Viability of Thermoformed Closed-Cell Foam Cores for Carbon Fiber Sandwich Rocket Fins

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Carbon fiber-reinforced sandwich panels are used for high-strength and lightweight vehicle structures in the aerospace industry. In supersonic rocketry, the panels' core material defines the fin geometry, while offering minimal strength support and contributing a significant fraction of the mass. A lightweight core material, such as a thermoplastic foam, thereby allows for improved fin design flexibility with regards to mass constraints. Thermoforming is a common manufacturing process for thermoplastic foams that allows for precise and uniform results. This paper presents the testing and manufacturing procedures developed to determine the viability of a thermoformed closed-cell foam as a core material for sandwich panel sounding rocket fins. The experiments were conducted using ROHACELL®51 to determine an alternative to denser fin core materials for vehicles built by Georgia Tech Experimental Rocketry (GTXR), a project team of the Ramblin' Rocket Club (RRC) at the Georgia Institute of Technology. The resulting fins were tested for accuracy of shape and replicability through metrological analysis. The fabrication observations and analysis results are presented with particular attention to challenges associated with complex fin geometries and strict consistency requirements. This manufacturing method enables GTXR to pursue additional weight optimization strategies for a planned space-shot attempt.

I. Nomenclature

c_r	=	root chord, $[mm]$
c_t	=	tip chord, $[mm]$
S	=	span, $[mm]$
$\bar{\epsilon}$	=	average global geometric error (mean deviation), $[mm]$
$\bar{\sigma}_s$	=	average surface standard deviation, $[mm]$
$\bar{x}$	=	mean
σ	=	standard deviation
$t_{max,tip}$	=	max thickness at tip, $[mm]$
$t_{max,root}$	=	max root chord thickness, $[mm]$
α	=	coefficient of thermal expansion, $[m/m°C]$
ΔL	=	linear thermal expansion, $[mm]$
ΔT	=	difference between mold temperature and room temperature, $[°C]$

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II. Introduction

Carbon fiber is a widely used material for structures in high stress environments throughout the aerospace industry due to its high strength-to-weight ratio and fatigue resistance [1]. In applications that require complex geometries, carbon fiber sandwich panels are manufactured from pairs of light but stiff carbon sheets, known as plies, separated by low density cores, providing impressive structural load support with minimal increase in weight [2] [3] [4].

In sandwich panel configurations, the core material is generally not load-bearing, and therefore is a prime candidate for weight savings. Common core materials include: Nomex® honeycomb, low density metals and composites, and closed cell foams made from rigid polymers [5].

Sandwich structures are most commonly used for flat shapes, allowing a very high number of core materials to be used due to ease of manufacturing. For complex three-dimensional structures, such as double-wedge fins, the number of materials available shrinks. Most commercial core materials are sold as standardized sheets of various thickness, meaning complex core geometries must be machined to shape. Machining can then lead to increased production times and costs. Core materials such as G10, a high-pressure fiberglass laminate, prove to be difficult to machine into complex core shapes due to the thin material chipping and health concerns due to airborne fibers [6]. Closed cell thermoplastic foams provide a middle ground for stiffness-to-weight ratio, while allowing safer manufacturing and easier sandwich panel construction [7].

Georgia Tech Experimental Rocketry (GTXR), a project team of the Ramblin' Rocket Club at the Georgia Institute of Technology has experimented with numerous fin core materials, each with varying levels of success. These materials have presented challenges related to uniformity, manufacturing precision, and carbon fiber sandwich construction.

These manufacturing limitations motivated the club to explore a core material that can be formed into complex geometries without extensive machining while maintaining tight dimensional tolerances. Additionally, the material must have low density and produce a structurally viable fin. Thermoforming low density thermoplastic materials provides this option. Unlike subtractive manufacturing processes, thermoforming reshapes materials like thermoplastic foams by heating above their forming temperature and compressing using a mold.

For aerospace applications, thermoformed polymethacrylimide (PMI) closed-cell foams are good candidates for sandwich panel structures [8]. ROHACELL®51 was chosen as the fin core material due to its low cost and compatibility with thermoforming and composite manufacturing processes; however, the feasibility of utilizing an industry-grade thermoforming process to produce fin cores for amateur collegiate rocketry applications has not been well-established, particularly for complex geometries with strict dimensional requirements.

This paper addresses this gap by presenting an adaptation of an industry-grade thermoforming manufacturing process to the collegiate level, developed by student members of GTXR. To assess the viability of this approach, thermoforming experiments were conducted, testing precision and effectiveness. A comprehensive comparison between the modeled fin core geometry and the experimental results is conducted, along with an evaluation of the challenges associated with the manufacturing method. Potential future improvements and design iterations are also discussed to enhance the reliability and repeatability of the process.

This paper aims to test the reliability, repeatability, and effectiveness of the thermoforming method for fin core creation in collegiate rocketry.

III. Experimental Methods

A. Test Article

The test articles in this experiment consist 0.375 inch thick sheets of ROHACELL®51, a rigid PMI closed-cell foam. This material was selected for its ability to maintain structure and surface finish during high temperature thermoforming processes.

One of the biggest advantages of using ROHACELL®51 foam is its compatibility with most commercially available adhesive systems. Due to its closed-cell structure, resin only fills into the cut cells at the surface of the foam, ensuring quality bonding while avoiding unnecessary weight that excess resin can add [9].

The nominal mechanical and thermal properties for ROHACELL®51 are summarized in Table 1, with data provided by MatWeb and Emkay Plastics [10] [11].

Table 1 ROHACELL®51 Material Properties

Property	Value	Units
Density	0.0521	g/cc
Tensile Strength at Break	1.90	MPa
Elongation at Break	4.0	%
Modulus of Elasticity	0.0700	GPa
Compressive Strength	0.900	MPa
Shear Modulus	0.0190	GPa
Shear Strength	0.800	MPa
Thermoforming Temperature	195	°C

A total of five test articles were created using a two-dimensional printed template that was generated from the projected double-wedge fin geometry. This stencil was used to outline the required perimeter onto the ROHACELL®51 foam surface, ensuring consistent initial dimensions across samples.

The blanks were partitioned from the ROHACELL®51 foam stock using a combination of cutting tools. Initial rough cuts were made with standard industrial box cutters and X-Acto blades. Final sizing and edge refinement was done with a Proxxon MICRO-Sonic Cutter.

B. Mold Fabrication and Preparation

To thermoform the complex double-wedge fin geometry, a custom mold is required. Because the thermoforming process requires the ROHACELL®51 foam to be heated to approximately $195°C$ ($383°F$), the mold material must possess high thermal conductivity and withstand elevated temperatures, in addition to being easily machinable. Aluminum was selected for the mold material as it properly met all of these conditions. The top and bottom halves of the mold were machined from aluminum stock using a CNC Haas Mill to create the precise negative of the double-wedge feature. These halves were aligned at each of the four corners using aluminum dowels. The computer-aided design (CAD) of the mold and the final assembly are shown in Fig. 1.

C. Thermoforming Procedure

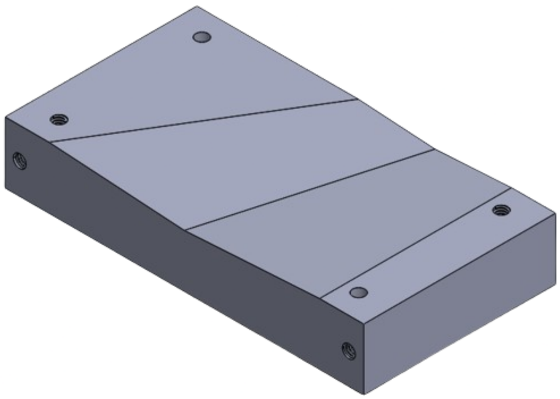
The thermoforming process was initiated by preheating the precut ROHACELL®51 foam blank and the aluminum mold components in the TPS Blue M Convection Oven. The foam blank was placed into the oven already centered on the bottom mold and the top mold was suspended above using two aluminum parallels, creating an open cavity that facilitated direct heat transfer to the exposed foam. The alignment dowels were pre-installed on both sides of the mold so that the top mold could be lowered onto the bottom mold once the target temperature was reached, sandwiching and compressing the foam blank. This pre-assembly configuration was implemented to minimize handling and assembly time while the components were at a high temperature.

To monitor the internal foam core temperature during the heating phase, a thermocouple was inserted into the thickest section of the foam (the root chord) to a depth of approximately 5 mm.

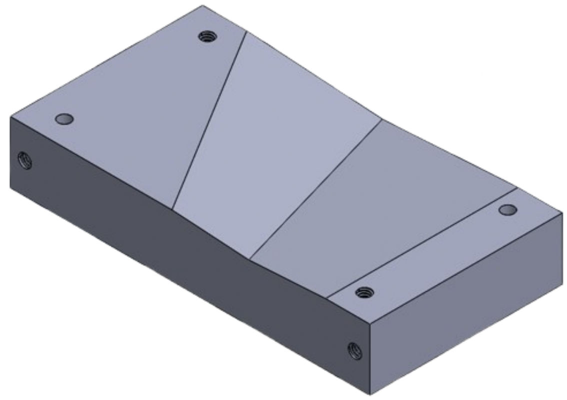
The thermal profile was governed by an oven ramp rate of 10°F per minute to a set point of 204°C (400°F). This ambient temperature, which exceeds the required 195°C (383°F) forming temperature, was necessary to drive adequate thermal energy into the highly insulative foam matrix. The assembly was heated until the internal thermocouple registered a target core temperature between 195°C and 197°C. Once reached, a thermal soak of 5 to 10 minutes was maintained to ensure complete internal thermal equilibrium.

Following the thermal soak, the oven was opened and the structural parallels were quickly removed. After verifying that the heated foam remained aligned with the mold geometry, the top mold was carefully lowered onto the blank to sandwich the foam and mitigate rapid convective heat loss.

The closed mold assembly was swiftly transferred from the oven to the hydraulic press as seen in Fig. 2. A compressive force of 4 metric tons was applied at the centroid of the mold assembly, rather than the geometric center. This off-center loading was necessary to account for the asymmetric material volume and varying thickness of the internal double-wedge geometry. By compressing at the centroid, the top mold maintained even, planar contact with the bottom mold during the compression of the ROHACELL®51 foam.



(a) Top mold CAD geometry



(b) Bottom mold CAD geometry

(c) CNC-machined aluminum mold assembly

Fig. 1 Double-wedge fin core tooling: (a, b) digital design of mold halves and (c) the final hardware used for thermoforming.

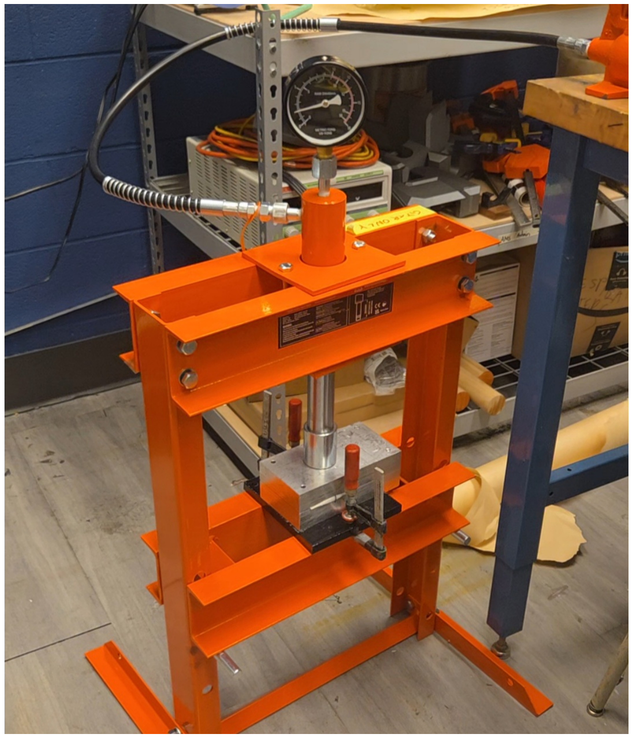


Fig. 2 Hydraulic press setup used to apply compressive force to the heated mold assembly.

The mold assembly was held under static pressure in the press until the internal temperature cooled to at least 80°C, sufficiently below the ROHACELL®51 foam's forming temperature threshold. After the sample was demolded, the excess flashed material extruded from the root and tip chords was retained on the formed fin, rather than being physically trimmed. This excess flash was instead removed digitally during the post-processing phase of the 3-D scanning mesh, which significantly reduced manual handling risks and localized physical measurement errors.

D. Three Dimensional Metrological Analysis

The EinScan-SP Platinum Desktop 3-D Scanner was used to create a 3-D mesh of each of the thermoformed fin cores. Before scanning the fin cores, a calibration test was conducted to ensure the accuracy of the tool. Each fin core was stabilized on the scanning platform by piercing a needle through the root chord and attaching it to a small cardboard stand. 360 degree scans of all 5 fin cores were conducted, making sure all surfaces were properly scanned and aligned. Once the scan was completed, the EinScan EXScan software was used to trim excess ROHACELL®51 foam on the root and tip chords that were apparent at manufacturing, the small amount of overflow foam on either end, as well as to remove any noise that was picked up in the scan. As an initial validation of the scan quality, the root chord was measured in the coordinate system of the software and compared to physical measurements of the fin core. After confirmation, reference points were chosen at the four corners of the thermoformed and CAD modeled fin cores and aligned to each other using the CloudCompare software. To account for human measurement error related to manual alignment, each alignment was conducted three times and the mean standard deviation was calculated.

IV. Results and Discussion

A. Results

The primary metric for evaluating the viability of the thermoforming process was the geometric accuracy of the final cores compared to the nominal CAD geometry. This was assessed through high resolution 3-D point cloud-to-mesh scanning and manual caliper measurements. The averaged results of the 3-D scanning analysis, which provides a global assessment of surface deviation, are summarized in Table 2.

Table 2 Averaged Surface Deviation and Geometric Accuracy Results From 3-D Scan (mm)

Fin ID	$\bar{\epsilon}$ (mm)	$\bar{\sigma}_s$ (mm)
Fin 1	0.16	0.13
Fin 2	0.38	0.24
Fin 3	0.29	0.15
Fin 4	0.31	0.14
Fin 5	0.28	0.17
Global Average	0.28	0.17

A selection of fin cores analyzed in the CloudCompare software are shown in Figures 3 through 7. These fin cores were chosen at random and visually illustrate the spatial distance deviations between the reference CAD geometry and the corresponding 3-D scanned fin cores.

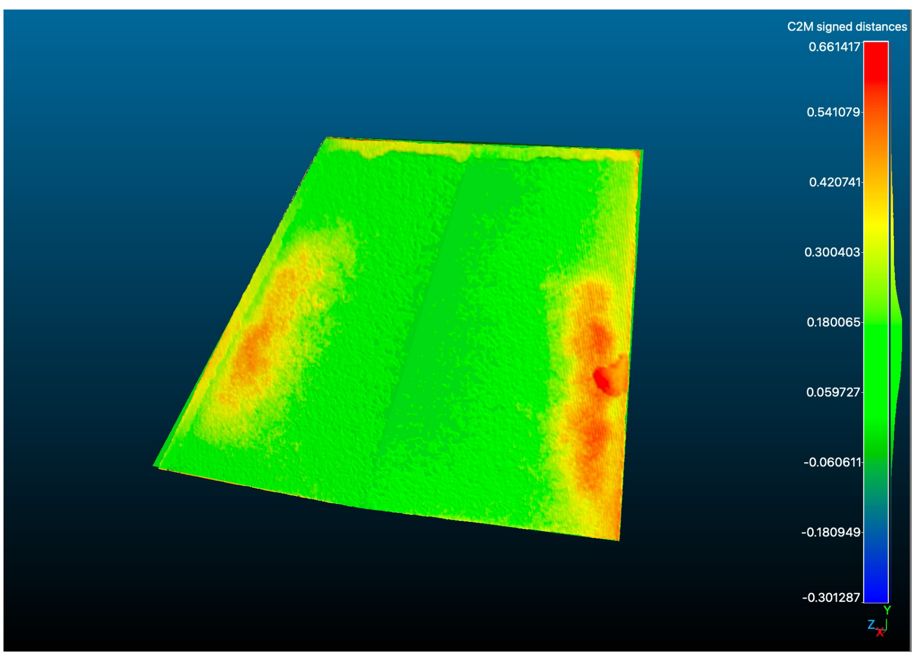


Fig. 3 Deviation Color Map of Fin 1 (Run 2/3)

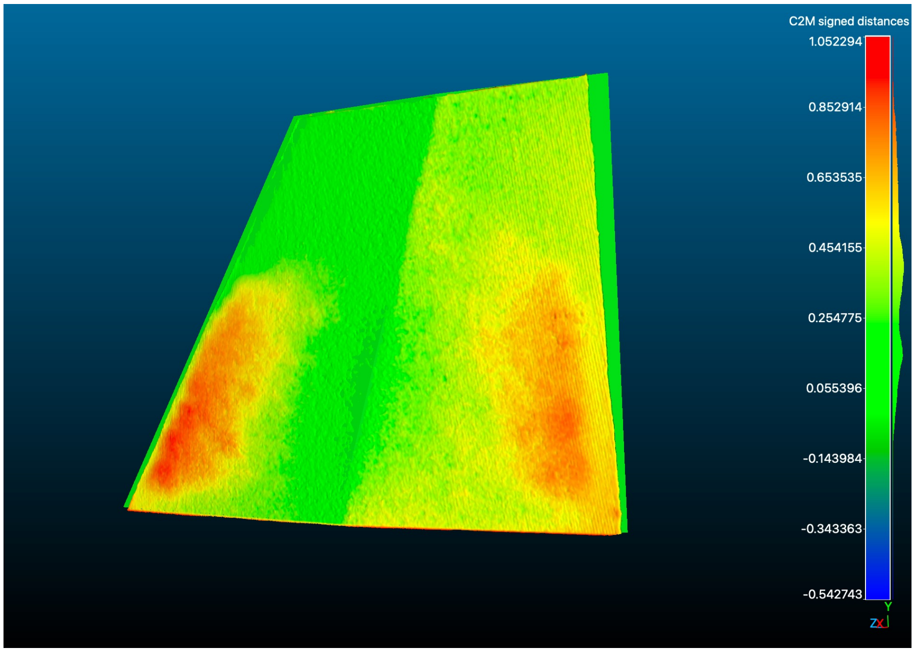


Fig. 4 Deviation Color Map of Fin 2 (Run 3/3)

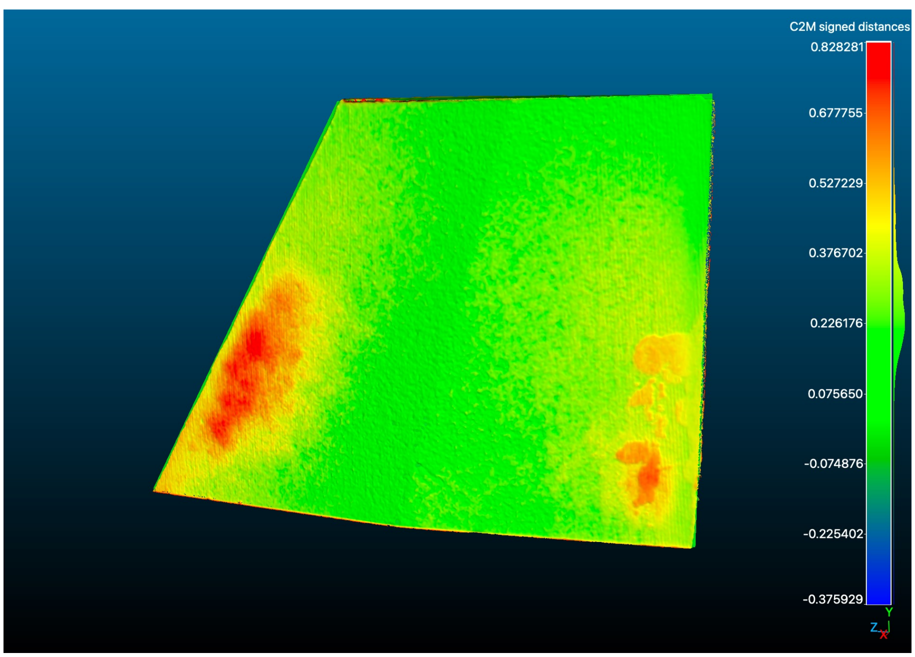


Fig. 5 Deviation Color Map of Fin 3 (Run 2/3)

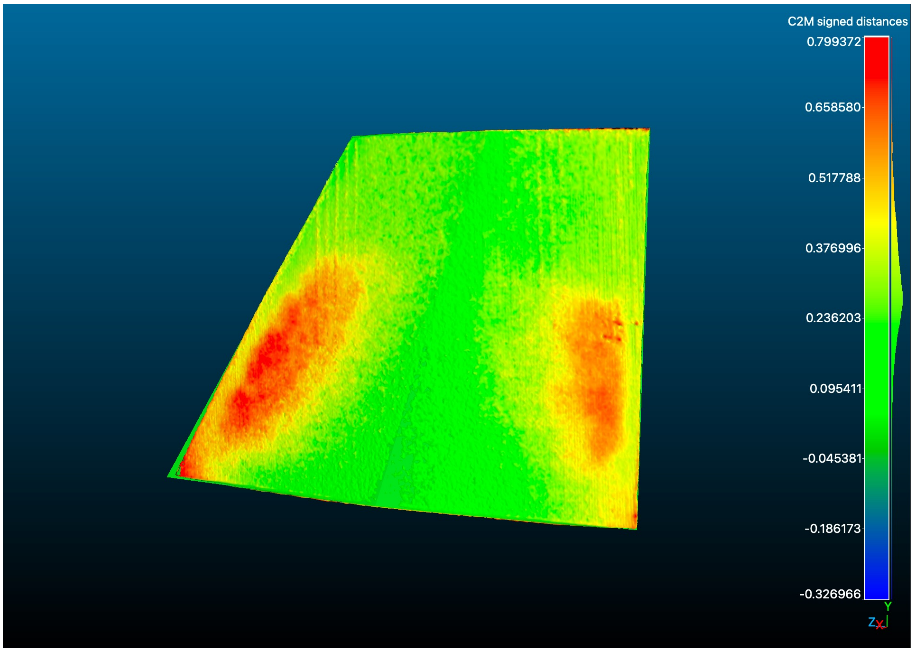


Fig. 6 Deviation Color Map of Fin 4 (Run 1/3)

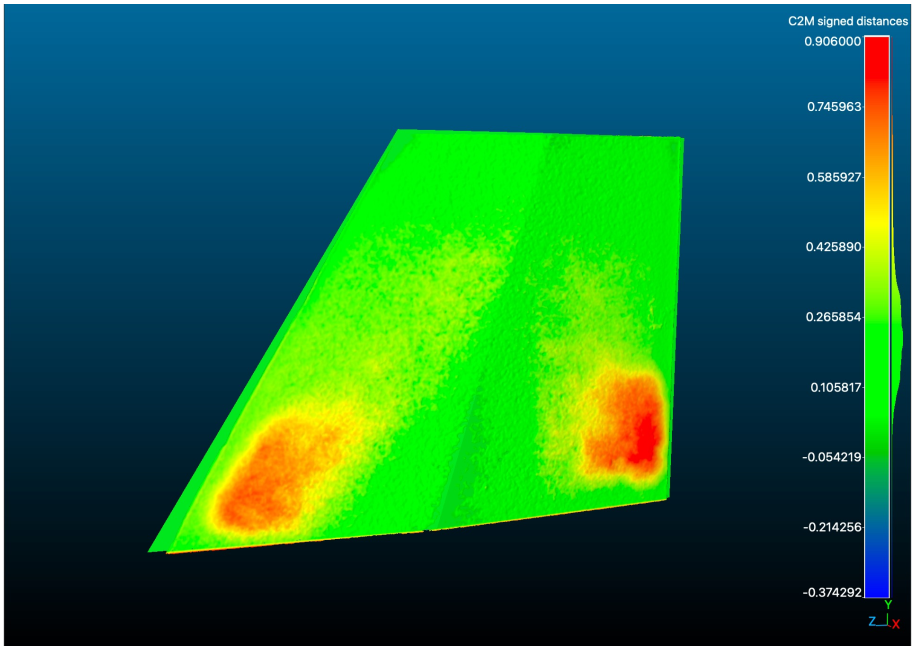


Fig. 7 Deviation Color Map of Fin 5 (Run 3/3)

To validate the 3-D scan results, manual measurements of key fin dimensions, including root chord (c_r), tip chord (c_t), and span (S), were taken, with results presented in Table 3. All numerical calculations were completed in Python. In addition to the 3-D scanning, the variability in fin dimensions was calculated with three independent trials measured for each fin using handheld calipers. The mean ($\bar{x}$) and standard deviation (σ) were computed using Formula 1:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i, \qquad \sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{1}$$

Table 3 Manual Geometric Measurements of Dimensions (mm) With Calipers. Reported as Mean ± 1σ.

	c_r	c_t	$t_{\mathrm{max,tip}}$	$t_{\mathrm{max,root}}$	S
Nominal	138.8	78.6	5.0	8.9	98.7
Fin 1	136.58 ± 0.07	79.21 ± 0.66	6.27 ± 0.07	8.71 ± 0.03	98.78 ± 0.14
Fin 2	136.53 ± 0.18	77.64 ± 0.14	6.05 ± 0.01	8.96 ± 0.45	98.81 ± 0.04
Fin 3	137.44 ± 0.03	78.85 ± 0.11	6.35 ± 0.14	8.50 ± 0.01	98.48 ± 0.39
Fin 4	137.13 ± 0.14	78.32 ± 0.41	6.45 ± 0.13	8.66 ± 0.12	98.91 ± 0.15
Fin 5	136.74 ± 0.04	77.60 ± 0.08	6.10 ± 0.03	8.93 ± 0.06	96.98 ± 0.18
Average	136.88 ± 0.39	78.32 ± 0.72	6.24 ± 0.17	8.75 ± 0.19	98.39 ± 0.81
Delta	−1.92	−0.28	1.24	−0.15	−0.31

B. Discussion

The data indicates that the thermoforming procedure is capable of producing double-wedge geometries with a high degree of fidelity. As summarized in Table 2, the process yielded an average global geometric error ($\bar{\epsilon}$) of 0.28 mm. Fin 1 demonstrated the best performance with an $\bar{\epsilon}$ of only 0.16 mm, suggesting that near-perfect alignment and thermal soak were achieved. The tolerances achieved with this fin are comparable to those of machined hard-material fins and are well within the acceptable margin of error for the GTXR flight program. Indeed, the machining tolerance of the mold itself ±0.06 mm, is a significant contributor to the variance of the larger surfaces. It is worth noting that the mold itself was not a perfect baseline; as seen in Fig. 1c, the mold hardware sustained non-measurable, yet relatively significant damage during manufacturing, including screw thread gouges, surface scratches, and excess non-machined material due to inefficient and incomplete tool paths. Consequently, the results in Table 2 represent a "worst-case" perspective of the process under suboptimal tooling conditions. Across larger fin surface areas, the error $\bar{\epsilon}$ is expected to remain relatively constant, as the deviation is driven primarily by the rigid-body geometry of the aluminum mold rather than a cumulative material expansion or localized foam instability.

The largest deviation observed was in Fin 2, which yielded an $\bar{\epsilon}$ of 0.38 mm. This fin was identified as an anomaly; during the transfer from the oven to the hydraulic press, a slight lateral shift of the foam blank was observed. This misalignment likely accounts for the increased error and the corresponding rise in the surface standard deviation ($\bar{\sigma}_s$). This issue was successfully mitigated in subsequent trials through more rigorous mold engagement practices. These results are corroborated by the manual measurements in Table 3, where the chord deviations for Fin 2 were noticeably higher than those of any other fin.

The average surface standard deviation ($\bar{\sigma}_s$) across all samples (ranging from 0.13 mm to 0.24 mm) represents the "texture" or localized roughness of the formed ROHACELL®51 foam. The standard deviation is attributed primarily to localized surface roughness rather than major geometric deviation. This is supported by manual measurements showing minimal differences from the nominal geometry. Discussed further in this paper, most of this misshapen geometry occurs in small deformed regions hereafter referred to as localized out-of-plane deformation. The $\bar{\sigma}_s$ values are on par with the typical thickness of a single sheet of carbon fiber. GTXR typically applies 6–10 sheets of carbon fiber to the fin core, so variability in the composite layup and manufacturing process would likely dominate over any performance effects introduced by core deformation. This indicates that the thermoformed core surface is sufficiently smooth for subsequent sandwich panel lamination without requiring additional sanding or surfacing. By avoiding post-process abrasion, the integrity of the ROHACELL®51 closed-cell structure is preserved, ensuring optimal resin bonding during the curing phase.

C. Error Analysis

While the surface fidelity of the thermoformed cores was sufficient for subsequent sandwich panel fabrication, several process-induced factors were identified as primary contributors to geometric deviation.

A prominent source of error is the inability to reliably center the ROHACELL®51 foam blanks inside the mold before thermoforming. The mold design did not include any borders to restrain the movement of the foam blank, which meant that alignment was performed by eye, aligning the center of the root and tip chords of the foam blank to the center of the mold. Additionally, this meant that the foam was free to move as it compressed. As a result, in some trials, the foam did not reach the end of the mold, creating an uneven core shape. Additional error may occur when trimming the excess material from the formed fin cores, which is not explored in this paper as the removal was done digitally on the 3-D scan.

Another reoccurring manufacturing defect observed in all trials was the localized out-of-plane deformation on the flat faces of the fins near the leading and trailing edges, represented by the red regions in Figs. 3-7. These raised regions also have a more porous texture compared to the more rigid texture of the rest of the formed core. A potential explanation of this phenomenon is the evaporation patterns of moisture trapped within the cells of the foam due to inadequate drying [12]. The heated moisture inside the cells evaporates, raising the pressure inside the cells, and eventually rupturing them, thus deforming the surface creating a new out-of-plane displacement. Another possible explanation of this phenomenon is uneven cooling of the fin throughout the thermoforming process. When the blank is taken out of the oven it is centered on the mold, and pressed with the hydraulic press. During the two to three minute transfer period, the ROHACELL®51 cools slightly before forming. Pressing at temperatures below forming temperature can lead to a phenomenon known as spring-back, the tendency of ROHACELL®51 to partially return to its original shape. [13][9]. While the foam was removed from the molds at proper low temperatures (less than 80°C), spring-back may still occur due to imperfections at other points in the thermoforming process.

A further source of geometric deviation arises from thermal expansion of the aluminum mold during heating. Aluminum 6061-T6 exhibits a coefficient of thermal expansion of approximately [14]

$$\alpha \approx 23.4 \times 10^{-6} \text{ m/m °C}.$$

For a root chord length (c_r) section of the mold, the expected linear expansion during heating to 200°C from room temperature 23°C, is calculated as

$$\Delta L = \alpha \cdot L_{\text{nominal}} \cdot \Delta T = (23.4 \times 10^{-6}) \cdot (138.8) \cdot (204 - 23) \approx 0.59\,\text{mm} \tag{2}$$

This represents the linear thermal expansion of the mold along the largest dimension (c_r) and is of the same order of magnitude as the observed measurement errors, $\bar{\epsilon}_s$ and $\bar{\sigma}_s$, found in Table 2. Heating the aluminum molds concurrently with the fins introduces an additional source of geometric deviation. This is particularly true because the final fin dimensional tolerances are the most critical aspect of the thermoforming process and the reasoning behind this research. Due to the coefficient of thermal expansion, α, the mold expands when heated to the forming temperature, effectively enlarging the cavity in which the ROHACELL®51 foam blanks are formed. As a result, the fins are formed in an oversized mold. Through the cooling process, as the mold returns to the original dimensions, uneven cooling, and compression of the foam beneath the forming temperature most likely leads to foam cell damage or other similar deformations. This was an experimental oversight that will be corrected in future experiments by taking into account the temperature of the forming molds themselves.

D. Conclusion

In conclusion, this research paper evaluates the viability of thermoforming closed-cell PMI foam cores as a manufacturing method for a double-wedge fin geometry at the collegiate rocketry level. By comparing the experimental results with the modeled core geometry, this study determined that thermoforming ROHACELL®51 can produce fin cores with high geometric fidelity and repeatability. This study achieved an average global standard deviation of 0.17 mm and a surface quality suitable for composite sandwich manufacturing. These results, despite excess experimental error, are very close to the required manufacturing tolerances of GTXR. Implementing the improvements discussed in this paper, GTXR could manufacture full scale ROHACELL®51 fin cores that meet all flight requirements.

Key findings revealed insights into the thermoforming process, particularly the influence of foam alignment to the mold, thermal uniformity, and mold quality on the geometric accuracy and surface fidelity of the formed cores. The analysis identified the key procedures and effective practices for ROHACELL®51 processing, as well as the primary challenges encountered during the thermoforming process.

Although this paper provides advancements in fin core manufacturing using ROHACELL®51, further refinement is required to achieve near-perfect thermoforming results. Improvements may include altering the thermoforming mold to include a cutting inset and using an oversized foam blank, requiring less precise alignment prior to thermoforming. Additionally, further root-cause analysis may be conducted to understand the high-porosity regions observed after the forming process and to develop targeted design solutions to address this issue. By documenting the manufacturing procedures and associated challenges, this paper establishes thermoforming closed-cell foam cores as a viable approach for fin core fabrication, allowing for increased design flexibility and weight optimization.

Acknowledgments

All authors thank the Ramblin' Rocket Club at the Georgia Institute of Technology for financial support in providing materials used in manufacturing and development of the ROHACELL® thermoforming tests.

All authors thank the Georgia Institute of Technology Aerospace Machine Shop and the Yang Aero Maker Space for providing manufacturing equipment, facilities, and expertise to conduct the ROHACELL® thermoforming tests.

All authors thank Georgia Tech's Student Government Association, the GT Aerospace Engineering Department, and the other club sponsors for making this research possible through financial contributions.

All authors thank Anja Govednik and Nathaniel Levander for their ongoing support, guidance, and structural expertise throughout the entirety of this project with Georgia Tech Experimental Rocketry.

All authors thank Donovan Nichols and Parth Garud for their mentorship and support throughout this project.

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