if the product has structural requirements, a FEA stress analysis can be conducted using the predicted thickness distribution. Design modifications or forming process changes can then be made early in the product development cycle, when they are the least expensive.

References

1. C.A. Taylor, SPE-*ANTEC*, “Finite Element Simulation of Thermoforming – Experiments and Analysis” (1989)
2. J. Throne, *SPE ANTEC,* “Computer-Aided Thermoformed Product and Process Design* (2000)

Key Words: finite element analysis, FEA, simulation, thermoforming, hyperelastic material properties

Figure 1: Thermoforming Results For Three Polymers and FEA Comparison

GE Plastics 1989

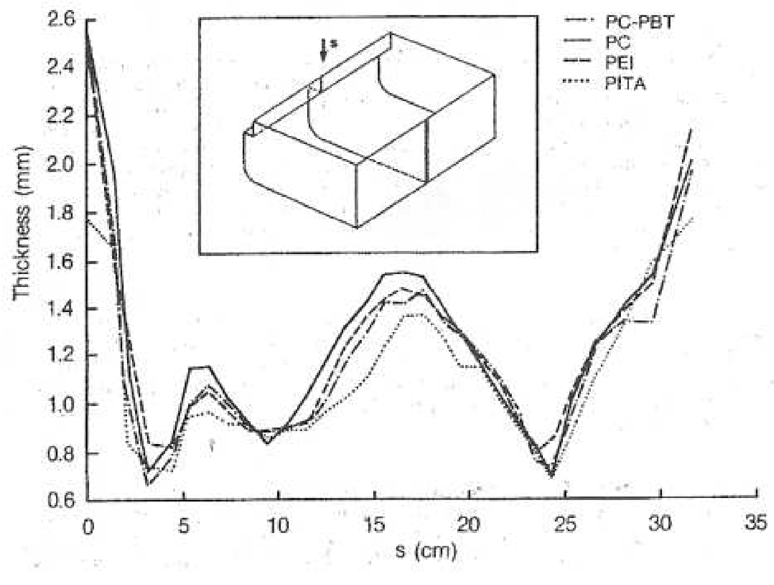
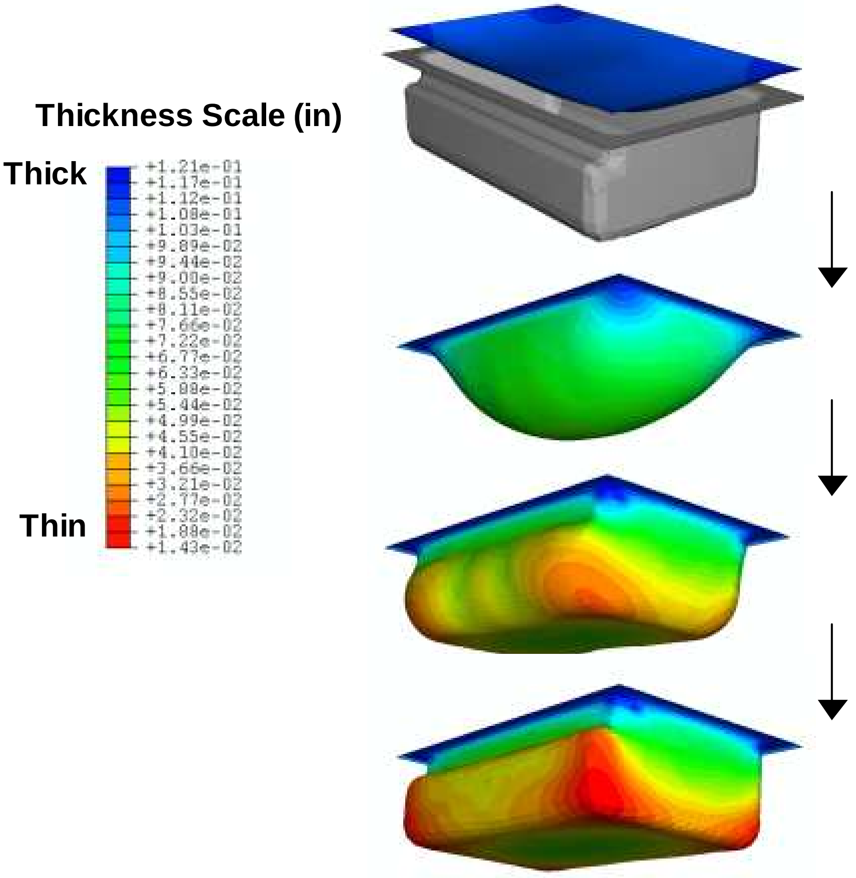
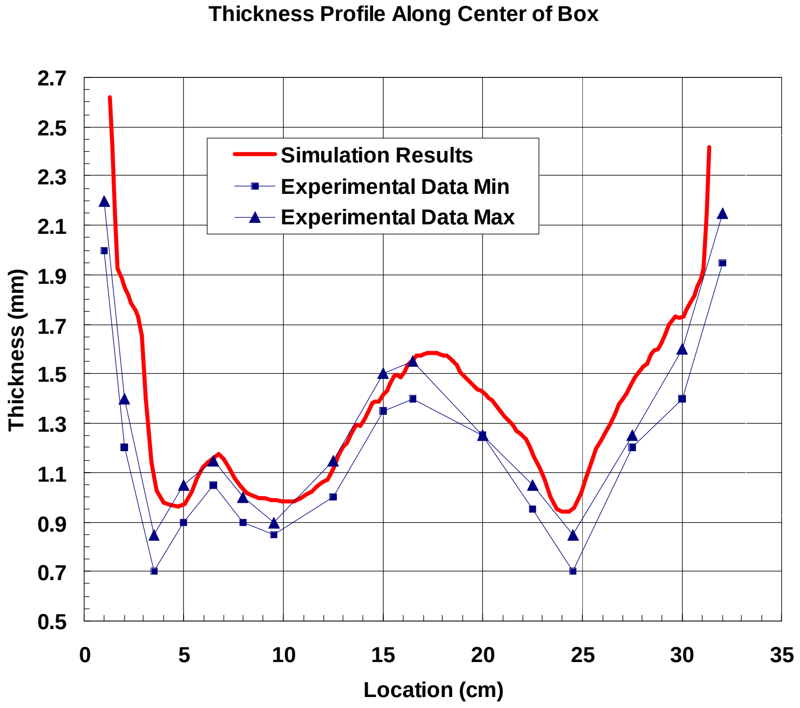


Figure 2: Simulation Results Using A Hyperelastic Material Model




Thickness Profile Along Center of Box

Results along centerline of box

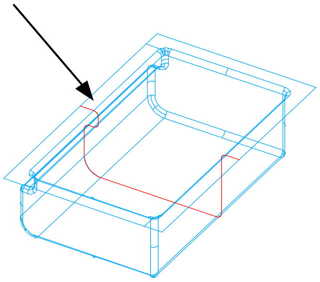


Figure 3: Simulation Results Using A Hyperelastic Material Model