Single Curvature Preforming of Ultra-high Molecular Weight Polyethylene (UHMWPE) Composites

by Michael Yeager and Travis Bogetti

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*Weapons and Materials Research Directorate, CCDC Army Research Laboratory*
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## 14. ABSTRACT
Ultra-high molecular weight polyethylene (UHMWPE) composites are highly oriented fiber-reinforced materials commonly used in ballistic protective applications, where the as-manufactured quality and performance of the finished part are closely related. UHMWPE composites, commercially available as flat sheets, require a multistep process to be transformed into compound curvature parts. A commonly used process involves preforming a UHMWPE stack at elevated temperature (i.e., thermoforming) followed by high-pressure consolidation between matched metal tooling. In this process, the individual sheets often wrinkle due to the large in-plane shear deformation necessary to conform them into complex shapes. Wrinkling obscures the relationship between the process parameters and individual deformation mechanisms of the preforming because wrinkling and shear are coupled with compound curvature geometries. A single curvature preforming apparatus (i.e., preformer) is developed here to isolate wrinkling from the material response and study the complex deformation mechanics during processing. A finite-element model of the preformer is also developed and used to gain further insight into how various processing parameters influence material response during preforming. Understanding the influence of processing parameters on material deformation will facilitate processing and design strategies to manufacture complex shape UHMWPE parts with improved performance.

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Table 1 Effect of friction coefficients (resin and fiber side) on peak punch load for a binder pressure of 2.35 kPa ......................................................... 13
Ultra-high molecular weight polyethylene (UHMWPE) composites, a thermoplastic polymer-reinforced composite material, are used for ballistic protection due to their high stiffness-to-weight and strength-to-weight ratios.\(^1\)\(^2\) These materials are commercially available in flat sheet stock that must undergo significant deformation to be transformed into compound curvature parts for personal ballistic protection.\(^3\) Manufacturing compound curvature parts from flat sheets of UHMWPE composite presents a number of challenges, despite the insights provided by computer-aided simulations.\(^4\) Consolidating flat sheets between compound curvature matched metal tooling at high pressures, without an initial preforming step, often results in substantial material wrinkling and tearing. Preforming is therefore used to gently coax the material into a near net shape at elevated temperature prior to adding large consolidation pressure, thus reducing material damage during processing.\(^3\)\(^4\) In the preforming process, a punch tool deforms a stack of UHMWPE composite sheets as they pass through a die plate, with a binder plate on top of the sheets to add an out of plane constraint,\(^3\) as illustrated in Fig. 1.

Two commonly recognized deformation mechanisms that occur during preforming are in-plane shear deformation and material wrinkling. Shear deformation is induced in the UHMWPE sheets due to the in-plane loading resulting from friction between the material and tooling. Wrinkles form when there is insufficient binder pressure constraining the stack of UHMWPE sheets. Fiber extension is negligible during the process due to the high axial stiffness in the UHMWPE sheets.\(^5\) The lack of fiber extension causes the material to slide in some areas while shearing in others to conform to the shape of the punch, resulting in the development of location-dependent shear deformation. These shear strain gradients cause thickness variations within the part, which could subsequently induce pressure gradients during the high-pressure consolidation step in the manufacturing process. Pressure gradients during consolidation can lead to location-dependent properties,
delaminations, and inconsistent part performance, as the impact performance of UHMWPE composites has been linked to consolidation pressure.\textsuperscript{6}

While in-plane shear is commonly recognized as the primary deformation mechanism in preforming, the coupling of this mechanism with material wrinkling makes it difficult to fully understand the influence that process parameters have on the quality and reproducibility of the as-manufactured part. In this work, a single curvature preforming apparatus is designed and used to explore various key deformation mechanisms without process-induced wrinkling. A half-section of a right circular cylinder is used for the punch tool geometry. The preformer allows us to form sheets of UHMWPE composite into curved laminates and explore the influence of various processing parameters, such as punch displacement rate, binder pressure, and the number of sheets in the preform stack. Experiments are conducted at elevated temperature to gain insight into how the process temperature affects in-plane shear deformation gradients. Modeling the preforming process of UHMWPE composites into geometries with compound curvature is difficult and most of the published work relevant to helmet forming simplifies the problem to a hemispherical geometry.\textsuperscript{3,7,8} A finite-element-based model, capable of predicting the material shear response in the part during preforming is also developed and verified in this work. Simulations are presented to help to elucidate the influence of fiber orientation and temperature-dependent in-plane shear constitutive behavior of the UHMWPE sheet on the material response during preforming.

2. Single Curvature Preformer Design

2.1 Design Requirements

The in-plane shear response for UHMWPE composites has been shown to be temperature dependent.\textsuperscript{9} It is anticipated that the coefficient of friction between the sheets are temperature dependent, but exact values have yet to be characterized. The preforming experiments conducted in this work were completed under isothermal conditions to prevent the complexities associated with transient temperature variation. To ensure isothermal processing conditions, the preformer was designed such that the apparatus could be operated inside of an oven with an interior dimension of 400 $\times$ 400 $\times$ 559 mm.

The functional parts of the preformer are the punch, die plate, binder, and stack of UHMWPE composite sheets. The sheets are sandwiched between the die plate and binder as the punch descends and forces the material to deform. In-plane tension resists sheet sliding and is counteracted by friction between the sheets and tooling (i.e., die plate and binder). The magnitude of the frictional force is dependent on
the applied binder pressure and the interfacial friction properties. In addition to the frictional characteristics, the UHMWPE composite deformation response is also related to the processing temperature and punch rate. Important considerations in the design of the apparatus include ensuring that the punch, sheets, and die plate are all properly aligned with negligible frame distortion.

The aforementioned considerations lead to the following set of functional design requirements:

- Adjustable binder pressure and a mechanism to prevent binder movement
- Tunable gap dimension between the punch, UHMWPE sheet stack, and die plate
- Die plate must be modular and easy to change for the radius of curvature studies.
- Alignment of the punch and die plate must be ensured.
- Frame must be designed to minimize its deformation during loading.
- Punch rate and stroke are regulated.

### 2.2 Overview and Design Features

The preformer is placed in an oven, which sits within an Instron 4505 screw-driven testing frame. The shaft for the punch attaches to the load cell and the preformer frame anchors to the Instron base. The design, shown in Fig. 2, includes the ability to add weights to manipulate the binder pressure, guards to keep the binder properly aligned, an adjustable gap spacing for the die plate, and a linear bearing to maintain punch alignment. The oven also has a 120- × 343-mm window for observation during testing.
2.3 Design Details

2.3.1 Preformer Frame and Binder

The preformer frame and binder plate apparatus are shown in Fig. 3, with other parts removed for ease of explanation. The frame bolts onto a platform connected to the Instron base, described later. The vertical force of the punch is transmitted to the die plate through the stack of UHMWPE sheets. The force from the weights, which supply the binder pressure, is transmitted to the frame via the die plates. The die plates are constructed of steel and are located directly over a 38- × 38-mm T-slotted column to ensure minimal frame deflection during preforming. The T-slotted framing can be moved horizontally to adjust the spacing between die plates, and therefore, the ratio of sheet stack thickness to tooling gap size, while still maintaining column loading. Brackets are added to the frame to provide additional stability.
The binder consists of two plates connected by 25- × 25-mm T-slotted framing. The spacing between binder plates is adjustable to match the die plate gap. The binder has guard rails with tunable locations to prevent the binder plate from sliding horizontally. This method is used to keep the binders in the correct location because the guard rails do not supply any vertical force, which eliminates the risk of counteracting the added binder weight. The binder has stabilizing rods to ensure the weights do not fall during the experiment, which could potentially damage the apparatus and/or the oven.

2.3.2 Sizing of Preformer Component Dimensions

The oven dimensions impose physical limits on the dimensions of the preforming apparatus and UHMWPE sheet stack. Referring to Fig. 4, Eq. 1 describes the criterion that must be satisfied for all components to fit in the oven lengthwise:

$$D_{\text{Punch}} = L_{\text{Oven}} - 2(tol + L_{\text{Binder}} + L_{\text{Overhang}} + t_{\text{Charge}}).$$

Fig. 4 Design tool established to ensure dimensions of subcomponents result in a preformer that fits within the oven
In Eq. 1, $D_{\text{punch}}$ is the punch diameter, $L_{\text{Oven}}$ is the overall length of the oven, $tol$ is the clearance between the oven walls and the UHMWPE sheet stack, $L_{\text{Binder}}$ is the length of the binder, $L_{\text{Overhang}}$ is the length of sheet stack that extends beyond the binder plate, and $t_{\text{Charge}}$ is the gap space between the punch and the die plate/binder assembly. A binder length, $L_{\text{Binder}}$, of 50 mm is chosen for the preformer. A clearance ($tol$) of 25 mm is assumed for each side to prevent small manufacturing and oven alignment deviations from causing issues. An initial overhang, $L_{\text{Overhang}}$, of 51 mm is chosen to ensure enough sliding can occur for the punch to be fully embedded in the material before the material edge is under the binder. The following considerations were taken when selecting a reasonable charge thickness. The preformer can simultaneously process up to 16 sheets of UHMWPE material with each sheet having a maximum original thickness of 0.356 mm and the capacity to shear thicken up to 250% of the original thickness. In addition to the sheets of UHMWPE material, peel plies with a thickness of 0.051 mm are used to prevent material residue from depositing on the tooling surfaces at elevated temperature. Substituting these dimensions into Eq. 1 yields a maximum punch diameter, $D_{\text{punch}}$, of 114 mm. The maximum punch stroke length, $L_{\text{Stroke, max}}$, before the end of the sheets reach the binder can be described by

$$L_{\text{Stroke, max}} = L_{\text{Overhang}} + \left(1 - \frac{\pi}{4}\right) D_{\text{punch}}.$$  

The maximum stroke length for the previous dimensions (before the edge of the UHMWPE stack is under the binder plate) is 75 mm, which is 18 mm more than the radius of the punch (18 mm past the point where the punch is fully embedded in the UHMWPE stack). This is an adequate stroke length because it allows the punch to be fully embedded in the UHMWPE stack, any material extension due to shear deformation will further increase the stroke length. The sheets would no longer be constrained by the binder (neglecting material extension) if the stroke length passed 126 mm.

### 2.3.3 Connecting the Preformer Frame to the Instron Base

A platform is used to anchor the preformer to the base of the Instron, as depicted in Fig. 5. The nuts on the center column (bottom-left view in Fig. 5) are tightened to secure the platform’s location. Corner brackets attach the framing to the platform to ensure it does not move during preforming.
2.3.4 Attaching the Punch to the Instron

The punch was manufactured by 3-D printing of an Ultum polymer feedstock at the CCDC Soldier Center. An adapter plate connects the punch to the shaft, eliminating stress concentrations in the polymer. The shaft connects to the load cell via a pin connection with a nut to ensure the shaft and load cell are flush.

2.3.5 Path Control of the Punch

The location of the die plate is fixed before processing, making it critical to control the path of the punch to ensure proper spacing between the punch and die plates. This is done by attaching a shaft guide mechanism to the frame, as shown in Fig. 6. A high-temperature, linear ball bearing attaches to the guide to minimize friction between the shaft and guide. The steel plate connected to the bearing helps provide stability to the frame.
3. Materials

Honeywell’s SpectraShield II SR-3136 is selected as the UHMWPE material for this work. The material is commercially available in rolls that are cut into flat sheets for the preforming experiments. Each sheet of SR-3136 consists of four unidirectional plies (fibers embedded in a matrix), with a fiber architecture of [0/90/0/90], referred to as the 0/90 orientation, with the 0° orientation being where the fibers are aligned in the roll direction. The fiber volume fraction of each sheet is approximately 80%. There is a resin-rich side (which is referred to as the resin side) and a resin-starved side (which is referenced as the fiber side), as shown in Fig. 7. The UHMWPE material is cut into 114- by 305-mm sheets, which are used in the experiments. The width of the sheets is set to be equal to the diameter of the punch to ensure that no fiber is under both binders at any time (using the minimum $t_{\text{charge}}$, occurring when there is only one sheet of $\pm 45^\circ$ sheet of material).
4. Experimental Procedure and Data Collection

Once the preformer is located in the Instron, the punch descends at a constant velocity and deforms the material until it reaches the end of its stroke length. The Instron testing machine records the punch load and displacement. A grid drawn on the sheets with a marker, shown in the Fig. 8, is used to measure in-plane shearing. The shear strains are measured using the angle between the intersecting lines using the image analysis software ImageJ. Measurements of shear angle were taken on both as-processed curved parts and parts manually flattened after processing. Analyzing in-plane shear strains from photographs of as-processed curved parts introduces the risk that the visual perspective could influence the measured shear deformation, where flattening the sheets brings the risk of inducing additional shear deformation. To evaluate the methods, images are taken from the same sheet, one directly after being removed from the apparatus (curved sheet) and one after being flattened. The flattened images were found to have more consistent shear angle values (when comparing the values at the four corners of an element in the grid pattern). Thus, it was determined that the perspective taken on the curved surface was introducing error. Consequently, all results presented in the remainder of this report are from flattened sheets.
5. Numerical Model

An explicit dynamics solid mechanics model is developed in LS-DYNA to describe the UHMWPE sheet deformation during the single curvature thermoforming process. The model consists of the punch, binder plates, die plates, and guide parts (boundary constraint, described later), as shown in Fig. 9.

![Initial model setup with exploded view of model, showing the location of all parts](image)

5.1 Material, Element, and Mesh Description

The LS-DYNA model uses the built-in thermoplastic pre-impregnated composite (MAT249) material definition to model the UHMWPE composite. MAT249 is a hyperelastic material model that allows for input of fiber directions within the UHMWPE sheet as well as a tabular input to describe the relationship between shear stress and strain.\textsuperscript{11,12} The direction of the fibers within all the elements composing the sheets is updated and tracked at each time step. The UHMWPE sheets and tooling are modeled with fully integrated shell elements (LS-DYNA, Type 16) as they were the most stable of the element options explored. All tooling was modeled with the rigid material definition.

The model is found to be insensitive to the frictional properties at the punch–UHMWPE interface, thus the coefficient of friction at this interface is assumed to be 0 for this work. The friction at other interfaces are characterized and discussed later. The UHMWPE sheets have identical $E_x$ and $E_y$ moduli of 45.6 GPa for the SR-3136 material.\textsuperscript{13} The in-plane shear response of this material, a subject of a future work, is shown in Fig. 10 and is assumed to follow the same general shape as a similar UHMWPE fiber-based system characterized in the literature, such as HB80.\textsuperscript{9}
5.2 Boundary Conditions

The punch has a fixed velocity boundary condition, the value of which will not influence the numerical predictions because it is a quasi-static simulation. The binder plates have an applied vertical (z-direction) load corresponding to the binder pressure and are fixed in the x- and y-directions. The die plates are also constrained in the x- and y-directions. The UHMWPE sheet is initially in contact with the die plates, guide parts, and binder plates, and has no applied boundary conditions. The guide parts (boundary constraints) are shell elements with fixed locations that are free to occupy the same spatial area as the elements on the bottom of the binder surface. The guide parts have both a static and dynamic friction coefficient of 0 to ensure they do not contribute any resistance to the material motion. The guide parts are a necessary boundary constraint for model stability as they prevent the binder plate elements from artificially oscillating as the elements representing the UHMWPE sheet travel around the tight corners of the die plates. An example case is simulated for a single sheet of UHMWPE, with a friction coefficient of 0.90 on the bottom of the sheet and 0.30 on the top of the sheet, to verify the guide parts are being implemented correctly. The predicted punch force versus displacement curve, shown in Fig. 11, does not change when the top guide parts are moved from coincident with the binder to outside of the binder area (over the green and yellow guide parts in Fig. 9). This confirms that the guide parts do not influence the model predictions, thus their inclusion in the model is acceptable.
6. Results and Discussion

6.1 Influence of Sheet Orientation and Repeatability of Tests

Figure 12 shows test results for the evolution of punch load as a function of displacement for both the resin-rich and resin-starved sides of SR-3136 sheets with a binder pressure of 2.35 kPa. The curves for each condition show the repeatability of the results for a small sample size. The curves for the fiber side down sheets have less volatility, likely due to the stick-slip phenomenon exhibited by the resin side down sheets. The resin side has a higher friction coefficient than the fiber side, leading to much larger peak punch loads for the resin side down sheets.
6.2 Determination of Frictional Properties

The LS-DYNA model of the preforming process is used to back calculate a suitable set of friction coefficients between the tooling (binder and die plate, which are both the same material) and resin side as well as the tooling and fiber side. A parametric study is conducted with the model to determine a set of friction coefficients that provide close agreement between the experimental and numerical (model) punch load versus displacement responses. The UHMWPE material is stacked with a 0/90 layup to ensure no shear deformation during the experiment. The 0/90 fiber orientation does not shear during single curvature preforming because all the fibers are aligned either parallel or perpendicular to the in-plane force. Numerical peak punch loads are taken from the simulated response of the process. Numerical oscillations similar to those observed in Fig. 11 are ignored and the peak load here is determined from a smooth curve representation of the model predictions, using the smoothing function in MATLAB.

A summary of the relationship between the numerical peak punch load and the friction coefficients is shown in Table 1 for a binder pressure of 2.35 kPa. The predicted peak punch load is found to be more sensitive to changes in friction coefficient on the side facing down since there is more contact area with the tooling. Friction coefficients of 0.60 (between the tooling and resin side interfaces) and 0.35 (between the tooling and fiber side interfaces) are found to provide the closest agreement between model predictions and the experimental response. The numerical and experimental punch load versus displacement curves for both the resin and fiber side down (against the die plate) cases are shown in Fig. 13.

Table 1  Effect of friction coefficients (resin and fiber side) on peak punch load for a binder pressure of 2.35 kPa

<table>
<thead>
<tr>
<th>Sheet orientation</th>
<th>Model resin/fiber side friction coefficient</th>
<th>Experiment value of peak punch load</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.90/0.30</td>
<td>0.70/0.30</td>
</tr>
<tr>
<td>Resin down</td>
<td>125</td>
<td>95</td>
</tr>
<tr>
<td>Fiber down</td>
<td>51</td>
<td>33</td>
</tr>
</tbody>
</table>
Fig. 13 Comparison of numerical and experimental results for both fiber and resin sides facing down for friction coefficients of 0.60 (resin side) and 0.35 (fiber side)

The friction coefficients are within the experimentally characterized range for fiber-based UHMWPE systems.\textsuperscript{14} This method of back calculation is useful in determining the friction coefficient for high-temperature and pressure processing conditions because it eliminates stick-slip issues often encountered with experimental setups at high temperatures, such as the test setup utilized by Boyd.\textsuperscript{14} Furthermore, this numerical study illustrates the significant influence that friction coefficients have on the punch load versus punch displacement response and, therefore, on the in-plane loading on the sheets during the preforming process.

### 6.3 Mesh Refinement Study

A mesh refinement study, with results shown in Fig. 14, is conducted using the friction coefficients characterized in the previous section to confirm the solution is mesh independent. The numerical oscillations are due to the elements in the UHMWPE sheets sliding around the small radius of curvature in the die plate, evidenced by the increased oscillation height and decreased frequency as the elements dimensions become larger. The computational efficiency of the 3.0-mm element model was found to be about 8 times faster than the 1.5-mm element model. Therefore models with 3.0-mm-square UHMWPE elements are used in the remainder of this work.
6.4 Binder Pressure

The sheets are loaded in-plane through friction at the tooling–sheet interfaces, which is induced by a pressure being applied to the binder. The binder pressure has a significant influence on the friction force resisting sheet sliding. This is clearly illustrated by the experimental results for punch load versus punch displacement of a 0/90 layup as a function of binder pressure, as shown in Fig. 15.

The punch load is translated into in-plane load within the sheets through friction. It is assumed that the punch load is equal to the in-plane load on the material. Normalizing the in-plane load by the cross-sectional area of the sheet yields the in-
plane stress on the material, which correlates to amount of shear deformation in the material during preforming.

Model predicted in-plane stresses are compared to experimental results over a range of binder pressures (2.35 to 11.91 kPa) in Fig. 16. The model uses the friction coefficients found in the parametric study mentioned previously. Good agreement between numerical predictions and experimental results provides additional confidence that the back-calculated friction coefficients determined previously are reasonably accurate. More importantly, this shows that the parametric characterization process of frictional properties is reliable within the range of binder pressures considered in this study. Figure 16 shows how binder pressure can significantly influence the in-plane stresses (in-plane force normalized by sheet cross-sectional area) within the UHMPWE sheets.

![Fig. 16 Experiment and numerical peak punch forces for select binder pressures](image)

The dependence of in-plane stress in the sheets on interfacial friction further demonstrates the importance of accurately characterizing friction at all relevant interfaces. In the more complex compound curvature forming problem, binder pressure becomes more important because it ultimately is responsible for the material being forced to shear instead of wrinkle. The remainder of studies presented in this work use a binder pressure of 6.81 kPa, which is near the center of the range studied and close to the 6.5 kPa used in the literature for single-sheet, wrinkle-free thermoforming.3
6.5 Fiber Orientation

It was determined experimentally that fiber orientation within the sheet does not influence the punch load versus displacement curve at room temperature. This indicates that the frictional forces acting on the sheet and the force required to bend the sheet are not significantly influenced by fiber orientation. This behavior is also replicated in the numerical model, as depicted in Fig. 17 with a comparison of the experimental and model results. The 0/90 sheet slipped out from the binder in the experiment shortly before 125 mm of punch displacement. The ±45 sheet did not slip out as early due to the sheet extending in length as it sheared, indicating that, even at room temperature, the material will experience some degree of shear deformation (at higher temperatures, the shear stiffness has been shown to decrease). The average shear angle for the ±45 sheet is only 2.4°, which was determined using the final length and width of the deformed sheet. The shear deformation of the sheet can be increased by adding binder pressure, flipping the sheet such that the resin side is down, or elevating the temperature in the oven.

![Fig. 17 Effect of fiber orientation on punch load, with similar peak loads but more extension in the ±45 ply](image)

6.6 Punch Displacement Rate

Preforming is commonly conducted at quasi-static punch displacement rates. A study is performed to examine if the frictional properties are rate sensitive at realistic punch displacement rates for a 0/90 sheet and the results summarized in Fig. 18. Over the range of 1 to 10 mm/s, the effect of punch displacement rate is insignificant. As seen before, fiber orientation does not influence the punch force at room temperature, thus performing this test with a ±45 sheet would be academic.
The rate dependence of the material will be examined at elevated temperatures in a future work.

Fig. 18 Correlation between displacement rate and punch load, which has been shown to have no relationship for room-temperature, “quasi-static” experiments

6.7 Number of Sheets

Practical armor applications of preformed UHMWPE composites require the processing of laminates with multiple sheets. It is desirable to know how the force required to induce material deformation scales with the number of sheets. A preliminary experimental study is performed to examine the influence of the number of sheets on the punch load versus punch displacement response, as depicted in Fig. 19. The gap between the punch and die plate for all three configurations is set to 6.3 mm, much greater than the largest charge thickness. This eliminates the possibility of additional pressure being added to the charge as it moves between the die plate and punch (if the gap was equal to the charge thickness for one sheet, then the three-sheet configuration would be pinched as it moved between the die plate and punch).
6.8 Shear Stiffness and Fiber Angle Investigation

At room temperature, a negligible amount of shear strain is observed during preforming. Increasing the processing temperature is known to significantly decrease the shear stiffness of the UHMWPE material, thus increasing formability and shear deformation. It is observed experimentally that two sheets of UHMWPE preformed at 80 °C do not slide with respect to each other and have the same shear strain distribution. It is therefore only necessary to measure the deformation on the top sheet. The shear strain distribution for two sheets preformed with a ±45° orientation is shown (on the top sheet) pictorially in Fig. 20. The value shown in the center of each square is the average shear value of the square’s four vertices. There is less shear deformation in the areas under the binder plates, and more in the central region, shown in Fig. 21 (x and y location are normalized by the width and height of the sheet, respectively).
Trends in shear strain distribution as a function of shear stiffness are also explored using the numerical model. Predictions of shear deformation as a function of shear stiffness are useful because they can be used in conjunction with shear characterization tests over a range of temperatures to determine an optimal processing temperature without the investment required to do preform experiments at each temperature. Preforming simulations are run with a fixed binder pressure of 9.3 kPa and shear stiffness curves ranging from 0.1 to 1.0 times the baseline room-temperature in-plane shear stiffness, as shown in Fig. 22. The effect of shear modulus on the distribution of shear strain in the sheet is shown in Fig. 23. Parts of the sheet under the binder and contacting the die plate do not experience the entire in-plane deformation force because there is a gradient of frictional force acting on the material at these locations. When the material is no longer in contact with the
binder and die plate, there is a significant amount of shear deformation. These trends are consistent with observations made on elevated-temperature preforming experiments.

![Graph showing evolution of in-plane shear strain vs. punch displacement for room-temperature and scaled shear stress–strain curves.](image)

**Fig. 22** Evolution of in-plane shear strain vs. punch displacement for room-temperature and scaled shear stress–strain curves

![Shear strain distribution at a 96-mm punch displacement for a) room-temperature in-plane shear stiffness and b) 1/10 room-temperature shear stiffness.](image)

**Fig. 23** Shear strain distribution at a 96-mm punch displacement for a) room-temperature in-plane shear stiffness and b) 1/10 room-temperature shear stiffness

The single curvature preforming model is next used to explore the influence of shear stiffness on the punch load versus displacement response and the level of shear deformation that develops in the UHMWPE sheet during thermoforming. As expected, the model predicts no relationship between shear stiffness and peak punch load (the punch load is governed by friction between the UHMWPE sheet
and the tooling). Shear modulus is, however, found to have a significant influence on the level of shear deformation that develops in the UHMWPE sheet during preforming. This is shown for selected in-plane shear modulus scale factors in Fig. 22. For all cases, most of the shear deformation occurs during the first 30 mm of punch displacement and then begins to level off after 80 to 90 mm of displacement, implying that a deeper draw would not have a large influence on maximum shear deformation.

7. Conclusions

The coupling of shear deformation, wrinkling, and interfacial friction makes it difficult to understand the influence of processing parameters on specific deformation mechanisms in compound curvature parts. A single curvature preforming apparatus was developed to isolate and investigate the influence of processing parameters on UHMWPE loading and deformation. Experimental results from this apparatus were used to validate a single curvature preforming numerical model. The model and experiment were used to study the effect of process parameters on preforming. It was found that most of the force resisting punch motion was due to friction at the UHMWPE–tooling interfaces, which translates the punch force into in-plane loading of the UHMWPE sheets. The die plate–sheet frictional properties were shown to be much more important to accurately characterize than those at the binder–sheet interface due to the increased contact area and normal force. The binder pressure was shown to have a significant influence on in-plane sheet loading. The in-plane shear strains that develop during preforming were also shown to be significantly higher for a material with a low shear stiffness response (found at elevated temperature) versus a high shear stiffness response (room-temperature behavior). Material deformation during forming was influenced by sheet orientation, binder pressure, frictional properties, and temperature.

The single curvature preforming apparatus and modeling capability developed in this work provide valuable insight into the various deformation mechanisms associated with the preforming of UHMWPE composites. The findings in this work are helpful in tuning process parameters to manipulate UHMWPE deformation during processing, ultimately facilitating the development of processing and design strategies that can be used in the manufacture of complex-shape UHMWPE parts with improved performance and reliability.
8. References


