Effect of Thickness Changes and Friction in Thermoforming Process Simulations in LS-DYNA® for UHMWPE Unidirectional Cross-Plies

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Abstract

This paper discusses the use of LS-DYNA for the modeling of thickness changes and frictions of DSM Dyneema® HB210, an Ultra-High Molecular Weigh Polyethylene (UHMWPE) unidirectional cross-ply thermoplastic laminate, during a thermoforming process. The thermoforming process being investigated consists of the preform phase that transforms the laminates to near net shape ply stacks and the subsequent consolidation phase that employs pressure and heat to join the preforms into a final part. During the preform phase, interply (ply/ply) and ply/tool frictions induce in-plane tension in the sheet of thermoplastic lamina. Knowing the effective tool/ply and ply/ply frictions such that the binder force can be prescribed is critical to preventing defects such as wrinkling, waviness and tears during the preforming process. The main mode of deformation of the laminate during the preform phase of the manufacturing process is in-plane shearing of the laminate, which can lead to variations in thickness. When multiple preform layers are compressed in the consolidation phase, the compounding of the thickness variations can adversely affect the uniformity of pressure distribution between matched die tooling, resulting in inconsistent consolidation. The modeling of the preform and consolidation steps can guide design changes in the processing conditions and ply blank geometries to achieve a well consolidated part. The temperature-dependent material properties derived from shear, bending, tensile and friction tests are implemented in a LS-DYNA simulation with a discrete-mesoscopic user subroutine for the material behavior of the cross-ply laminates. Beam elements capture the fiber orientations and carry the tensile and bending loads, while shell element exhibit the shear stiffness as a function of shear angle. The effect of thickness change of the laminate is investigated through the comparison of general shell elements without thickness change to thickness stretch shell elements (Elform=25) that change in thickness due to shearing, stretching and compression. The sensitivity to tool/fabric, as well as fabric/fabric, friction is also investigated in combination with thickness changes. Single-layer and triple-layer preforms are simulated and results produced support the need for both accurate friction inputs as well as including changes in thickness in the simulation.

Introduction

Thermoforming is an attractive manufacturing process for high-volume low-cost production of composites parts, and simulation is a valuable tool to guide the design of the processing parameters that can result in producing high-quality continuous fiber-reinforced composite parts. A credible simulation requires the input of material properties and an associated material characterization program that documents the shear, tensile and bending mechanical behaviors, as well as frictions involved in the process.

The typical thermoforming process consists of the preform phase that transforms a set of laminates to near net shape ply stacks and the subsequent consolidation phase that employs pressure and heat to join the preforms into a final part (Figure 1). During the preform phase, interply (ply/ply) and ply/tool frictions induce in-plane tension in the sheet of thermoplastic lamina. This in-plane tension is induced through the application of a binder and mitigates the development of out-of-plane wrinkles and in-plane waviness. However, care must be taken as to the magnitude of the in-plane tensile force. Too little force, and localized compression states can develop over the sheet, and then local wrinkling and waviness can occur. Too much induced force, and the laminate can tear. Thus, it is very important to know the effective tool/ply and ply/ply frictions such that the binder force can be prescribed so defects such as wrinkling, waviness and tears are not developed during the preforming process.

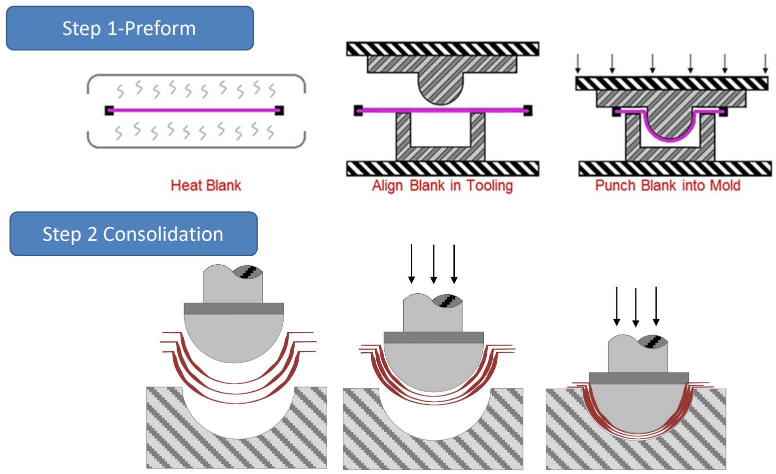

Figure 1. Thermoforming process: Step #1 – Preforming and Step #2 – Consolidation.

Past research has shown that the effective friction coefficient can be a result of the combination of the normal force applied to the sheet, the material temperature and the slip speed [1, 2]. Experimental methods are used to determine these static and dynamic ply/ply and tool/ply frictions.

A thermoforming simulation must also include tensile, bending and shear properties of the laminate. In-plane shear of the material is the major mode of deformation, and the picture-frame test is a popular test for characterizing this behavior as function of temperature and deformation rate. As a consequence of material incompressibility of a thermoplastic material system, the thickness of the lamina will increase due to conservation of volume during in-plane shear. Dangora et al. [3] verified this phenomenon with micrographs taken of laminates sheared to 0°, 20°, and 60°. Figure 2 shows the calculation of the conservation of volume approximation compared to experimental data.

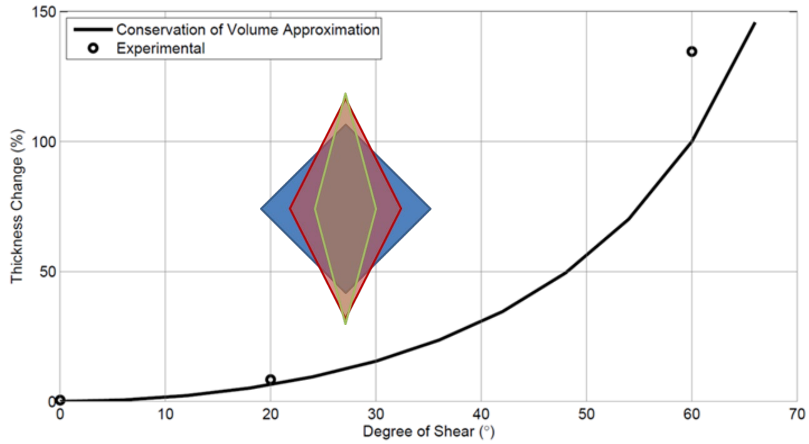

Figure 2. A conservation of volume approximation used to calculate the change in lamina thickness as a function of shear, which correlates well with experimental data. [3]

Thickness variations of the individual plies can influence the friction and lead to wrinkles in the preform step [4]. However, the effects of thickness changes are not limited to the preform stage. After the preform step, heat and pressure are used in combination with matched dies to consolidate the preform(s) and cure the part. Figure 3 shows how nonuniform thickness distribution in the preform stacks can lead to pressure variations across the part and inconsistent/poor consolidation.

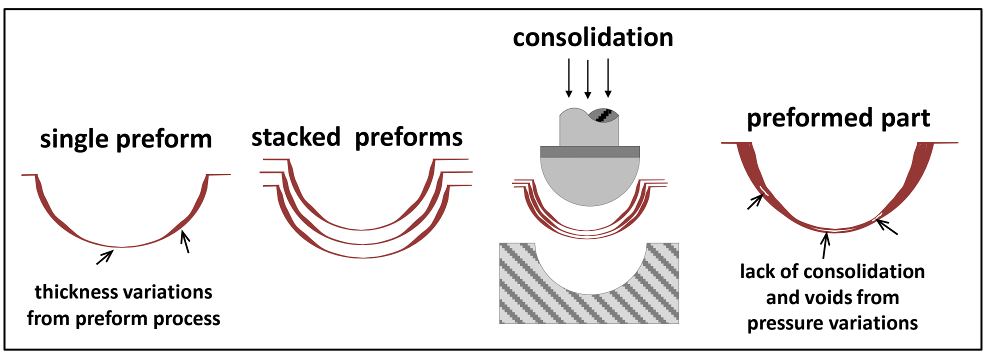

Figure 3. Variations in preform thickness leads to inconsistent/poor consolidation.

The static and dynamic coefficients of friction are determined from a test program that quantifies the friction coefficient as a function of temperature, speed and normal pressure. The coefficients are then used as inputs into a multi-layer finite element thermoforming simulation to explore how various combinations of binder-ring pressure, forming speed and material orientation impact part formability and thickness uniformity. This paper presents the effects of including laminate thickness changes and varying ply/ply and tool/ply frictions on the outputs of single-ply and triple-ply preform simulations of DSM Dyneema® HB210, a fiber-reinforced Ultra High Molecular Weight Polyethylene (UHMWPE) material systems.

Modeling Approach

The composite laminate investigated in this research is Dyneema HB210. This material system is a thermoplastic cross-ply containing four unidirectional layers oriented in a $(0/90)_2$ fiber configuration with each ply comprised of UHMWPE fibers and a thermoplastic polyurethane (TPU) based matrix. Although the simulation methodology is evaluated for this specific material system in this paper, the methodology is applicable to a wide range of material systems undergoing a similar manufacturing process. Tensile, bending, and shear frame testing were performed at elevated temperatures to inform the user-defined material subroutines and ply/ply and tool/ply friction testing was performed to determine the static and dynamic friction inputs [5, 6].

The modeling performed for this research was based on a mesoscopic scale using a discrete approach developed by Jauffrès et al. [7] employing a hypoelastic element description with an explicit formulation. Beam elements incorporate the tensile and flexural properties of the fibers, and the shell elements define the shear response of the sheet. For example, a cross-ply is discretized into a mixed-mesh grid where each unit cell consists of four beam elements and one shell element (Figure 4).

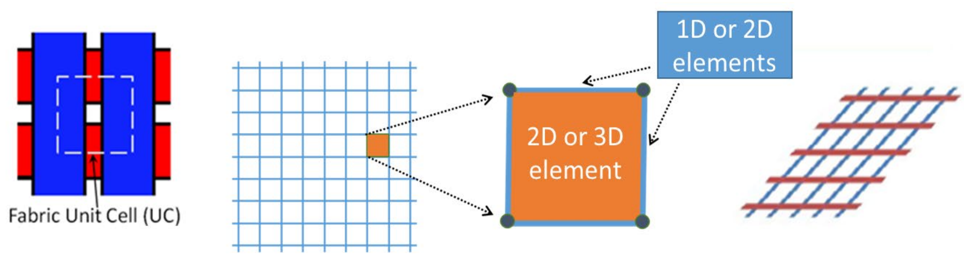

Figure 4. Unit cell configuration for mesoscopic laminate material model.

In the version by Jauffrès et al., the shell and beam elements serve specific roles. The shell element has no tensile/compression properties and only possesses the in-plane shear stiffness that varies with the degree of shear at that point in the ply and does not account for thickness changes. The two horizontal beam elements are defined using properties of the 0° direction fibers/tows, and the two vertical beam elements are defined using properties of the 90° direction. A single node is used to connect the intersecting beam elements at each of the shell corners. This joining of the beams assumes a "no slip" condition between 0° and 90° layers and has been demonstrated through the correlation of the model with experimental data to be an acceptable assumption for the materials being investigated. This modeling technique has been successfully applied to a variety of textile architectures including woven, unidirectional, and non-crimp fabrics [7].

For this research, the Jauffrès et al. material subroutine was updated to accommodate 3D material properties for the use of thickness stretch shell elements (ELFORM25) [8]. Thickness stretch elements offer the advantage of thinning during stretch and thickening in shear, thereby providing the ability to track the thickness changes during forming (Figure 5). Likewise, the thickness changes combined with friction will affect the formation of wrinkles during the process. Beam elements that exhibit a high stiffness in tension, but a low stiffness in compression are used to capture the bending properties of the laminate, a method used successfully by Dangora et al. previously in Abaqus® [9].

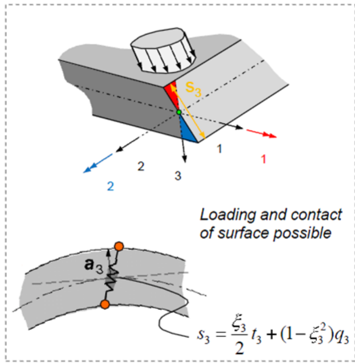

Figure 5. Thickness stretch shell elements (ELFORM25) [8, 10].

The hemisphere preform being modeled has a punch radius of 76.2 mm (3 in.) and the laminate blank used in the process is 381 mm x 381 mm (15 in. x 15 in.) square shown in Figure 6. In the simulation, the punch is pushed through the material farther than the radius so that an extended hemisphere shape is formed with flat sides to make the part more complex than a pure hemisphere. The tensile, shear and bending properties at 120° were provided from previous testing [5, 6] and shown in Table 1.

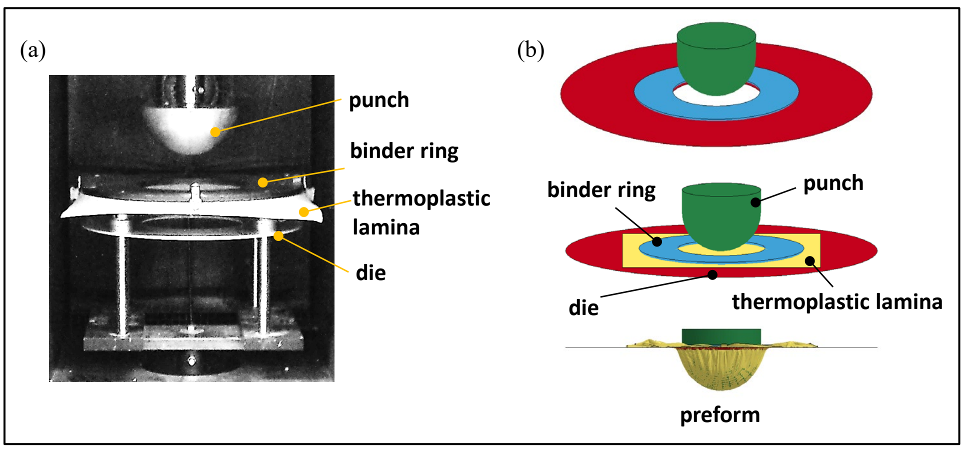

Figure 6. Hemisphere preform (a) experimental setup and (b) simulation in LS-DYNA.

Table 1. Material Properties for Simulations

Material System	Temperature °C	Shear Stiffness MPa	Tensile Modulus MPa	Compressive Modulus MPa
Dyneema HB210	120	$4068\lvert\gamma\rvert^6 - 11408\lvert\gamma\rvert^5 + 12342\lvert\gamma\rvert^4 - 6410\lvert\gamma\rvert^3 + 1614\lvert\gamma\rvert^2 - 179\lvert\gamma\rvert + 9$	13222	57

*Note that γ is defined as the shear strain of the composite lamina

In the current laboratory setup, the maximum binder ring pressure that can be achieved is 0.00575 Pa, while the actual process pressure is near 1 MPa. Therefore, these are the two extremes that were examined so that the model could be validated with at least one case that could be completed in the lab, but also used to predict the actual process. In previous modeling efforts, it was assumed that a constant friction coefficient of 0.3 for static and dynamic was reasonable. However, experimental testing of Dyneema HB210 at 120°C and at pressures corresponding to the models found much lower coefficients as shown in Table 2. Simulations using both sets of friction values were performed for comparison. Single-layer simulations and triple-layer simulations were performed to incorporate the effects of layer/layer friction combined with friction changes.

Table 2. Friction Coefficient used in Simulations

	Tool/Ply Static	Tool/Ply Dynamic	Ply/Ply Static	Ply/Ply Dynamic
Assumed	0.300	0.300	0.300	0.300
Actual	0.067	0.054	0.117	0.057

Results and Discussion

The effect of pressure and friction were examined for the models that did not incorporate shell thickness changes and for the models that updated shell thickness based on the state of shear and stretch. Comparisons were made on the frequency and size of the wrinkles, as well as the distribution of shear deformation. Figures 7 and 8 show elements with thickness change capabilities, as well as those without, are equally effective in predicting the locations and amplitudes of wrinkles. The amplitude of wrinkles is diminished by increasing the pressure, while using the same coefficients of friction. The trend that is seen when maintaining the same binder pressure while increasing the coefficient is more wrinkles of smaller amplitude, likely because of higher tension developed under the binder ring. Interestingly, when the binder pressure is at the higher value, but the coefficient of friction is at the lower value (actual experimental coefficients), the shape across the top of the part has fewer out-of-plane defects because of lessened friction between the laminate and the punch. Effects of using thickness stretch elements are not extremely evident from the wrinkle profiles of single-layer preforms, but could be amplified with more layers.

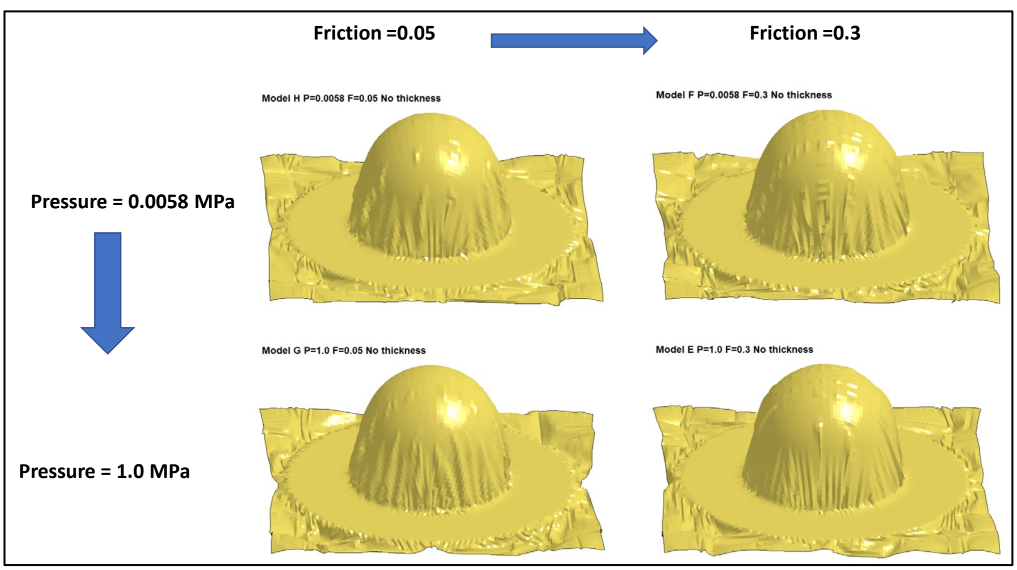

Figure 7. Wrinkle formation of single-layer hemisphere preform with varying binder pressure and tool/ply friction with out thickness change.

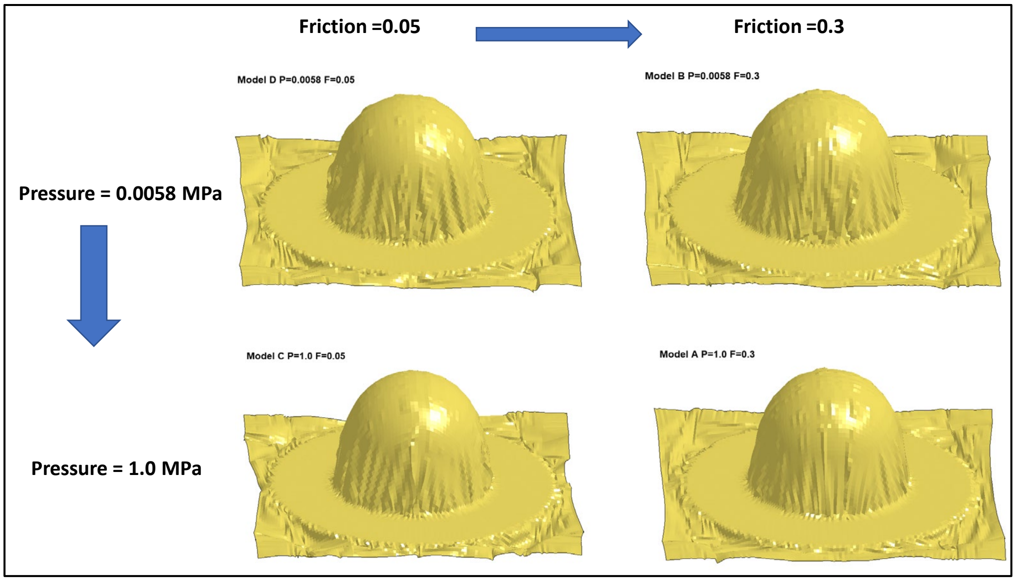

Figure 8. Wrinkle formation of single-layer hemisphere preform with varying binder pressure and tool/ply friction with thickness stretch shell elements.

Figures 9 and 10 show how the shear deformation varies over the part in response to changes in the binder ring pressure and the coefficient of friction. When thickness change is not incorporated, the maximum shear angle reached increases with the applied binder ring pressure and with increased coefficients of friction. However, when the material is allowed to compress or thicken, this trend changes and is more dependent on the combination of binder pressure and friction. The models with the higher coefficient of friction exhibited a decrease in the maximum shear angle with an increase in binder pressure, although the lower coefficient of friction models exhibited the same shear increase with binder pressure as the general shell models. An explanation for this result could lie in the ability of the material to redistribute the binder pressure and eliminate sharp peaks in tension with the ability to change thickness. As further evidence for this, the shear angle distribution is less varied with the thickness stretch shell elements. Information such as shear and thickness uniformity is essential in predicting the pressure distribution during the consolidation process.

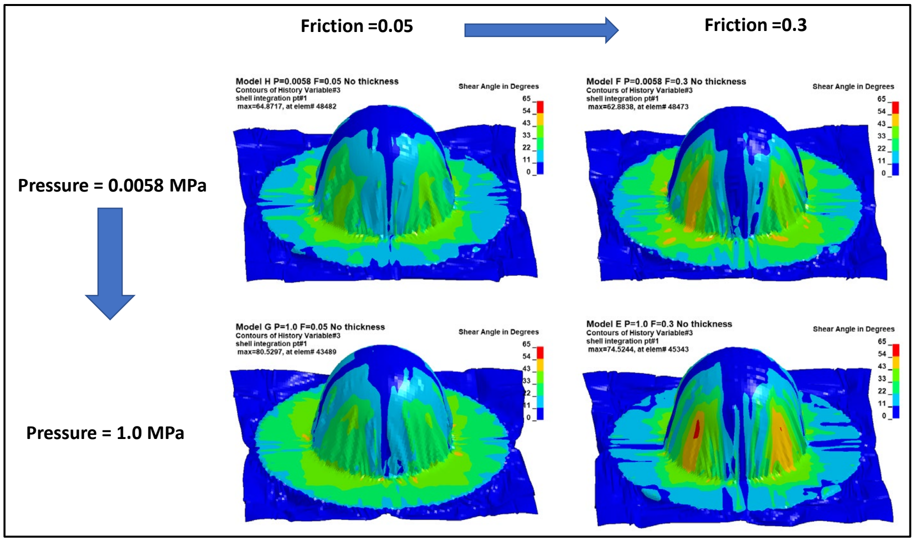

Figure 9. Shear deformation of single-layer hemisphere preform with varying binder pressure and tool/ply friction without thickness change.

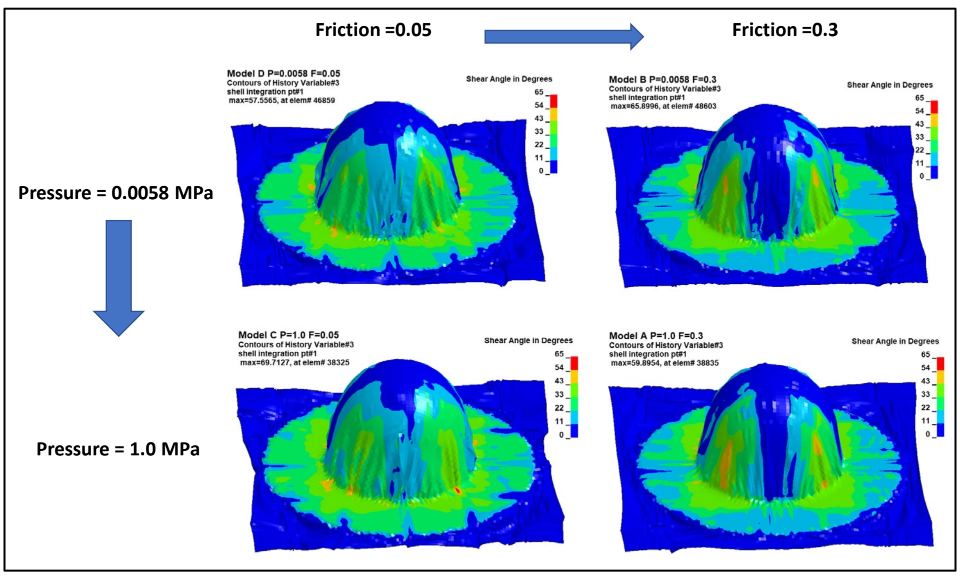

Figure 10. Shear deformation of single-layer hemisphere preform with varying binder pressure and tool/ply friction with thickness stretch shell elements.

Figures 11 and 12 show the wrinkle formation and shear deformation results from the partial simulation of triple-layer preforms. Updates to the models will need to be made to complete the entire punch displacement. A binder pressure of 1.0 MPa was used for these models, with varying friction coefficients between both the tooling and fabric as well as between the fabric plies. A comparison of the use of general shell elements to those with thickness stretch show little difference in the wrinkle formation for three layers, but would likely show differences if 10-20 layers were modeled. The shear deformation shows similar difference as the single-layer models in that the binder pressure is more evenly distributed in the thickness stretch elements, decreasing the localized tension spots. This distribution is replicated in the more even distribution of shear deformation in the part. More work needs to be done in getting the model to run to completion, as well as refining the mesh to capture the small wrinkles that can form under the binder ring. Addition layers , up to 10 or 20, will be simulated in future work.

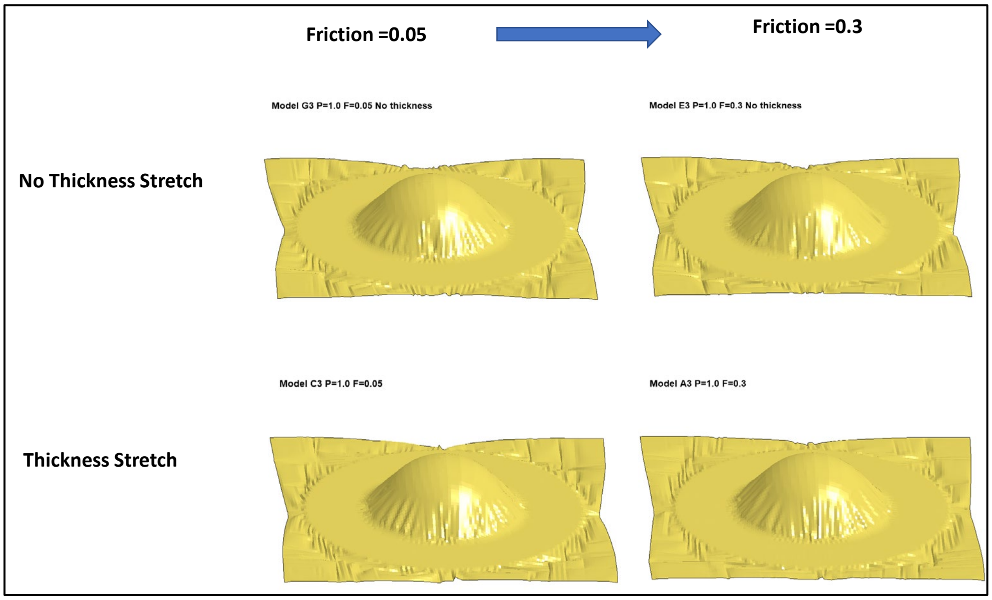

Figure 11. Wrinkle formation of triple-layer hemisphere preform with 1.0 MPa binder pressure and varying tool/ply and ply/ply friction with varying shell elements.

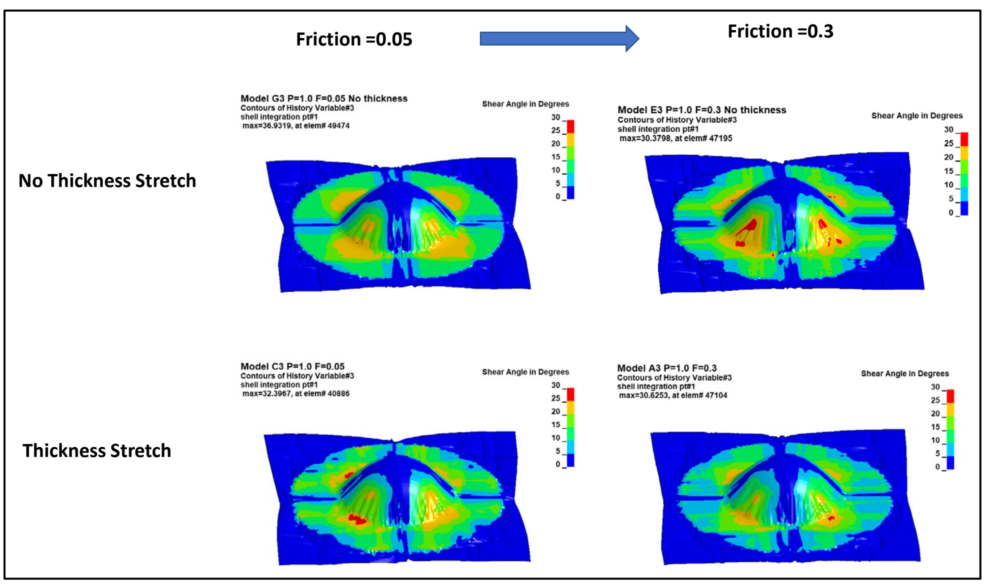

Figure 12. Shear deformation of triple-layer hemisphere preform with 1.0 MPa binder pressure and varying tool/ply and ply/ply friction with varying shell elements.

Conclusions

Single- and triple-layer preform simulations were completed with varying binder pressure and coefficients of friction, comparing the use of thickness stretch (ELFORM25) shell elements to general shell elements without thickness changes. Both types of elements captured the amplitude and location of wrinkles in the preform part. Wrinkle amplitude decreased with increase binder pressure, but overall shape deformations were reduced most with a combination of increased binder pressure and actual coefficients of friction from experiments. The uniformity of shear was better predicted with a model that included shell element thickness changes from compression and shear. More work needs to be done to refine the triple-layer models to run to completion. However, based on these results, actual friction data and thickness capturing elements should be used for a predictive forming model to best predict the pressure distribution and consistency of consolidation.

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