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A thermoforming student project including experiments, simulations, and theory.

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A Thermoforming Student Design Project Including Experiments, Simulations and Theory

Abstract

The project described in this paper involved undergraduate mechanical engineering students. Thin-gauge thermoforming is a process used to manufacture plastic blisters, cups, containers and other products for retail. The paper presents the design, building and testing of a thermoforming apparatus together with Ansys Polyflow simulations of the draping process. Theoretical results are presented in comparison with experiments and simulations for the stretching aerial and linear draw ratios and thickness reduction of the formed product. Finally, the paper will include a description of the outcomes for the project, student involvement and response, and an assessment of student learning.

Introduction

Thermoforming is a manufacturing process in which a sheet of plastic or other thermoplastic material is heated to a pliable forming temperature, formed to a specific shape in a mold, and trimmed to create a finished product. It is a versatile process that can be used to create a wide range of products, including packaging, automotive parts, medical equipment, and consumer goods. The process can be performed using either vacuum forming or pressure forming techniques, and can be used with a variety of materials, including ABS, polystyrene, and PVC. Overall, thermoforming is a cost-effective and efficient method for producing large quantities of complex-shaped parts with consistent quality.

The purpose of this project is to introduce students to thermoforming and drape forming. Drape forming is a simplified version of vacuum forming where a sheet of plastic is heated to a sufficiently high temperature so that it can be formed around an object. The plastic sheet can be heated in an oven and stretched over the pattern using suction or vacuum. Thin-gauge thermoforming is used to manufacture parts such as containers, cups, lids and trays while thick-gauge thermoforming is used to make plastic pallets, vehicle door and dash panels, and utility vehicle beds. Figure 1 shows the principle of thermoforming as described by Groover [1] . The fundamentals of plastics thermoforming and tool design have been studied by Klein [2],[3].

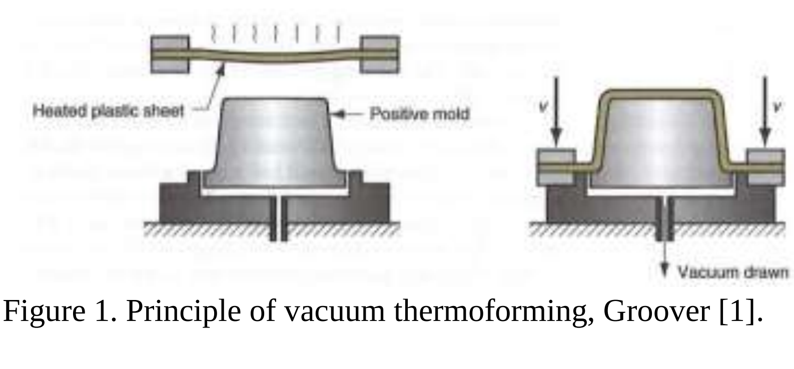

Figure 1. Principle of vacuum thermoforming, Groover [1].

Object Patterns

Three different object patterns or positive molds were used for thermoforming in this project: an instrument panel, a seat and a cowl for the Paolo Severin ¼ scale Piper J3 Cub [4]. Figure 2a) is showing the object pattern made of wood for the instrument panel. Holes with diameter 1/10" were drilled at the center of each instrument circle to enable suction and a better final shape of the thermoformed plastic. The maximum width of this object pattern is 6.5", maximum height 2.25" and maximum thickness 3/8". The center distance between holes is 1". Figure 2b) is showing the seat made of plywood with dimensions 6.5" x 4.5" at the base, a max height of 3" and four suction holes positioned 1.083" apart. Figure 2c) is showing the fiberglass cowl or nose cone that was used as the third object pattern. The hollow cowl has a length of 7", a maximum height at the base of 7.5" and a maximum width 6.12".

Figure 2a) Instrument panel pattern made of wood and shown as a SOLIDWORKS model

Figure 2b) Seat pattern made of plywood

Figure 2c) Cowl made of fiberglass and shown as a 3D scanned model

Heating Unit

The heating unit is made of plywood with ¾" thickness, see Figures 3a). An oven heating element is mounted at the bottom of the unit, see Figure 3b). The inner dimensions of the heating unit are 13.5" x 18.5". The heating element is mounted ¾ inch above the bottom of a thin steel sheet metal pan that is one inch high, see Figure 3c). The vertical walls of the heating unit are covered with aluminum foil that reflects the heat and increases the temperature of the plastic sheet that is mounted in an aluminum frame that sits on top of the heating unit. The distance from the heating element to the plastic sheet is 6.5" when the plastic is not heated. The sheet metal pan is mounted on four 1.5" x 3.5" wooden studs, see Figure 3c), that elevates the pan with the heating element from the base of the heating unit. The distance between the base and pan is 9.5" and the distance between the studs in Figure 3c) is 9.5". The distance between the studs and the outer wall in Figure 3a) is 1".

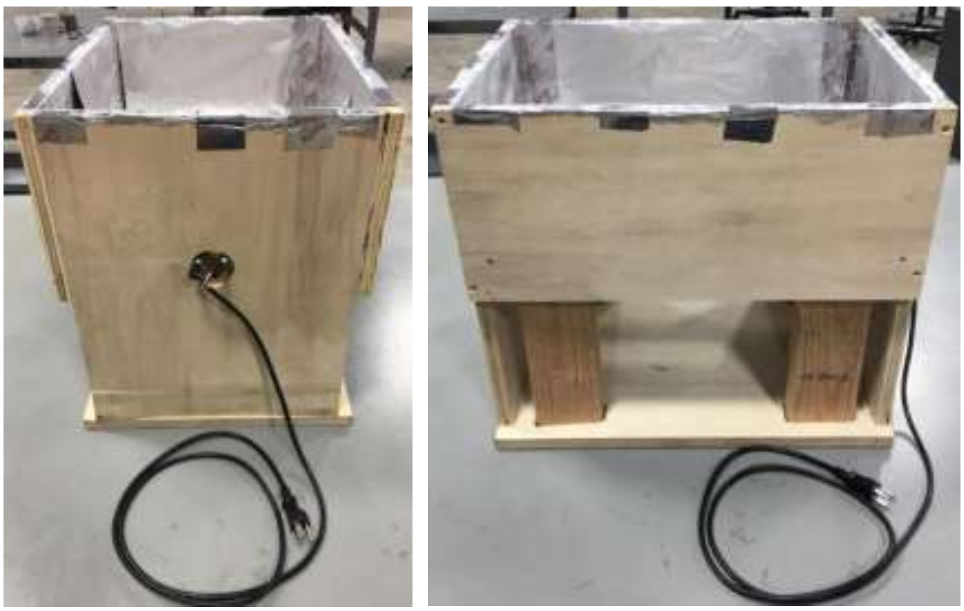

Figure 3a) Heating unit for thermoforming

Figure 3b) Heating element   Figure 3c) View from below of sheet metal pan

Aluminum Frame

The frame in Figures 4a) is made of 1/8” aluminum and used in this project to secure the edges of the plastic sheet during the thermoforming process. The frame top dimensions are 15” x 20” and the bottom dimensions are 15.5” x 20.5”. Figure 4a) shows the black rubber weather sealant that is used to fix the edges of the plastic sheet. The rubber is 1.25” wide and the depth of the aluminum frame around the bottom is 1”. The aluminum frame is shown mounted on top of the heating unit in Figure 4b).

Figure 4a) Open and locked aluminum frame for plastic sheet

Figure 4b) Aluminum frame mounted on top of heating unit

Suction Unit

The suction unit is a separate box with dimensions 15” x 20” x 3.48”. The 0.08” aluminum around the edges is 1.5” wide. A vacuum cleaner hose with 2.25” outer diameter is attached and centered to the bottom of the suction box and thereby suction of the thermoformed plastic is accomplished during the thermoforming process, see Figure 5a). Figure 5b) is showing a side view of the suction box that has a 1.9” inner gap between the bottom and top plates. The top plywood plate is perforated as shown in Figure 5c). The holes with diameter 0.205” are arranged in a square inline pattern with a center distance between holes of 0.7”. On top of the perforated plywood plate is a 0.05” thick steel screen mounted with a staggered holes arrangement. The diameter of the holes is 1/8” and the center distance between holes is 3/16” in one direction and 5/32” in the orthogonal direction.

Figure 5a) Suction box for thermoforming

Figure 5b) Side view of vacuum hose attachment to suction box

Figure 5c) Hole pattern in plywood

Thermoforming Procedure

The aluminum frame is mounted on the heating unit at the top of the unit as shown in Figure 4b). The temperature of the heating element is around 545 ºF. A Fluke 62 MAX+ Mini InfraRed IR thermometer is used to measure the temperature of the sheet at the center and the temperature is recorded over time until the temperature of the plastic sheet has stabilized at around 300 ºF. A lid on top of the plastic sheet is used to even out the temperature over the heated sheet and to increase the maximum temperature of the sheet.

When the 0.03” PolyStyrene PS plastic sheet has reached a final temperature of minimum 300 ºF at the center of the sheet, the vacuum is switched on. The lid is removed from the plastic sheet and the aluminum frame is lifted off from the heating unit and the plastic sheet is draped over the positive mold that is centered on the suction box, Figure 6a), so that the sheet forms around the object. This is a very fast process and the movement and alignment of the aluminum frame on the suction unit will need to be practiced before starting the heating process of the plastic sheet.

Figure 6a) Heating unit with aluminum frame and suction box with mold pattern side by side.

The draping process is shown in detail in Figure 6b). It is observed that wrinkles developed on the plastic sheet towards the base of the formed part. This problem was solved by mounting the pattern object on a 1” thick base made of plywood.

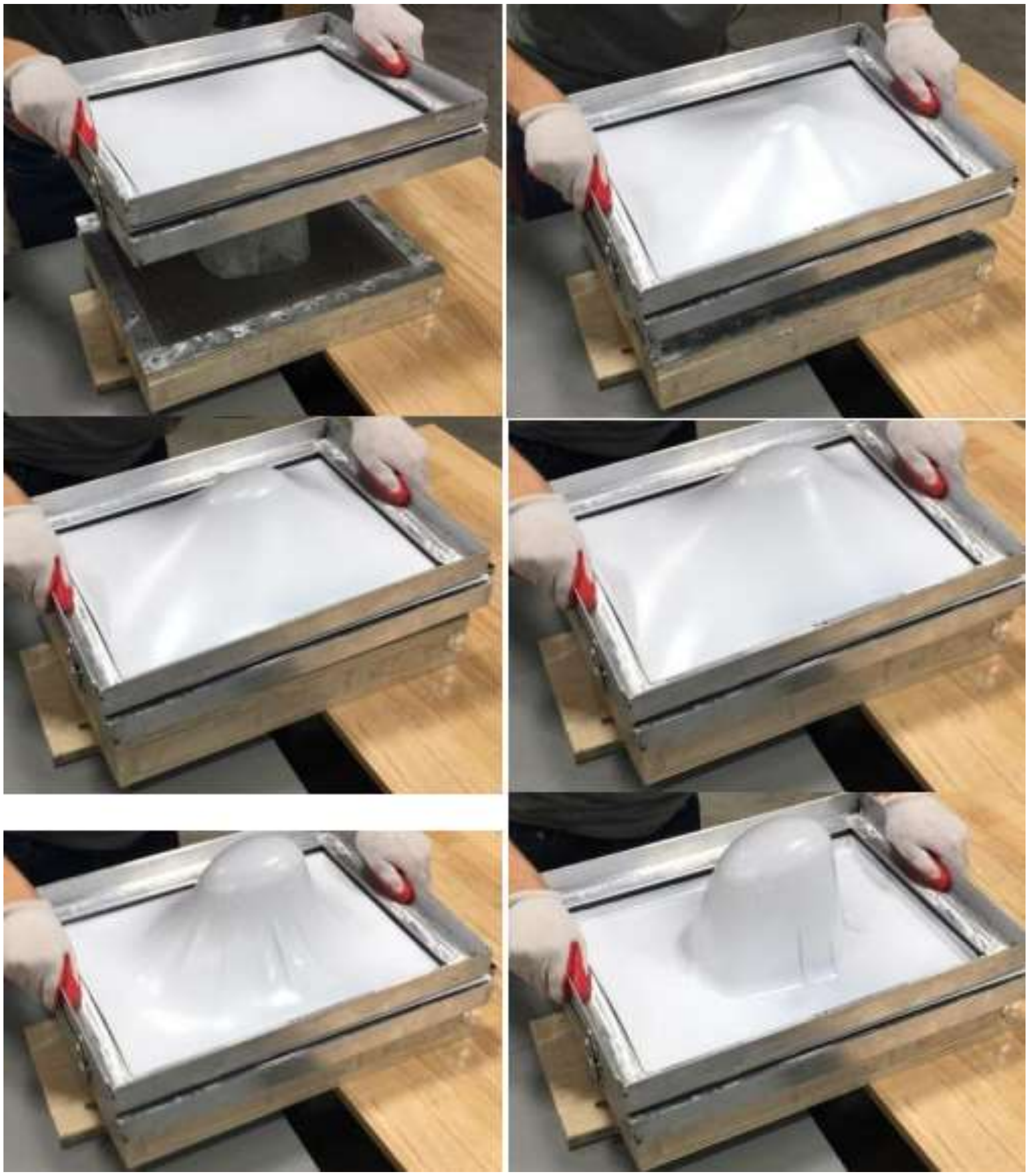
Figure 6b) Sequence of pictures showing the thermoforming process of the cowl.

Theory

The Aerial Draw Ratio *ADR* is the overall stretching of the plastic sheet. The value $ADR > 1$ is determined from the surface Area of the Formed Part *AFP* divided by the Sheet Surface Area *SSA*

$$ADR = AFP / SSA \quad (1)$$

The maximum values of ADR for different plastics are shown in Table 1. We see from this table that the plastic Polystyrene PS that is used in this project has the highest max *ADR* of all plastics listed.

Plastic	Maximum *ADR*
ABS	5.5
Acrylic	3.4
HDPE	6.5
LDPE	6.0
PP	7.5
Polystyrene PS	8.0
PVC	4.3

Table 1 Maximum Aerial Draw Ratio for different plastics

The Average Thickness Reduction *ATR* is defined as

$$ATR = 1 / ADR \quad (2)$$

Another draw ratio that we can use is the Linear Draw Ratio *LDR*. This ratio compares the length of a straight line on the sheet before and after forming including only the forming area.

$$LDR = LFP / LBF \quad (3)$$

where *LFP* is the line Length on Formed Part and *LBF* is the line Length Before Forming. Values for *AFP*, *ADR*, *ATR*, *LBF*, *LFP*, and *LDR* for the different formed parts can be determined experimentally based on their definitions and compared with results from Ansys Polyflow simulations.

Ansys Polyflow Simulations

Ansys Polyflow is a computational fluid dynamics (CFD) software for simulating the flow of fluids and gases in complex systems. It can be used for a wide range of applications, including product design and optimization, flow analysis, and process simulation. With its advanced numerical methods and user-friendly interface, Ansys Polyflow is designed to help engineers and scientists make better design decisions and reduce the time and cost of product development.

Ansys simulations of the thermoforming process has been studied by Modlawski and Jaruga [5] and Sarakhun, Tamna and Thammakornbunjut [6]. The students used several tutorials and the professor’s instruction to help them simulate the draping process of a plastic sheet over a positive mold. The CAD geometries were 3D scanned using the EinScan SP laser scanner with a turntable and modeled in SOLIDWORKS. After launching Ansys Workbench and selecting Polyflow, the geometries were imported to Ansys Designmodeler, A mid-surface was created for each geometry and the mesh was created in Ansys Meshing.

Next, Ansys Polydata was launched and the domain of the mold was defined followed by the generation of contact conditions for the same mold. A translational velocity was imposed for the mold as transient motion in the form of a ramp function. Thereafter, a subtask was created for the thin plastic film and its domain was defined. Inflation pressure was imposed in the form a second ramp function. A contact wall was defined with associated slipping coefficient, penalty coefficient and penetration accuracy. Material data for the thin plastic film was also defined and included inertia, density and viscosity. Numerical parameters including transient iterative parameters were also defined.

Post processing was completed using CFD-Post and contours of the thickness of the half model was visualized. The half-model was mirrored to create the full model plastic sheet and the time step selector was used in CFD-Post to create contours at different times. An animation of the draping process was generated followed by refining of the mesh. Adaptive meshing was used for mesh refinement with updated values. The refined thickness contours were generated and animated. A clip plane was constructed and inserted followed by the generation of a point cloud. The point cloud was exported and the wall thickness variation in a symmetry plane was graphed in Excel.

Results from a study of the draping process of a 0.1 mm plastic sheet on a positive nose cone mold is shown in Figure 7a) for the subdomain and boundaries used in Ansys Polyflow. The adiabatic mold moved upward towards the plastic sheet that is fixed at Boundaries 1 – 3 while Boundary 4 is a symmetry boundary. Pressure was applied to drape the sheet around the mold. Only half the mold and sheet are modeled as a symmetry boundary condition was used to save computational time for simulations.

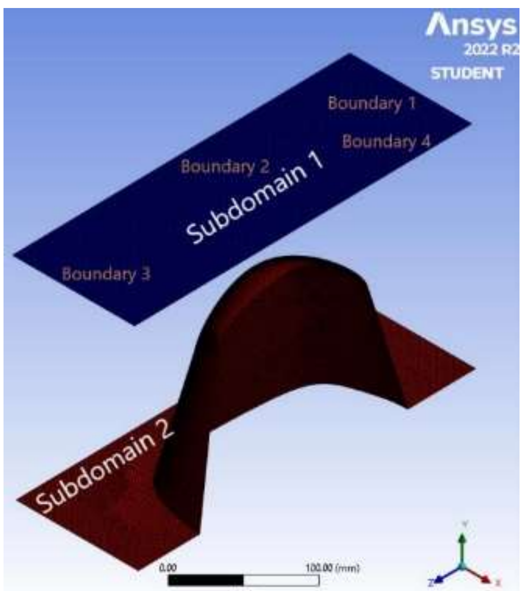

Figure 7a) Subdomains and boundaries for Ansys Polyflow

Figure 7b) is showing the time sequence for the draping process of the plastic sheet around the nose cone cowling. These results from Ansys Polyflow are very similar in appearance to the sequence of pictures of the thermoforming process as shown experimentally in Figure 6b). We observe that the draping process is almost completed after 0.13 s and that the change in thickness up to 0.6 s is minor and mostly occurs around the base of the cowl. In Figure 7c) is the draping process for the creation of the instrument panel shown. The thickness of the plastic sheet on top of the instrument panel does not change from the thickness of the original undeformed sheet. The circles on the instrument panel are clearly developing over time and at 1 s the circles are fully developed.

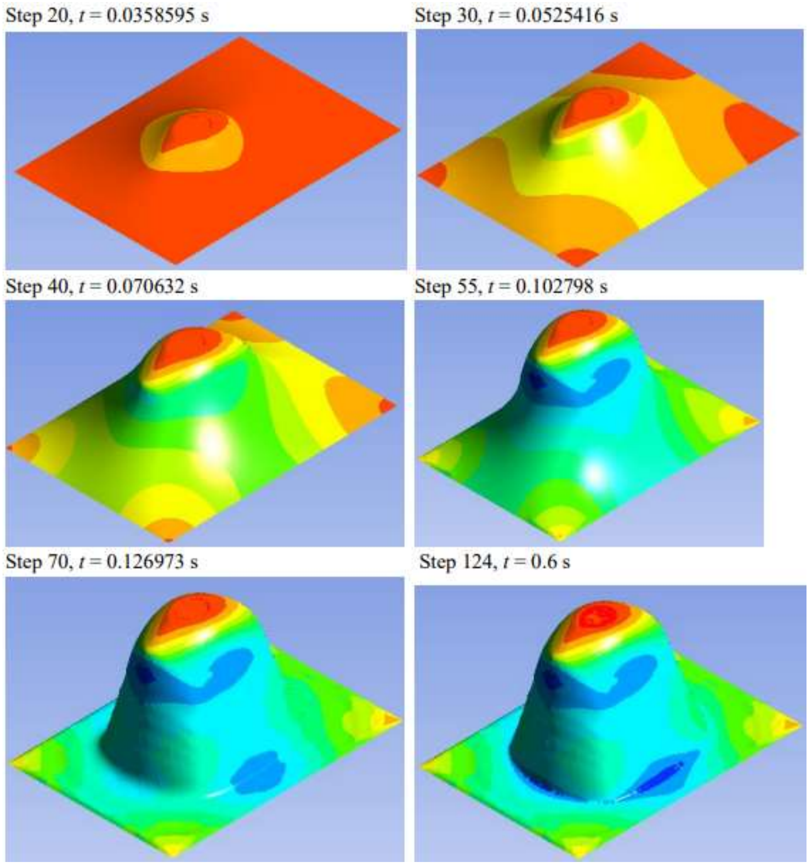

Figure 7b) Thickness contour plots during draping process for the cowl.

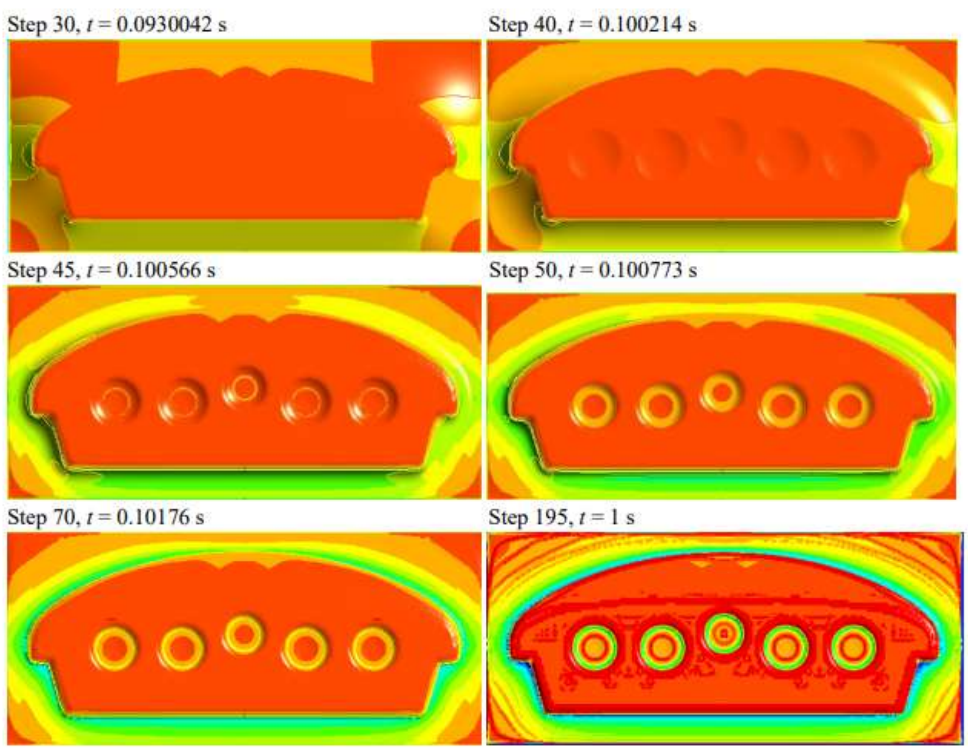

Figure 7c) Thickness contour plots during draping process for instrument panel.

The thickness distribution of a thermoformed plastic part has been studied by Li [7]. Figure 7d) is showing the instrument panel dimension profile from the point cloud in CFD-Post and Excel together with the formed plastic thickness variation in a symmetry plane. The thickness is smallest in regions with large stretching of the plastic.

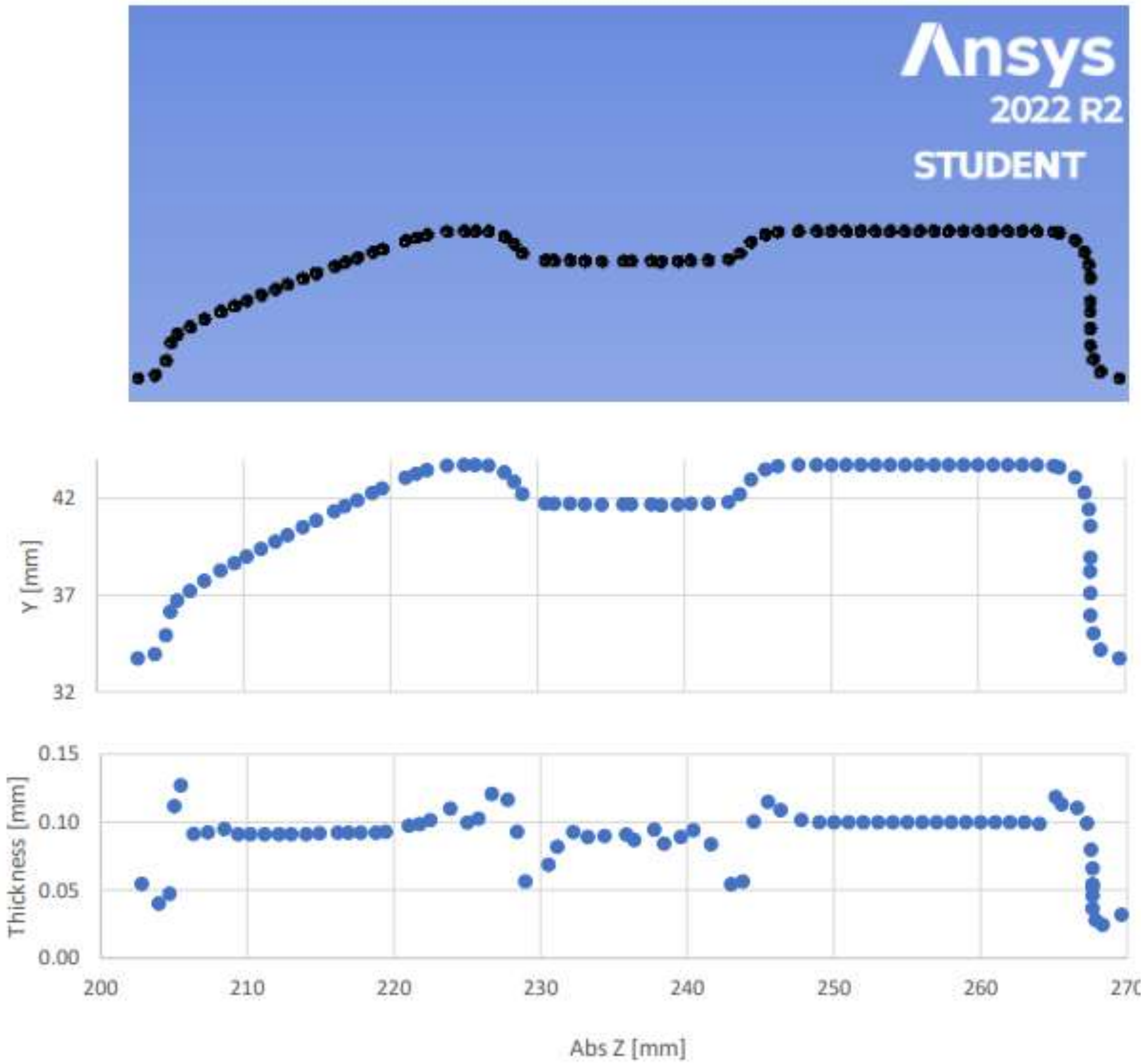

Figure 7d) Instrument panel dimension profile & wall thickness variation in symmetry plane.

Student Involvement

Students helping with the project learned valuable skills relating to experimentation and the development labs. The student had the opportunity to compare theory and experimental measurements, which allowed them to reinforce what they learned in lecture. The students were able to apply skills they had learned in courses such as Fluid Mechanics and Experimental

Methods, and they learned new skills that will help them in future courses and with their senior design project.

The students took one of the thermoformed instrument panels and devised a way to measure the thickness of the cross-section so that they could compare it to simulated values. They took measurements and entered the data into Excel to generate a plot similar to that shown in figure 7d. By finding a method to create a plot of experimental values of thickness compared to theoretical values, the student learned how to verify simulated data experimentally. The students also considered how the simulated and experimental values could be improved, and they brainstormed methods to improve experimental measurements by seeing a demo for the Magna-Mike 8600 thickness gage that uses a magnetic probe to make accurate thickness measurements on nonferrous materials such as plastics. They had the opportunity to hear from a technician and ask questions concerning the Magna-Mike 8600, and were able to use the device to measure the thickness of the instrument panel and other thermoformed parts. The students were able to present their feedback on the benefits of using this device over traditional methods of measuring thickness, and had the chance to use a highly accurate instrument.

The students gained experience by running Ansys Polyflow simulation with known values for the density and initial thickness of the polystyrene sheet used to create the nose cone. They were able to complete Ansys simulations with known initial thickness of the polystyrene sheets, and furthermore they considered how future improvements could be made in the simulations by running a non-isothermal simulation to account for heating and cooling during the thermoforming process. The students used their experience running these Ansys simulations to gather feedback on the Dell Precision 7865 Tower Workstation powered by AMD Ryzen Threadripper PRO processors. The students found the unit to operate faster and more reliably than other units, and they were able to pass feedback along to the IT department as part of the Dell Product Seed Program.

The students also researched costs for the plastic sheets used in the thermoforming process. They created an Excel file comparing different brands from different websites and calculated values for how much each sheet would cost if a larger sheet was cut down to the size needed for the thermoforming machine. Through this process, the students developed skills relating to economics and selected a variety of sheets for thermoforming while also staying under budget. Making choices based on cost is part of the reality of being an engineer, and by comparing different manufacturers and sources for the plastic sheets the student were able to gain experience.

Student Assessment

The students were involved in using the concepts of engineering analysis to construct the experimental aspects of the project. The concept of this project started as a project for an honors student in the engineering program and later became a senior design and research project. For the final class grade in the senior design course, the students submitted weekly written reports worth 10% of the grade and a project progress report worth 20% of the grade. The students presented their project with an oral project defense at 15% of the grade with an off-campus presentation at an engineering conference or professional society meeting at 5%. The students will also submit the final written project report at the completion of the course for 15% of the grade.

In Table 2, one can see the objectives for developing sound reason and explanation for the students to learn. As shown in the table, the main focus is to achieve intellectual pursuit, global engagement and a bold vision. By developing these skills, the students can be equipped with the right tools needed to be successful for creating ideas and enhancing what they already know.

OUTCOMES	Significant	Moderate	Minimal
Intellectual Pursuit			
EGR 499: Demonstrate, in a controlled environment, the knowledge and skills developed during the previous years of engineering study.	X		
EGR 499: Become an authority on a small phase of a project.	X		
EGR 499: Learn the fundamental skills, techniques, and procedures for conducting engineering projects.	X		
EGR 499: Successfully complete the design project, which is culminated in a final written and oral report.	X		
EGR 499: Design a system to meet realistic design constraints and goals, referencing applicable engineering standards.	X		
An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.	X		
ABET: An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.	X		
ABET: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.	X		
ABET: An ability to acquire and apply new knowledge as needed, using appropriate learning strategies.			X
Global Engagement			
ABET: An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.		X	
ABET: An ability to communicate effectively with a range of audiences.		X	
Bold Vision			
ABET: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.		X	
ABET: An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.		X	
ABET: An ability to acquire and apply new knowledge as needed, using appropriate learning strategies.			X

Table 2. Objectives for student learning from course syllabus

Conclusion

This paper has shown a project where the students designed, built and tested a thermoforming apparatus and compared experiments with Ansys Polyflow simulations of the draping process. The project offered an opportunity for students to experience classroom learning together with real-world applications of the thermoforming process.

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Appendix

The total cost of the project excluding shipping is $340. A breakdown of costs may be seen in the following table:

Vendor	**Item Description**	**Item# or Model#**	**Price**
amazon.com	Reynolds Wrap Heavy Duty Aluminum Foil,50 Sq.Ft	N/A	$4.48
homedepot.com	FlexFix Nashua Tape 1.89" x 30 yd.	1529786	$6.38
homedepot.com	Furno 300 Heating Gun	0503059	$27.00
homedepot.com	Plywood ¾" x 4ft x 8ft	106128	$46.37
homedepot.com	Prime Whitewood Stud	058449	$3.35
lowes.com	Fluke 62 MAX Mini Digital IR Thermometer	806179	$95.24
professionalplastics.com	Styrene White His Sheet, 0.030 Thick, 48" x 96"	SHISWH.030	$27.56
toni-clark-shop.com	Fiberglass Cowl	N/A	$56.00
toni-clark-shop.com	Instrument Panel	N/A	$13.00
toni-clark-shop.com	Seat	N/A	$21.00
walmart.com	GE Range Broil Element WB44x149	N/A	$39.99
		Total	$340.17