Materials Research Proceedings 41 (2024) 513-522 https://doi.org/10.21741/9781644903131-57

An investigation into the relationship between hemisphere tooling parameters and thickness changes during the thermoforming of a thermoplastic composite

WHITE Kari D.[1,a*] and SHERWOOD James A.[1,b]

[1]Department of Mechanical Engineering, University of Massachusetts, Lowell, One University Ave., 01854, Lowell, MA, USA

[a]Kari_White@uml.edu, [b]James_Sherwood@uml.edu

Keywords: Composite, Thermoforming, Simulation, Tooling, UHMWPE

Abstract. Thermoforming is an economical and fast means of transforming a flat sheet of thermoplastic composite material into a complex shape. The two-step process consists of a preform phase that transforms the laminates to near net shape ply stacks and of a subsequent consolidation step that employs pressure and heat to join the preforms into a final part. During the preform step, many aspects of the process must be regulated to minimize undesirable affects. A binder ring applies pressure to the material to induce in-plane tension, aiding in the initiation of shear deformation in the laminate. The material increases in thickness as it undergoes in-plane shear to conform to the preform shape. The degree of shear varies over the part, creating variations in thickness and subsequent challenges with uniform consolidation. While material attributes and processing parameters are critical in successful preforming, refining the tool geometry can also lead to significant changes in the preform outcome. Although many of these challenges have been addressed in a design-build-test approach, the goal of this research is to develop a virtual process that can guide design changes in the tooling to achieve a well consolidated part. A discrete mesoscopic modeling approach was implemented in LS-DYNA using thickness-change shell elements (ELFORM25) that can incorporate 3D material properties, including through-plane thickness changes. The current state of the simulation effectively incorporates material behavior, tool/ply friction and thickness changes that reflect variations in pressure. The simulation is used to investigate the significance of the punch/die gap size and the die fillet radius on the tooling geometry. The modeling approach was verified through comparison to experimental results with two types of tooling geometry. A parametric study was then performed to investigate tooling changes in relation to the number of layers, or thickness, of a unidirectional ultra-high molecular weight polyethylene (UHMWPE) material, DSM Dyneema® HB210. The outcomes of the result were evaluated by comparing wrinkle formation, shear deformation and thickness variations. The research shows that the radius of the die fillet has a significant impact on the uniformity of thickness in the preform. A combination of fillet radius and die affects can lead to more desirable outcomes in terms of wrinkle formation and thickness uniformity.

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 typical thermoforming process consists of a preform step that transforms a set of laminates to a near-net-shape ply stack, and a subsequent consolidation phase that employs pressure and heat to join a set of the preforms into a final part. Friction plays a critical role in the preform phase of the manufacturing process.

Intra-ply shear is the dominant mode of deformation during the forming process, and various degrees of material shearing are what allows the material to conform across a compound curvature part. Adding complexity to the forming process outcome is the increase in thickness of the lamina due to conservation of volume during in-plane shear. Dangora et al. [1] documented the incompressibility phenomenon with micrographs taken of laminates of DSM Dyneema® HB80 sheared to 0°, 20°, and 60° showing the associated thickness increases corresponding to conservation of volume. Based on that research, variations in thickness can be linked to variations in shear. The implications of thickness changes during the process are two-fold: (1) thickness variations in the preforms and (2) effects on friction during the forming.

After the preform step, heat and pressure are applied in combination with matched dies to consolidate the preform(s) and to cure the part. Figure 1 depicts how thickness variations in individual preforms can lead to poor-quality consolidation and voids due to pressure variations. Therefore, these thickness changes must be considered in a forming simulation.

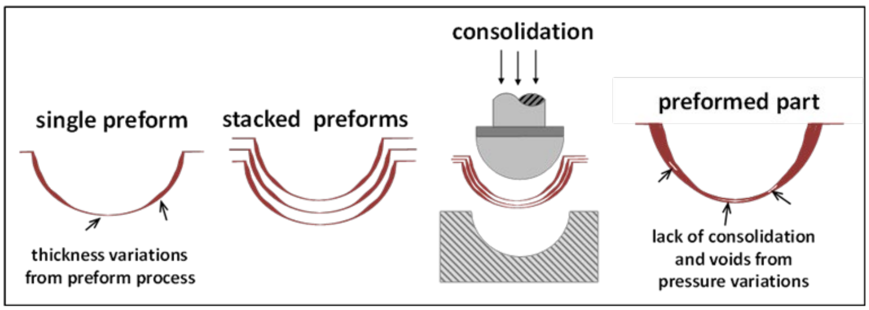


Figure 1. Variations in preform thickness leads to inconsistent / poor consolidation.

The thickness changes due to shearing also affect material surfaces involved with frictional interactions. The friction between the binder ring and the material adds tension so that the material undergoes shear, even under the binder ring. Studies have shown that friction between two sliding surfaces can create unwanted outcomes such as distortions in the final part shape, residual stresses, and wrinkles [2-6]. Moreover, in the use of binder rings, this friction can help to reduce the formation of wrinkles with an appropriate pressure [1, 7-11]. Hemisphere preforming trials accomplished by Dangora et al. [1] showed the reliance on binder-ring pressure in regulating the size and appearance of wrinkles for a unidirectional cross-ply material system, DSM Dyneema® HB80.

However, tooling also contributes to the uniformity of preform thickness, the development of wrinkles, and the overall quality of the preformed part. The gap between the binder ring and the punch, the gap between the die and the punch, and the radii of both the binder ring and the die are parameters that can be altered to influence the preform results.

This paper presents a parametric study to study the influence of tooling geometry on the quality of a multi-layer thermoformed hemisphere. Simulation is used to examine the preform outcomes using a combination of binder and die geometries.

Methodology

Experimental Hemisphere Preform. Hemisphere preform experiments were conducted using the two experimental setups shown in Figures 2 and 3. For both setups, the punch was attached to the crosshead of the Instron Universal Testing Machine, and load and displacement data were recorded. The hemisphere preform has a punch radius of 76.2 mm, and the laminate blanks used in the process are 381 mm by 381 mm. The crosshead descended at a rate of 6.35 mm/sec to replicate the conditions of the actual preform process.

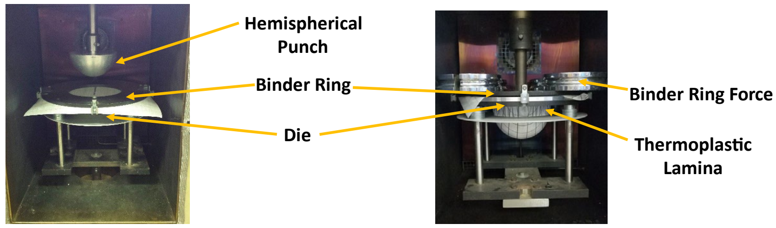


Figure 2. Original experimental preform experimental setup.

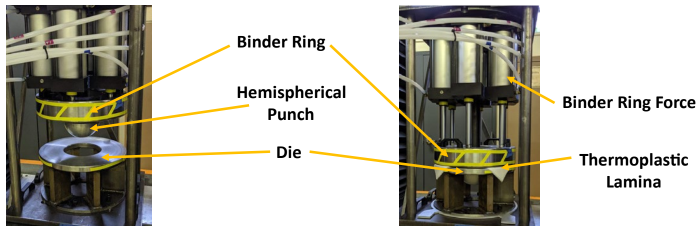


Figure 3. Redesigned experimental preform experimental setup.

In the original setup, after the laminate sheets were in place, free weights were placed on top of the binder ring to develop pressure on the laminate. The entire setup was located inside an Instron oven to heat the material to the desired testing temperature. The maximum binder ring pressure achieved with the original setup is 5.75 kPa.

Finite element simulations showed that much higher binder pressures are required to mitigate wrinkle formation when considering multiple plies. The preform setup of Figure 2 was redesigned to accommodate more layers and to use a series of pneumatic cylinders to apply a greater force to the binder than was possible in the original design. The redesigned setup can apply pressures of up to a MPa to the laminate under the binder ring and includes a larger gap between the punch and the binder ring to accommodate up to ten layers of laminate. However, the redesigned test setup cannot fit in the Instron oven. Thus, the material is heated slightly above testing temperature in an infrared oven, and then quickly transferred to the new setup for forming.

Modeling Approach. The Sherwood Group [12] developed a discrete modeling approach that has been shown to successfully simulate the forming of a plain-weave hemisphere shape. Conventional elements available in commercial finite element software are used in the unit cell approach shown in Figure 4. Fiber directionality is described and tracked by beam elements that represent the tensile and flexural properties of the laminate. The shear load is carried by shell elements that capture the evolution of the in-plane shear stiffness as a function of the degree of shear. In the case of woven materials, the horizontal and vertical beams represent the warp and weft tows with of a bilinear modulus for the beam elements to capture wrinkling behavior [13]. In the case of a 0/90 cross-ply, the horizontal and vertical beams can be assigned tensile and flexural properties of the 0° and 90° layers.

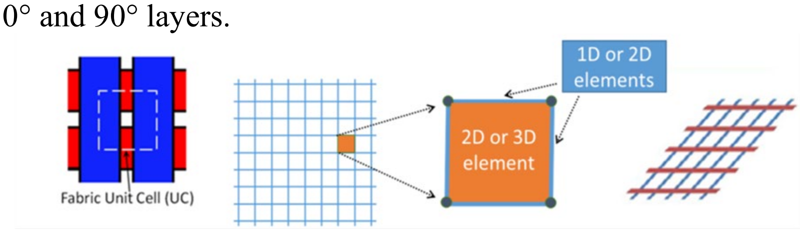


Figure 4. Unit cell configuration for mesoscopic laminate material model.

Plane-strain shell elements are widely used to model the in-plane shear behavior of laminate forming, but this class of shell elements does not capture the thickness changes caused by shearing, compression and/or stretching. The element formulations in LS-DYNA that can model through-plane strains were evaluated, and one formulation was chosen for further consideration. The LS-DYNA thickness-enhanced shell formulation (thick-thin shell), SHELL ELFORM25, is a general shell element that includes an additional feature of linear strain through the thickness compared to a Hughes-Liu general shell element. Loading and contact of the surface are possible to allow for tooling and laminate plies to interact when contact algorithms are define [14]. The thickness stretch of the element requires a 3D constitutive model, and the element is defined by a midsurface with only four nodes (Figure 5).

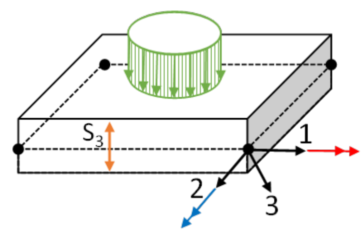


Figure 5. Thick-thin shell element.

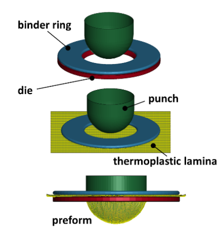


Figure 6. Hemisphere preform simulation in LS-DYNA.

Evaluation of this element choice required that the user-defined (UMAT) discrete mesoscopic material model used in LS-DYNA consider 3D material behavior. The in-plane tensile behavior is still carried by beam elements that provide directionality to the elements carrying the shear load. The in-plane shear behavior as a function of shear angle remains the same as the plain-strain implementation. However, through-plane stress and strain are updated in the UMAT, whereas general shell elements do not have strain in that direction. Validation of the shear behavior application was done through comparison to shear-frame, also known as picture-frame, experimental data conducted with a constant shear rate of 0.1 sec^{-1} [15]. The hemisphere preform simulation as shown in Figure 6 was modeled after the experimental setup, modified appropriately to represent the binder ring and die sizes. The friction coefficients for the material were calculated from data that was recorded using the UMass Lowell friction tester as redesigned by Campshure et al. [16-18].

The composite laminate system investigated in this research is DSM® 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 [19]. The tensile, shear and bending properties at 100°C for Dyneema® HB210 are provided from previous testing [15, 20, 2] and shown in Table 1, where γ is defined as the shear strain of the composite lamina. The friction values are a result of averages between fiber orientation and resin condition, as the hemisphere is symmetrical with each condition represented equally.

Table 1. Material Properties for Hemisphere Preforming Simulations (MPa)

Shear Stiffness as a Function of Shear Strain (MPa)	**Tensile Modulus (MPa)**	**Compressive Modulus (MPa)**	**Tool/Ply Static**	**Tool/Ply Dynamic**
$1723-5002\vert\gamma\vert^5+5677\vert\gamma\vert^4-3179\vert\gamma\vert^3+909\vert\gamma\vert^2-125\vert\gamma\vert+7$	19300	5000	0.110	0.077

Setup of Parametric Study on Tooling Geometry

Simulations of both experimental preforming setups were completed to validate the material properties and friction values used in the simulation. Measured punch force, shear angle distribution, draw-in profile, and visual wrinkle distribution were metrics used in the evaluation. All models showed good correlation with the experimental results, and it was concluded that the model was valid to move forward with the parametric study of the tooling.

Investigation of Tooling Parameters. Specific geometry attributes were identified to be relevant to the preforming outcomes. Figure 7 shows the upper gap as the distance between the inner radius of the binder ring and the outer radius of the punch. The lower gap indicated the distance between the inner radius of the die and the punch. The lower radius is a measure of the fillet, or curvature, of the die.

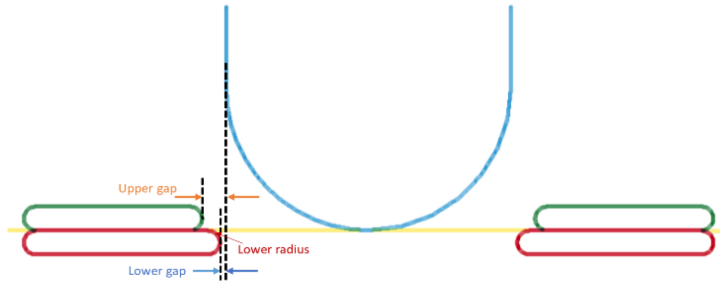


Figure 7. Tooling parameters analyzed in study.

The experimental preform setups had the geometric values listed in Table 2, and the simulations were created to reflect these values. An initial parametric study was conducted that used combinations of the existing tooling to evaluate the sensitivity of the model to parameter changes. Based on the preliminary results, a set of tooling parameters was chosen to expand the range of binder gap (upper gap) and die fillet radius (lower radius). The range of values used in the study are listed in Tables 4 and 5. A binder pressure of 300 kPa was used to replicate the experimental pressure used with the four layers of laminate with the redesigned tooling. All simulations were performed with the properties of DSM® Dyneema® HB210 at a processing temperature of 100°C. Each simulation was a combination of a letter from Table 4 and a number from Table 5, e.g. “a1”.

Table 2. Geometric Properties of Experimental Preform Setup

Tooling	Upper Gap [mm]	Lower Gap [mm]	Lower Radius [mm]
Original	8.26	3.18	12.7
Redesign	12.7	3.18	6.35

Table 3. Binder (upper) gap radius values

Model Designation	Upper Gap [mm]
a	7.62
b	8.26
c	10.2
d	12.7
e	15.2

Table 4. Die fillet (lower) radius values

Model Designation	Lower Radius [mm]
1	2.54
2	5.08
3	7.62
4	10.2
5	12.7

Three metrics were used in comparing the results from the study. Thickness distribution over the hemispherical portion of the preform gives guidance on how well the preform can be consolidated into a uniform part. As controlling thickness uniformity is a goal of this project, measures of thickness variation were used as a quantitative comparison. A general assessment of the quality of the preform includes the locations and amplitudes of wrinkles. Finally, the in-plane shear angle distribution contributes to both the thickness uniformity and an indication of how well the binder ring can engage appropriate shearing of the laminate into the hemispherical shape.

Results and Discussion

The initial thickness of the material was 0.72 mm, and the final thicknesses of the elements over the hemisphere portion of the preform were normalized to this initial thickness to evaluate the relative change in thickness. Box and whisker plots were employed to visualize the distribution of element thickness over the part. Figure 8 shows normalized thickness results for all 25 tooling configurations that were analyzed. The box for each configuration represents the middle 50% of the data, while the lines extending to the top and bottom represent the max and min data values.

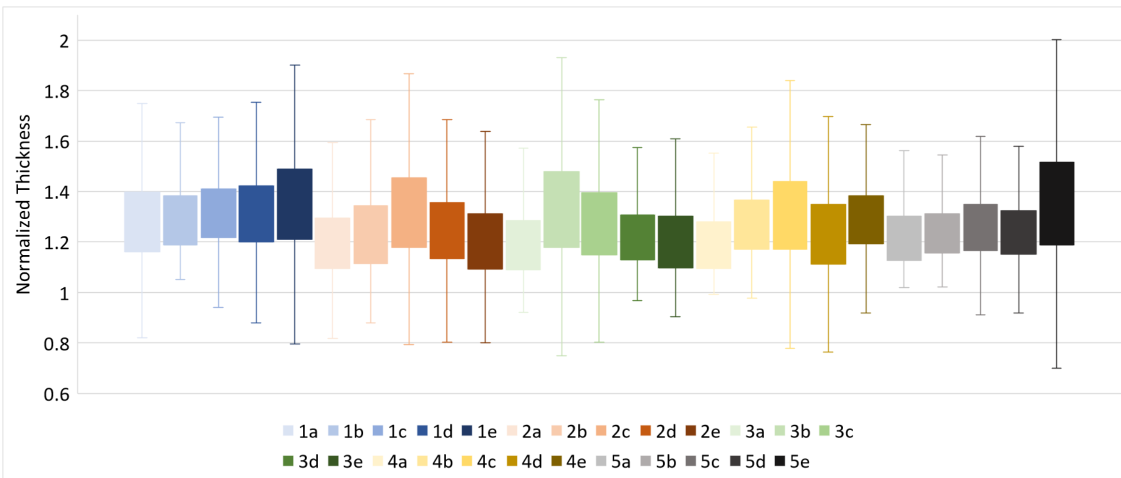


Figure 8. Normalized thickness variation for all tooling configurations.

Thickness of the material over the preformed part is also tracked to indicate how well a set of preforms will be consolidated. The goal is to keep the variation in the thickness small. Therefore, the tighter (or narrower) the box and the smaller the range between the maximum and minimum the better. For example, configuration 5b in Figure 8 has a tight data spread while 5e has a large spread, and the thickness variation can be seen in the contour plots of Figure 9.

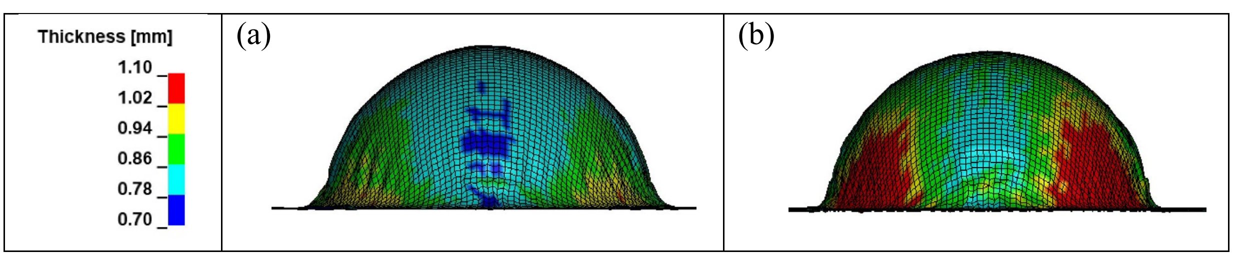
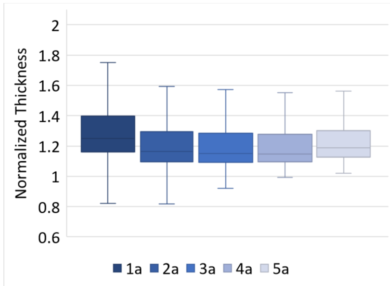


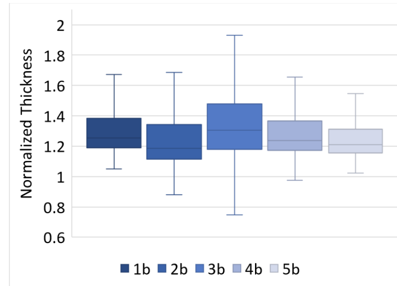
Figure 9. Thickness variations over hemisphere portion of preform for configurations (a) 5b and (b) 5e.

The variations shown in Figure 8 demonstrate that tooling does affect the uniformity of thickness and choices can be made to improve that uniformity. Identifying the sensitivity of thickness variations to individual tooling components is critical. Figure 10 shows the 25 data sets parsed by the upper binder gap. It can be seen in this figure how the thickness uniformity changes as a function of changing the die fillet radius, with a subtle trend of increasing uniformity with increasing fillet radius. However, not all the results fit the trend, indicating there may be competing effects with other tooling parameters or initial material thickness.

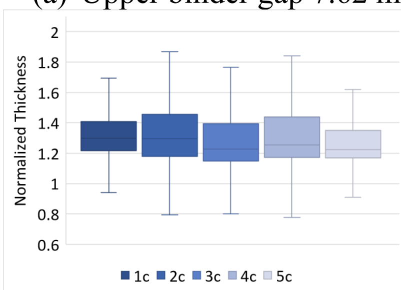
Increasing die fillet radius



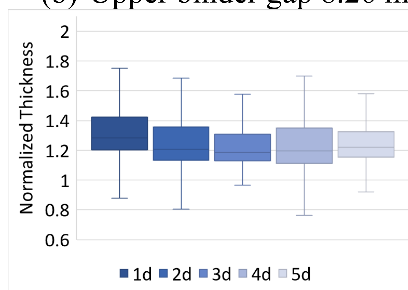
(a) Upper binder gap 7.62 mm



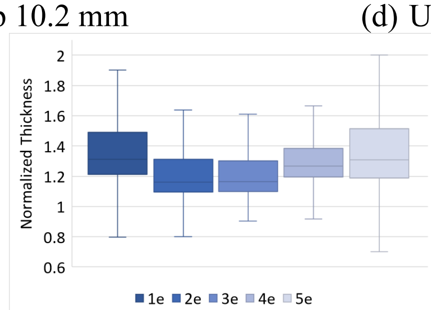
(b) Upper binder gap 8.26 mm



(c) Upper binder gap 10.2 mm



(d) Upper binder gap 12.7 mm



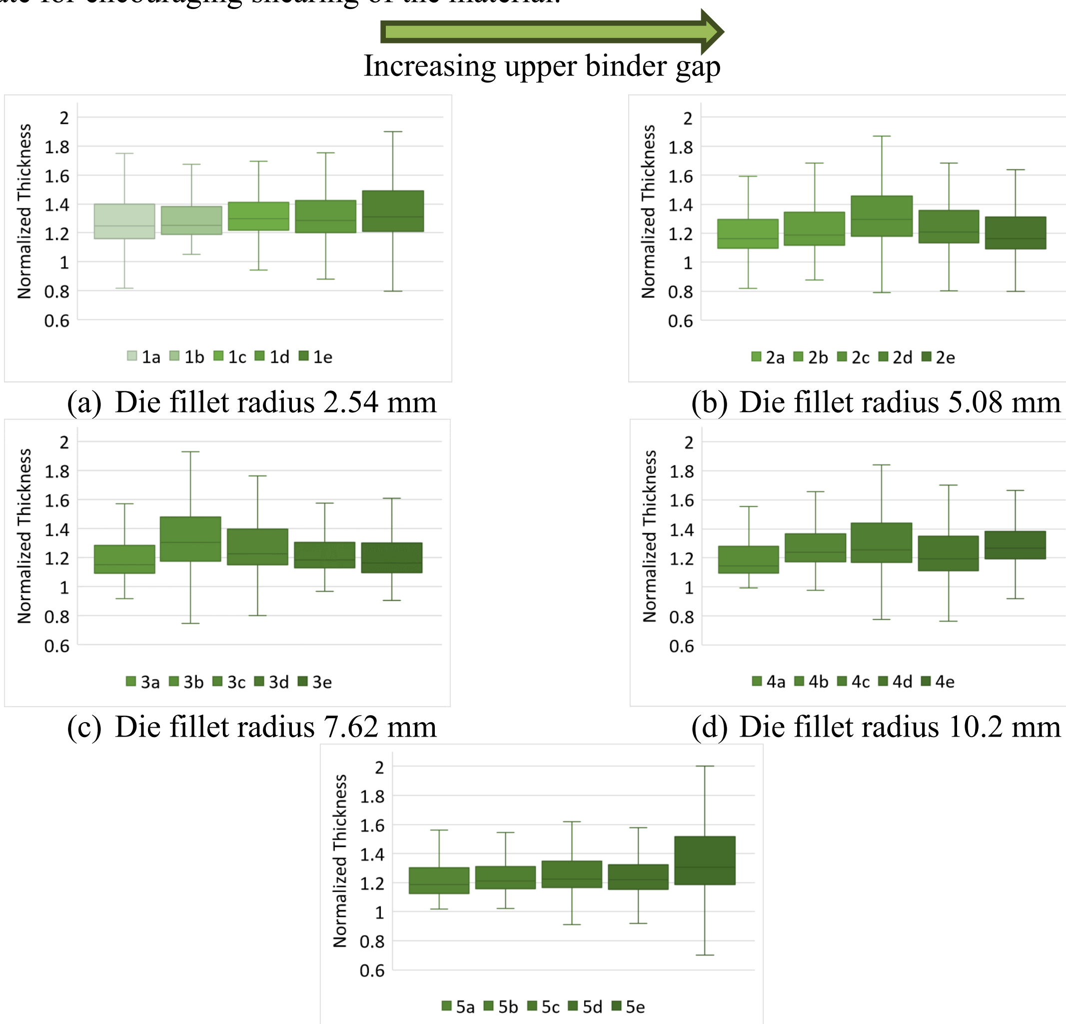
(e) Upper binder gap 15.2mm

Figure 10. Thickness variations as a function of increasing die fillet radius for five binder gaps (a-e).

Figure 11 shows the same 25 results when parsed by fillet radius. As the binder gap is increased, there is no recognizable trend in the thickness uniformity. These results imply that the fillet radius plays a larger role in controlling the uniformity of the preform thickness than the binder gap.

Based on the thickness uniformity results, the four configurations with the least variation in thickness were compared visually for part quality in terms of visible wrinkling. The preform surfaces of the four configurations are shown in Figure 12. Based on visible inspection, configurations 3d and 4a (Figure 12c) show the least amount of waviness and wrinkles extending up into the hemisphere from the base. Likewise, the amplitudes of the wrinkles appear to be less than the other configurations. Based on these results, specific combinations of binder gap and fillet radii would produce acceptable results. However, more research is necessary to quantify the amplitude and frequency of the wrinkles.

Figure 13 shows the shear angle contours for all four configurations. The shear results confirm that the material is being sheared adequately in the first two configurations, therefore the uniformity of material thickness is occurring because of the combination of the shear and tension effects. However, configurations with largest die fillet radius, the tension is not maintaining a level adequate for encouraging shearing of the material.



(a) Die fillet radius 2.54 mm
(b) Die fillet radius 5.08 mm
(c) Die fillet radius 7.62 mm
(d) Die fillet radius 10.2 mm
(e) Die fillet radius 12.7 mm

Figure 11. Thickness variations as a function of increasing binder gap for five fillet radii (a-e).

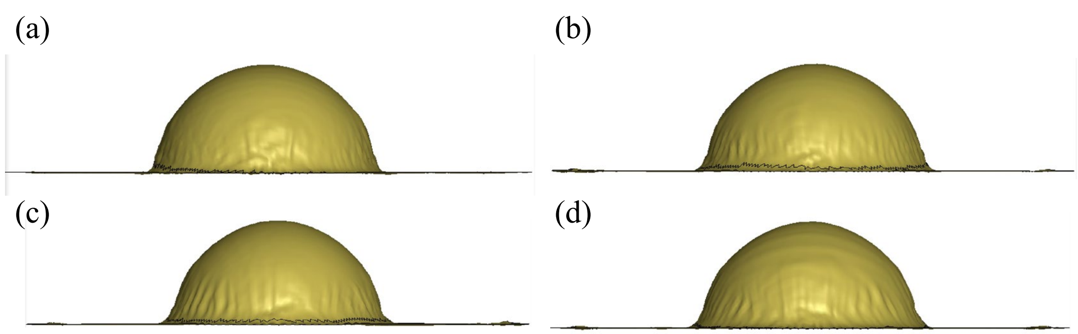


Figure 12. Preform wrinkle patterns for (a) 3d, (b) 4a, (c) 5a, and (d) 5b.

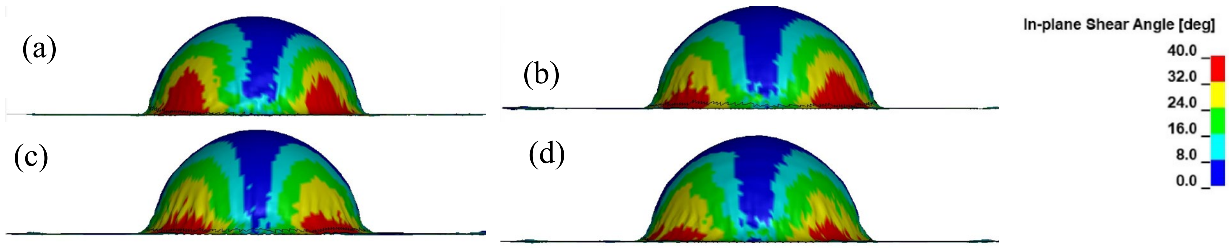


Figure 13. Preform shear results for (a) 3d, (b)4a, (c) 5a and (d) 5b.

Based on the preliminary studies, both the binder gap and die radius as well as combined affects contribute to the thickness uniformity and the wrinkle formation of the preform. Future work will strive to quantify the frequency and amplitude of the preform wrinkles for comparison.

Summary

In this research hemisphere preforming simulations were performed on a unidirectional thermoplastic cross-ply material systems materials, DSM Dyneema® HB210. The simulation was successfully validated experimentally with two different tooling configurations. A parametric study was performed to evaluate the role of the binder gap (space between the punch and the binder) and the die radius (the curvature of the die that the material is pushed through). Results showed significant influence of lower radius in the uniformity of the thickness of the preform. The binder gap, in conjunction with the die fillet radius, plays a role in the wrinkle formation through appropriate shear in the material. Future studies will analyze the frequency and quality of wrinkling for quantitative comparison.

Acknowledgement

This work was performed under Cooperative Agreement W911NF-18-2-0033 with the US Army Research Lab. The material was donated by DSM and LS-DYNA was donated by ANSYS.

References

[1] Dangora, L.M., C.J. Mitchell, J. Sherwood, and J.C. Parker, Deep-Drawing Forming Trials on a Cross-Ply Thermoplastic Lamina for Helmet Preform Manufacture. Journal of Manufacturing Science and Engineering, 2017. 139(3): p. 031009. https://doi.org/10.1115/1.4034791

[2] Ersoy, N., T. Garstka, K. Potter, M.R. Wisnom, D. Porter, and G. Stringer, Modelling of the spring-in phenomenon in curved parts made of a thermosetting composite. Composites Part A: Applied Science and Manufacturing, 2010. 41(3): p. 410-418. https://doi.org/10.1016/j.compositesa.2009.11.008

[3] Ersoy, N., K. Potter, M.R. Wisnom, and M.J. Clegg, An experimental method to study the frictional processes during composites manufacturing. Composites Part A: Applied science and manufacturing, 2005. 36(11): p. 1536-1544. https://doi.org/10.1016/j.compositesa.2005.02.010

[4] Larberg, Y.R. and M. Åkermo, On the interply friction of different generations of carbon/epoxy prepreg systems. Composites Part A: Applied Science and Manufacturing, 2011. 42(9): p. 1067-1074. https://doi.org/10.1016/j.compositesa.2011.04.010

[5] Lightfoot, J.S., M.R. Wisnom, and K. Potter, A new mechanism for the formation of ply wrinkles due to shear between plies. Composites Part A: Applied Science and Manufacturing, 2013. 49: p. 139-147. https://doi.org/10.1016/j.compositesa.2013.03.002

[6] Arafath, A.R.A., R. Vaziri, and A. Poursartip, Closed-form solution for process-induced stresses and deformation of a composite part cured on a solid tool: part I–flat geometries. Composites Part A: Applied Science and Manufacturing, 2008. 39(7): p. 1106-1117. https://doi.org/10.1016/j.compositesa.2008.04.009

[7] Breuer, U., M. Neitzel, V. Ketzer, and R. Reinicke, Deep drawing of fabric-reinforced thermoplastics: Wrinkle formation and their reduction. Polymer composites, 1996. 17(4): p. 643-647. https://doi.org/10.1002/pc.10655
[8] Lee, J.S., S.J. Hong, W.-R. Yu, and T.J. Kang, The effect of blank holder force on the stamp forming behavior of non-crimp fabric with a chain stitch. Composites science and technology, 2007. 67(3-4): p. 357-366. https://doi.org/10.1016/j.compscitech.2006.09.009
[9] Lin, H., J. Wang, A. Long, M. Clifford, and P. Harrison, Predictive modelling for optimization of textile composite forming. Composites Science and Technology, 2007. 67(15-16): p. 3242-3252. https://doi.org/10.1016/j.compscitech.2007.03.040
[10] Obermeyer, E. and S.A. Majlessi, A review of recent advances in the application of blank-holder force towards improving the forming limits of sheet metal parts. Journal of Materials Processing Technology, 1998. 75(1-3): p. 222-234. https://doi.org/10.1016/S0924-0136(97)00368-3
[11] Akkerman, R., R. Ten Thije, U. Sachs, and M. De Rooij. Friction in textile thermoplastic composites forming. in Proceedings of the 10th international conference on textile composites-TEXCOMP. 2010.
[12] Jauffres, D., J. Sherwood, C. Morris, and J. Chen, Discrete mesoscopic modeling for the simulation of woven-fabric reinforcement forming. Vol. 3. 2010. 1205-1216. https://doi.org/10.1007/s12289-009-0646-y
[13] Dangora, L.M., C.J. Mitchell, and J.A. Sherwood, *Predictive model for the detection of out-of-plane defects formed during textile-composite manufacture.* Composites Part A: Applied Science and Manufacturing, 2015. **78**: p. 102-112. https://doi.org/10.1016/j.compositesa.2015.07.011
[14] Haufe, A., K. Schweizerhof, and P. Dubois, Properties & Limits: Review of Shell Element Formulations. 2013: https://www.researchgate.net/publication/312053480_Properties_Limits_Review_of_Shell_Element_Formulations.
[15] White, K.D., C. Krogh, and J.A. Sherwood. Investigation of shear characterization of a UHMWPE unidirectional cross-ply for finite element simulation of composite processing. in AIP Conference Proceedings. 2019. AIP Publishing LLC. https://doi.org/10.1063/1.5112522
[16] Fetfatsidis, K.A., L.M. Gamache, J.L. Gorczyca, J.A. Sherwood, D. Jauffrès, and J. Chen, Design of an apparatus for measuring tool/fabric and fabric/fabric friction of woven-fabric composites during the thermostamping process. International Journal of Material Forming, 2013. 6(1): p. 1-11. https://doi.org/10.1007/s12289-011-1058-3
[17] Campshure, B., K.D. White, and J.A. Sherwood, Friction Characterization of UHMWPE Cross-Ply Composite Sheets for Thermoforming Processes. 2021. https://doi.org/10.25518/esaform21.759
[18] White, K.D., B. Campshure, and J.A. Sherwood, Effects of Thickness Changes and Friction during the Thermoforming of Composite Sheets. 2021. https://doi.org/10.25518/esaform21.506
[19] DSM Dyneema® Industries. 2018 [cited 2017 June]; Available from: http://www.dsm.com/products/dyneema/en_US/home.html.
[20] White, K., M. Yeager, J. Sherwood, T. Bogetti, and J. Cline, Material Characterization and Finite Element Modeling for the Forming of Highly Oriented UHMWPE Thin Film and Unidirectional Cross-ply Composites, in ASC 33rd Technical Conference. 2018: Seattle, WA. https://doi.org/10.12783/asc33/25944
[21] White, K.D., L. Dangora, and J.A. Sherwood, Temperature Dependent Flexural Rigidities and Thickness Investigation, in ASC 31st Technical Conference. 2017: Williamsburg, VA.