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Low-Cost Aero Technology Demonstrations

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Low-Cost Aero Technology Demonstrations

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List of Acronyms

AM	Additive Manufacturing
CAD	Computer Aided Design
CTE	Coefficient of Thermal Expansion
ECS	Environment Control Services
eVTOL	Vehicles - Electric Vertical Takeoff And Landing
FDM	Fused Deposition Modeling
OML	Outer Mold Line
PEI	Polyetherimide
RTM	Resin Transfer Molding
UAM	Urban Air Mobility
VARTM	Vacuum Assisted Resin Transfer Molding

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1. Executive Summary

The main focus of this work was to demonstrate the use of polymeric additive manufacturing (AM) to create tooling for both preforming and consolidation. Polymeric tooling was utilized where both modest and higher pressures are used for part consolidation. The key focus for the AM tooling development was for fabrication of complex structures such as ducting, C-channel stiffened skins, and airfoils where conventional male tooling would typically be trapped in the cured part. The AM tooling was evaluated for use as a tool master used to fabricate and re-shape deformable/re-formable mandrels based on SpinTech's shape memory composite technology known as Smart Tooling. The AM tooling was also evaluated for use as a mold for composite infusion and consolidation.

Key performance parameters were tracked for project schedule completion with each step comprising of "art to part" cycle time, cost, and model fidelity for dimensions, performance, and cost. The primary focus of this demonstration was to determine if a 50% cost reduction was achievable, for each AM tooling-set, as compared to conventional processes. UDRI leveraged project partner SpinTech, who manufactures tools and parts in these categories and thus provided a baseline regarding current best practices and provided valuable feedback during the entirety of this demonstration.

This demonstration primarily focused on the use of AM tooling for fabrication of three composite component structures which are typically utilized in aircraft and comprise salient geometric features of broad interest. These components are often tooling intensive and have features requiring extraction of male tools which are usually trapped by the geometry. The three structures selected by the team included:

1) A one-piece airfoil shell comprised of compound contours where male tooling would be trapped unless the part were manufactured in two halves as is typically the case.
2) A one-piece duct used for air handling, comprised of compound contours where male tooling would be trapped unless the part were manufactured in two halves, or a washout mandrel were to be used.
3) A co-cured C-channel stiffened skin where typically C-channels would be individually manufactured and then bonded to a cured skin.

The demonstration was comprised of three main tasks:

- Task 1: AM Tool Feasibility Study – ensure the AM tooling meets the performance requirements as specified by SpinTech to match baseline performance.
- Task 2: Complex Tool Demonstration – Fabricate tooling, preforms, and parts representative of an airfoil and duct.
- Task 3: Large Aerostructure Fabrication Demonstration – Fabricate tooling, preforms, and part representative of a C-channel stiffened skin.

With the conclusion of this project, a decision tree was developed to determine the key considerations necessary to determine if use of AM tooling for the three selected structures was able to attain the same quality as historically achieved on metallic tooling, while providing a significant cost reduction.

2. Introduction

There are several advantages to using composite aerostructures, but they come with a significant tooling investment. Conventional or hard tooling approaches offer the ability to survive 180° Celsius through hundreds of production cycles while maintaining dimensional stability. Typically, prototyping tools are manufactured with use of aluminum, but these metallic tools have a high coefficient of thermal expansion (CTE). Invar can be used if high dimensional tolerances are needed and for high durability, however the use of this nickel-iron alloy can be very costly and can have very significant lead times.

SpinTech's Smart Tooling is a reusable shape memory polymer tooling system that allows more efficient and lower cost production of complex composite parts with trapped or captive geometries, such as ducts, inlets, UAV bodies, spars and control surfaces. Smart Tooling's advantage is that it is rigid for lay-up and then is flexible for de-mold, and then easily reformed to its original shape. It can be tailored to be rigid at cure temperature, replacing dissolvable or metal mandrels; or elastic at cure temperature for use as a bladder or caul. This allows faster tool prep, better part quality, reduced cost, and higher throughput. Further, at the part design stage, it allows products to be manufactured more efficiently by consolidating parts. For example, SpinTech worked with a customer on a complex multi-piece part that took them one month to produce and assemble. By using Smart Tooling they were able to redesign the part into a single piece and reduced production time to one week with a 70% cost reduction. SpinTech has extensive experience in both tooling for complex geometries as well as converting prepreg composite structures to dry fiber and resin infused structures.

Smart Tooling fabrication requires use of tool masters to both create the Smart Tool and reform it after each use. The objective of this project was to determine if polymeric AM tooling could serve the function of a master tool while reducing procurement time and cost by 50%.

3. Background

Additive manufacturing is a processing technique that is being used to significantly decrease the cost of manufacturing tools and composite molds while also decreasing the lead time of manufacturing tools. Additive manufacturing is now being used globally for low-cost aerospace composite tooling by most commercial and defense aerospace manufactures. Low-cost tooling is critical for lowering composite fabrication costs. Taking advantage of AM, UDRI has been able to demonstrate 50% reduction in tooling costs and significantly shortened lead times versus conventional tooling.

Faster, larger, and less-expensive AM machines are now starting to become more readily available that can be used for creating composite tooling. This program featured the use of UDRI's Titan Atlas 2.5 pellet to part printer shown in **Figure 1**. The Atlas is a fused deposition modeling (FDM) 3D printer that can be used for both pellet and filament extrusion. Pellet extrusion was selected for this program because it allows for use of carbon fiber filled pellets for enhanced performance and because the pellet feedstock is cheaper than filament. A 20% carbon fiber filled polyetherimide (PEI) feedstock from SABIC Innovative Plastics was selected due to the researchers' familiarity with the material and its proven ability to withstand typical autoclave or oven cure cycles while maintaining dimensional stability in composite tooling. The team decided to use a 2mm nozzle for the entirety of the project for optimization of print speed and quality, although a 4mm nozzle was used in some of the cost analyses to help determine if it would reduce print lead times and cost. Polymeric tools up to 42" x 42" x 48" can be fabricated with use of this printer.

4. Results and Discussion

Task 1: AM Tool Feasibility Study

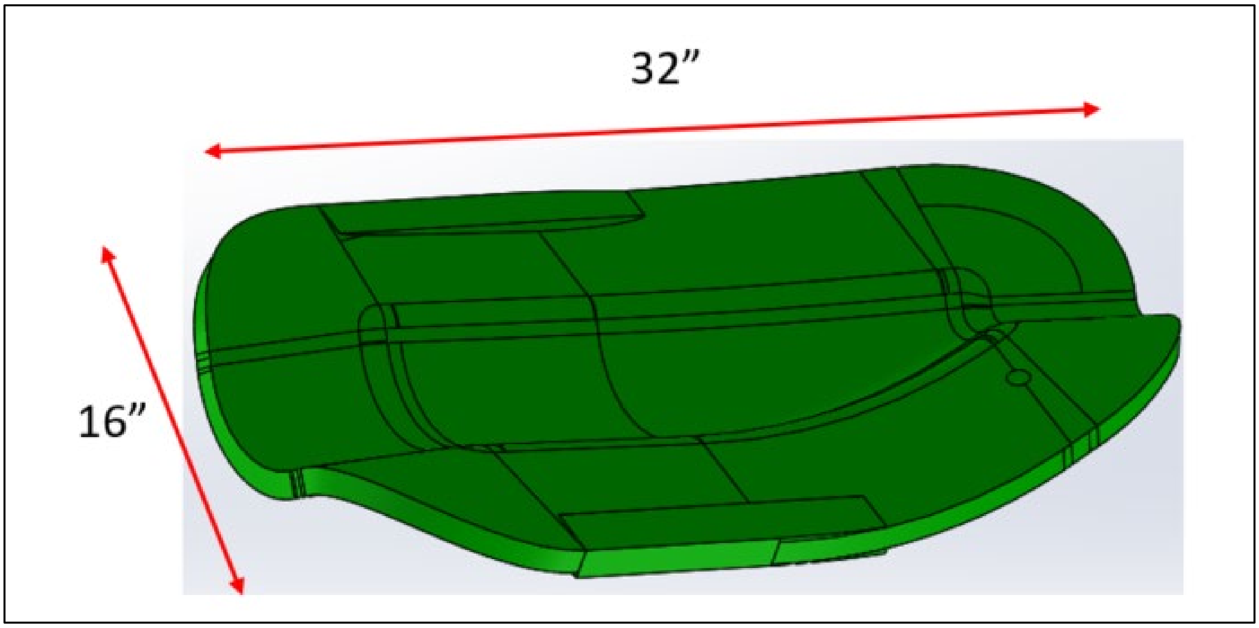
A tool feasibility study was conducted to determine if additively manufactured (AM) polymeric tooling can meet the needs for complex aero structure manufacturing. AM tooling for composite structures has been demonstrated by UDRI, but it has never been demonstrated in conjunction with extractable/re-formable tooling technology, known as Smart Tooling. Of particular importance is to determine the tool vacuum integrity at cure temperature which would be required for a VARTM infusion of the Smart Tool.

A single-side tool (bird bath geometry) and two tubular-shaped tool sets (demo tubes) were used to evaluate the tool characteristics. Various methods of finishing the tool post-printing were also investigated. Target specifications were determined by SpinTech and were treated as requirements during the project. Project objectives centered on vacuum leak rate and dimensional stability operating at 100 psi and 350°F.

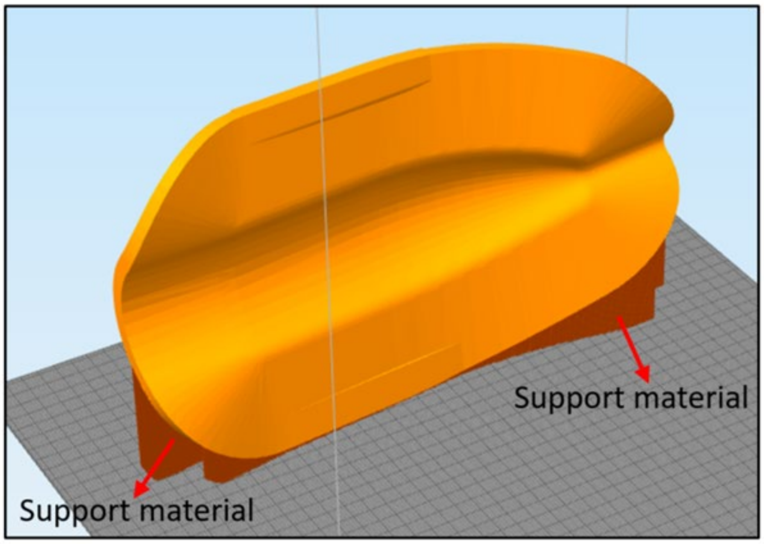
- *+/-0.005" profile tolerance on tooling surface*
- *Surface finish of Ra32*
- *Vacuum leak rate of <0.2" Hg over 30 minutes*
- *Structural integrity up to 350 °F*
- *Structural integrity up to 100 psi (OML tool only, and only if envelope bagged)*
- *Known and predictable thermal expansion coefficients*

Bird Bath Tool

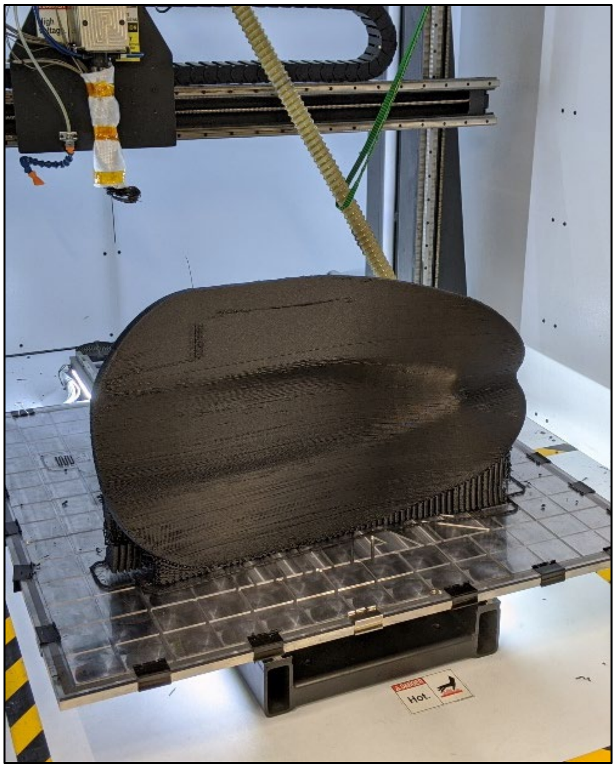
The “bird bath tool” geometry represents a one-piece airfoil shell. This tool would allow for the option of a top side envelope vacuum bag for the caul manufacturing process while allowing for the vacuum leak rate to be measured. The original tool file was received from SpinTech and then optimized into a thin shell using SOLIDWORKS as shown below in **Figure 2**.



The tool design was modified in SOLIDWORKS to allow for ease of printing and machining, then the part was sliced using Simplify3D slicing software. The bird bath tool was printed upright, as shown in **Figure 3**, to maximize print resolution while also saving material by significantly reducing the amount of support material required to stabilize the part while printing. Support material was used on the backside of the tool to help secure it to the printing bed, while also helping to prevent deformation during the printing process. The support was printed in a low-density format so that it could be easily removed without damaging the tool after the printing process was complete.



The part took a total of 24 hours to print while using roughly 32.3 lbs of material. A ¼" of extra thickness was added onto the top surface to allow for machining down the tool to its net geometry while providing a smooth surface finish. The fully dense printed tool, shown in **Figure 4**, had final dimensions of approximately 32" x 16" x 1".

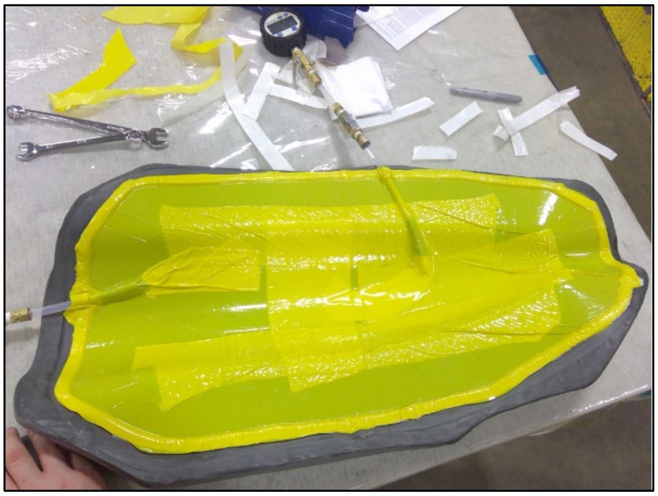


The tool surface was then machined, and hand sanded progressing in grit size of 120 to 320, to achieve the equivalent of a Ra32 surface finish.

A vacuum integrity check was conducted on the tool with use of a surface vacuum bag. UDRI has been actively involved in fused deposition modeling (FDM) 3D printing research for several years and has observed that the microstructure is never fully dense, which allows air to easily flow through high levels of porosity that are present in the prints such as the bird bath tool. As expected, vacuum integrity was never achieved but knowing that the manufacturing process would take place with use of an envelope bag, this check was only made for future reference. Envelope bagging of the tool shell was possible because there was no remaining support structure to accommodate. This bagging approach is not possible for large tools which retain and utilize backside support structures. Given the drive to reduce cost 50% over standard tooling options, it was cheaper to envelope bag the tool rather than apply a sealer in multiple steps in an attempt to achieve vacuum integrity.

A prior vacuum integrity check was completed on a duplicate bird bath tool using a BJB Enterprises epoxy sealer (TC-1614 A/B), but it failed to maintain vacuum integrity with a surface vacuum bag. After deciding on the envelope bag approach, the tool was then delivered to SpinTech for the caul manufacturing process. SpinTech caul tools are fabricated using a trade secret fiber and fabric reinforcement, a combination of shape memory polymers (SMP), and a vacuum assisted resin transfer molding (VARTM) process that allows the SMP caul tool to expand up to 20% bi-directionally when heated above its Tg and pressurized. The SMP caul tools are manufactured using the VARTM process to the net inside mold line (IML) shape of the composite part (with bulk factor offsets if necessary).

SpinTech's main goal with the bird bath tool was to further evaluate the vacuum integrity of the tool while also gauging its potential use with liquid molded composite part lay-ups. For SpinTech's first test, a leak check was performed on the surface of the tool using an NBF-600 vacuum bag and GS-43MR sealant tape as shown in **Figure 5**. With use of these materials, only -13.2 inHg was able to be achieved using a surface vacuum bag. When the vacuum sources were turned off all vacuum pressure was lost to 0 inHg almost immediately, indicating that the tool had significant porosity allowing air flow.

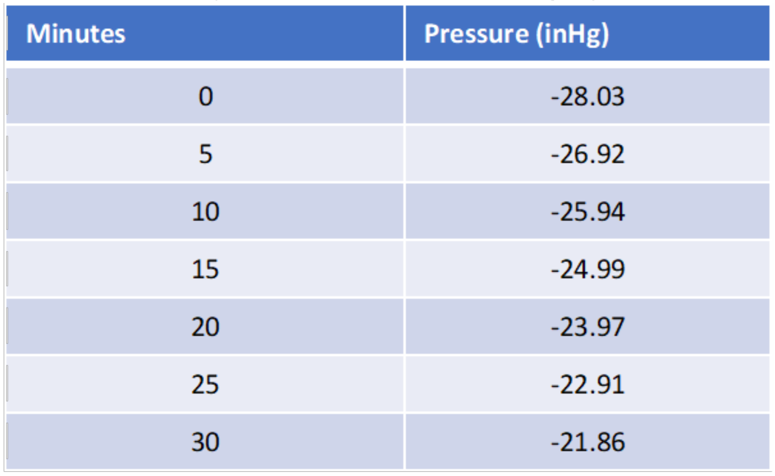


For the next test, a barrier ply of Airtech Tooltec-CS5 as shown in **Figure 6** was applied over the tool side of the AM tool and vacuum formed in place.

The entire tool was then wrapped in breather and enveloped bagged using WN1500 vacuum bagging film along with GS-43MR sealant tape as shown in **Figure 7**. Vacuum was pulled down for 30 minutes to a maximum vacuum level of -28.03 inHg.

A vacuum leak check over 30 minutes was conducted on the envelope bagged tool. The vacuum integrity check resulted in a failure over the 30 minutes as displayed in **Table 1**. It is likely this could have been that the part was slowly outgassing, resulting in vacuum decay, or the bag sealant was leaking and needed more time to seal properly.

Table 1. SpinTech Initial Vacuum Integrity Check



Minutes	Pressure (inHg)
0	-28.03
5	-26.92
10	-25.94
15	-24.99
20	-23.97
25	-22.91
30	-21.86

Vacuum was left pulling on the envelope vacuum bag overnight. The maximum vacuum level that was able to be achieved was -28.23 inHg when checked the next morning. Another 30-minute vacuum integrity check was conducted to see if the leak rate had improved. The vacuum pressure started at -28.23 inHg and ended at -28.03 inHg after 30 minutes as shown in **Table 2, resulting in a successful vacuum integrity metric.**

Table 2. SpinTech Overnight Vacuum Integrity Check

Minutes	Pressure (inHg)
0	-28.23
5	-28.18
9	-28.16
11	-28.15
17	-28.12
22	-28.08
30	-28.03

After completing the vacuum integrity study, SpinTech proceeded to manufacture a Smart Tool from the bird bath tool. Dry fabric was laid up on the bird bath tool that remained covered in the barrier layer of Tooltec-CS5. The infusion media was laid up over top of the dry fabric. An NBF-600 vacuum bag was sealed on the edge of the tool, acting as a resin dam. An NBF-600 envelope bag was then applied followed by a WN1500 envelope bag applied over that to act as a double bag.

The fabric was dried in an oven overnight at 250°F to remove any moisture from the fabric and the AM tool, and then infused the next day. The fabric was infused at 194°F and then ramped to 365°F for part cure as shown in **Figure 8**.

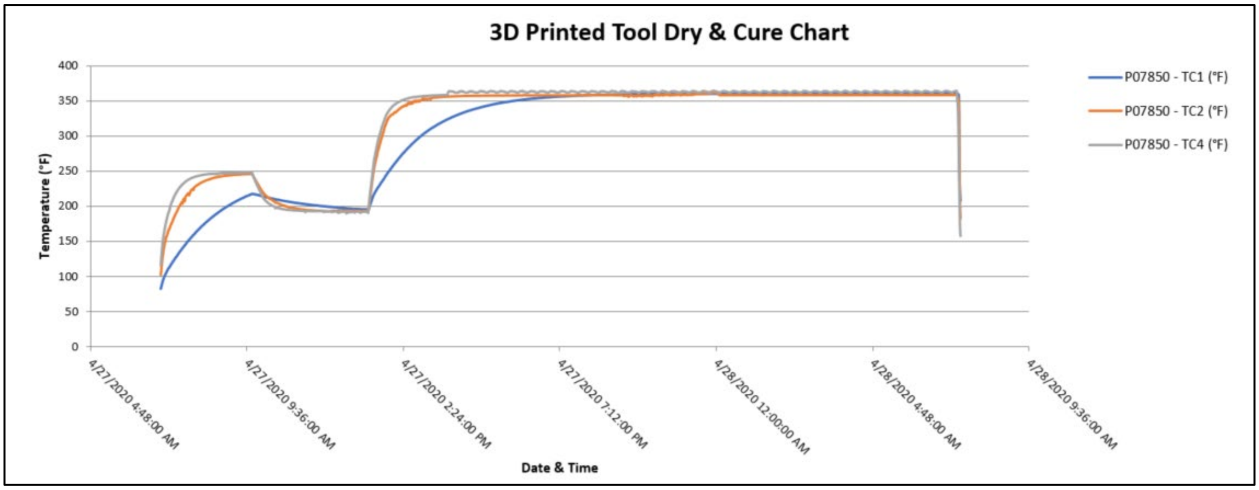


Figure 8. SpinTech Cure Cycle for Smart Tool Infusion

The Smart Tool produced from the AM tool, shown below in **Figure 9**, was of comparable quality to that made from aluminum tooling, with the exception of the Tooltec-CS5 seam mark-off that transferred from the tool surface, which likely could be eliminated if the Tooltec-CS5 was placed in one piece.

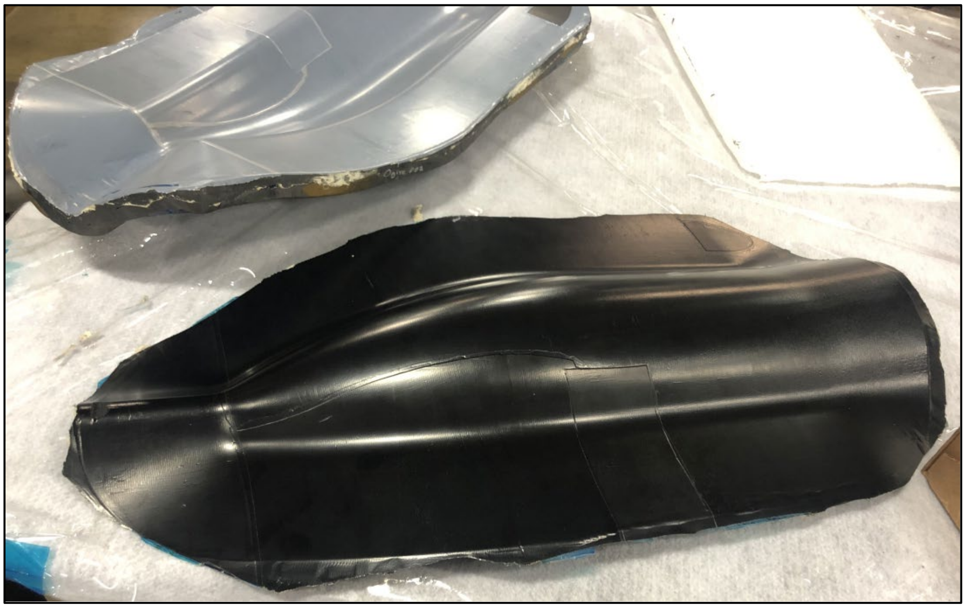


Figure 9. Smart Tool Demolded from the Bird Bath Tool

In conclusion, the bird bath AM tool itself appeared to be porous through the thickness of the tool. The Tooltec-CS5 barrier helped improve the vacuum integrity on the top side of the tool, but it was still not good enough to achieve the stringent leak rate requirement of <0.2 inHg over 30 minutes. Envelope bagging the tool allowed the leak rate requirement to be met while making a high-quality liquid molded part. It appeared as if it took a long time to pull all air out of the tool, so it was assumed that one should not go straight from bagging to infusion of the part. SpinTech acknowledged that the bird bath tool could easily be used to manufacture or reform several more Smart Tools if it remained durable.

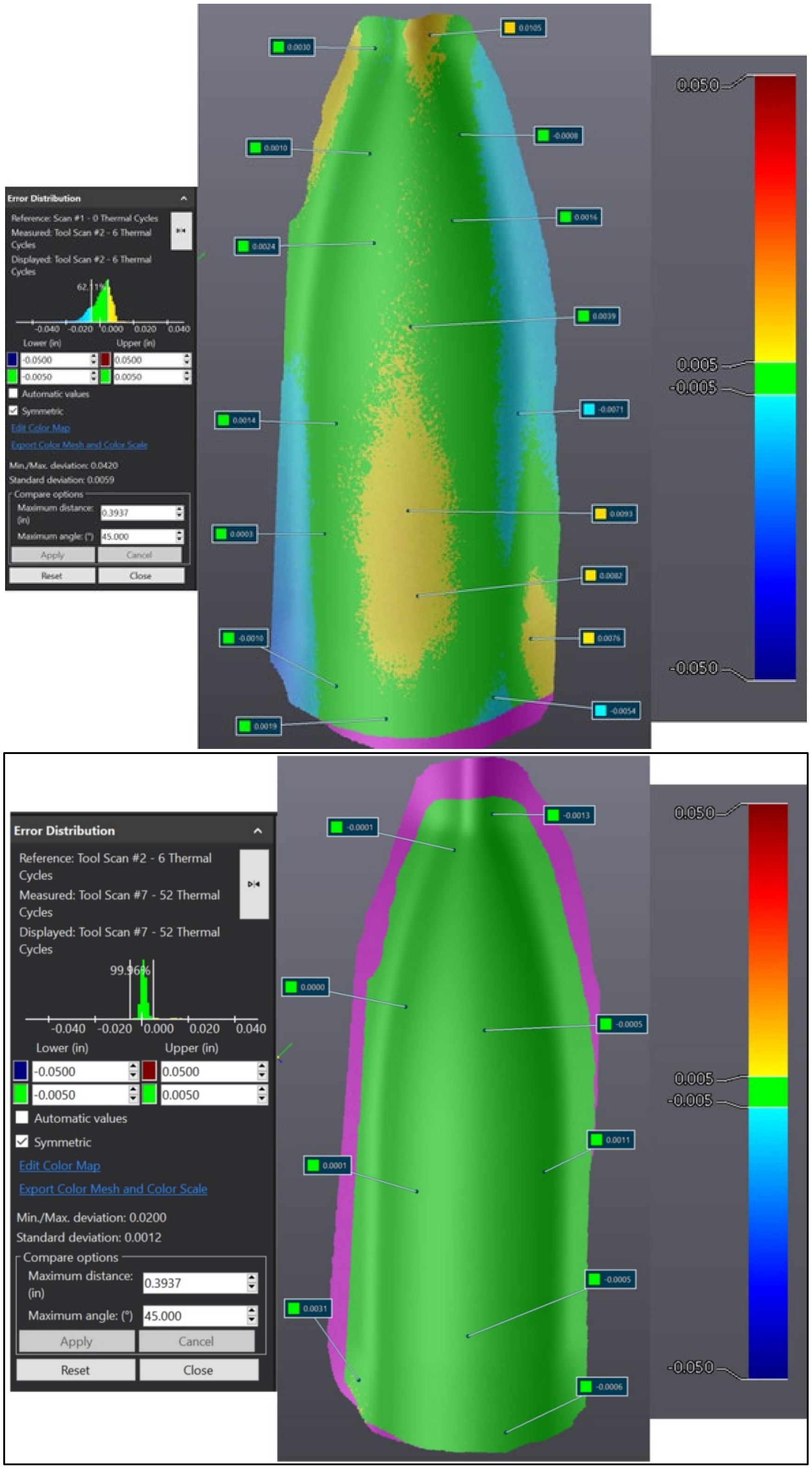
Following the manufacturing process of the final part, UDRI conducted a thermal and dimensional stability study on the bird bath tool. The study was completed to investigate if +/-0.005" profile tolerance on the tooling surface and structural integrity up to 350°F could be achieved over the course of approximately 50+ thermal cycles. The thermal cycle log for this tool was created, as shown below in **Table 3**. Dimensional scans were captured with use of the Creaform HandySCAN700, a metrology-grade 3D scanner that uses laser triangulation technology to monitor the dimensional stability of the tool.

Table 3. Dimensional Scan Schedule for the Bird Bath Tool

Cycles	Date	Location	Cure Profile	Dimensional Scan
1	4/27/20	Spintech	365°F for 16 hrs	N/A
2-6	5/6/20	UDRI	250°F for 45 min	Yes
7-11	5/8/20	UDRI	250°F for 45 min	Yes
12-21	5/11/20	UDRI	250°F for 45 min	No
22-31	5/15/20	UDRI	250°F for 45 min	Yes
32-41	5/22/20	UDRI	250°F for 45 min	No
42-51	5/24/20	UDRI	250°F for 45 min	Yes
52	5/26/20	UDRI	365°F for 16 hrs	Yes

The baseline 3D scan was completed after the bird bath tool was received back from the machine shop. After thermal cycle #6, the first dimensional scan comparison was completed. The tool exhibited some movement after the first 6 thermal cycles but appeared to be within roughly +/-0.010" profile tolerance from the baseline scan. The error distribution histogram showed there were some low and high spots present, but the high spots could notionally be machined or benched down into tolerance, which would then increase the acceptable tolerance percentage given on the histogram. The error distribution histogram in **Figure 10-upper**, shows the values of all the deviations present on the tool between the limit values of +/- 0.050" as the color green. The percentage value shown on the histogram determined by the VXelemnts software shows that about 62% of the tool scan (green region on the heat map) is within the specified acceptance/tolerance.

After recording scans approximately every 10 thermal cycles, the team decided that if the tool were exposed to an initial thermal cycle or heat treatment process, such an annealing stage just below the melting temperature of the polymer, it would help remove any residual stresses built up in the tool, thus preventing movement during the 50+ thermal cycles. To illustrate what a polymer annealing stage might look like with this tool, the last 3D scan, tool scan #7 (52 thermal cycles), was compared to tool scan #2 (6 thermal cycles). This comparison showed essentially no movement at all occurring on the tool surface as 99.96% of the heat map showed to be green and within the +/-0.005" region as shown in **Figure 10-lower**. This led the team to believe that an annealing stage before having the tool machined would lead to a dimensionally stable tool when being used for 50+ production cycles.



Error Distribution

Reference: Scan #1 - 0 Thermal Cycles

Measured: Tool Scan #2 - 6 Thermal Cycles

Displayed: Tool Scan #2 - 6 Thermal Cycles

Lower (in): -0.0500, -0.0050

Upper (in): 0.0500, 0.0050

☐ Automatic values

☑ Symmetric

Min./Max. deviation: 0.0420

Standard deviation: 0.0059

Compare options

Maximum distance: (in) 0.3937

Maximum angle: (°) 45.000

Error Distribution

Reference: Tool Scan #2 - 6 Thermal Cycles

Measured: Tool Scan #7 - 52 Thermal Cycles

Displayed: Tool Scan #7 - 52 Thermal Cycles

Lower (in): -0.0500, -0.0050

Upper (in): 0.0500, 0.0050

☐ Automatic values

☑ Symmetric

Min./Max. deviation: 0.0200

Standard deviation: 0.0012

Compare options

Maximum distance: (in) 0.3937

Maximum angle: (°) 45.000

Figure 10. Bird Bath Tool Scan Comparison at 7 (upper) and 52 Thermal Cycles (lower)

Square Trial Panel Vacuum Integrity Study

Square trial panels were printed and evaluated in tandem with the bird bath tool to investigate effect of process variables on tool density and hence air flow or leakage. Varying the extrusion rate and bead layer height parameters on the Titan Atlas printer, along with application of TruDesign HT Sealer, should improve the overall vacuum integrity to where a vacuum leak rate of <0.2inHg over 30 minutes could be passed. Six panels measuring roughly 12" x 12" x 0.5", as shown below in **Figure 11**, were printed with varying parameters that included the bead layer height and extrusion rate. The bead layer height was varied from 0.8mm to 1mm and the extrusion rate was varied from 1.05 to 1.15 in an attempt to increase part density or minimize porosity, leakage.

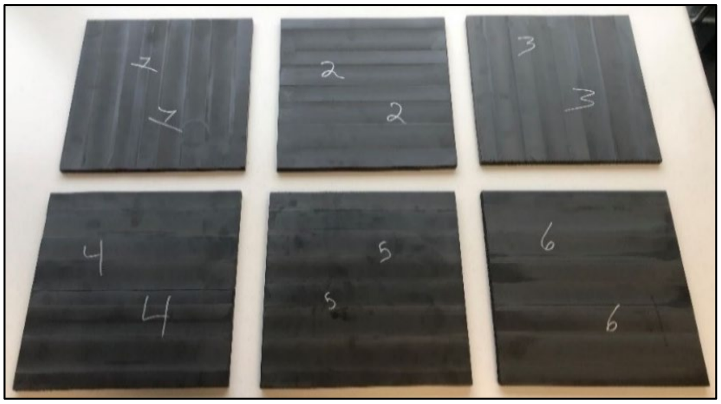


Figure 11. Square Trial Panels

Following the tools prints, they were all delivered to be machined and then sanded in the same manner as the bird bath tool.

A successful leak rate test was completed on a baseline metal tool plate with no vacuum pressure drop over 30 minutes to confirm the equipment being used was reliable. Following the baseline test, an initial vacuum integrity study was completed on the six panels, as shown in **Figure 12**, with surface vacuum bags and leak rates recorded over 1, 2, 5, and 30 minute intervals. All the vacuum integrity tests resulted in instant failures with an immediate drop to 0 inHg after the vacuum source was turned off.

Figure 12. Surface Vacuum Bag Configuration on Square Trial Panel

After the initial failed vacuum integrity check, the team decided to coat all the panels with TruDesign HT Sealer at ambient temperature followed by a postcure at 250°F for 1 hour. TruDesign coating products are best known for their use in the AM industry for their ability to maintain a vacuum tight seal at high service temperatures of up to 350°F.

A second vacuum integrity leak rate check was then completed on the six panels following the sealer application. Three of the six panels were able to pass the leak rate requirement over 30 minutes. A third leak rate check was recorded at ambient temperature with all six panels having exposure to a single thermal cycle of 365°F for 16 hours. The same time intervals were used as in the previous leak rate checks. The same three panels were again able to pass the leak check over 30 minutes.

A fourth leak rate check was completed at ambient temperature with of one of UDRI's autoclave vacuum pumps to provide a higher vacuum (-29inHG) and again the same three panels passed. A fifth and final leak rate check was recorded at part cure temperature (365°F), with use of the three panels identified that had been successful in passing the two previous vacuum integrity leak checks. The oil-free electric vacuum pump was again used for this study as the panels were placed in an oven. All three panels were unsuccessful with passing the leak rate check at cure temperature as all panels lost around 5 to 7inHG over 30 minutes.

In conclusion of the square trial panel study, the tools could not achieve the required vacuum integrity required for VARTM using a single-sided vacuum bag and with application of TruDesign sealer at the SpinTech part cure temperature (365°F). Tooling leakage requirements for curing prepreg however allow for a 2-5 inch Hg loss over a 5-minute span, thus it appears to be a viable option. The AM tools will have to be envelope bagged to meet stringent vacuum integrity leak rate requirements as displayed with use of the thin shell, bird bath tool.

The use of the TruDesign HT sealer helped improve the vacuum integrity of AM tools significantly, but still not to where stringent leak rate requirements for SpinTech's liquid molding process could be passed with use of a single-sided vacuum bag. Further research is needed to explore how the use of the TruDesign sealer could be applied more efficiently to seal the tool while maintaining vacuum integrity at cure temperature, or if other materials or processes are present to help the tools maintain vacuum integrity at elevated temperatures.

AM Tooling Used to Fabricate a Tubular Shaped-Part and Meet the 100 psi Requirement

Two hard toolsets were additively manufactured to produce a final tubular shaped-part as shown in **Figure 13**. The first toolset, shown in **Figure 13-upper**, was printed and used as a master tool to manufacture the actual Smart Tool/mandrel/re-formable tool. This toolset also can be used to reform the Smart Tool after every part cycle. The second toolset, shown in **Figure 13-lower**, also known as the cure mold, was printed and used in conjunction with the Smart Tool to make composite parts. The Smart Tool, which had dry reinforcement fabric wrapped around it, was placed inside the second toolset and then was infused. After the cure was complete, the final tubular shaped part was demolded from the cure mold toolset and the Smart Tool was then extracted and reformed in the first toolset.

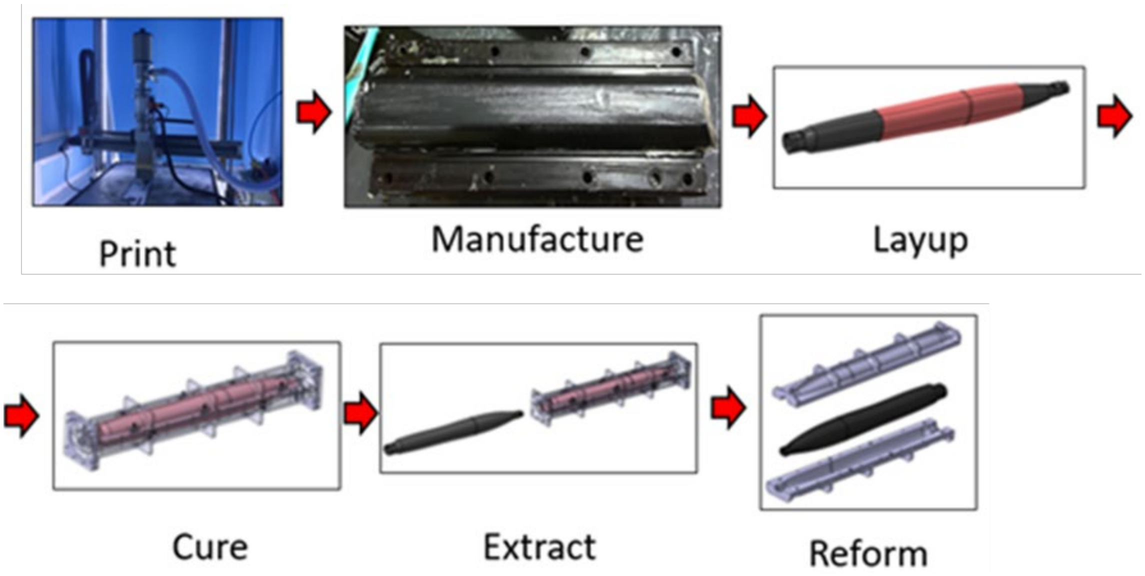


Figure 13. Processing Scheme Using AM Tool Master with Smart Tool to Fabricate Dem

Two “demo tube” tool sets were additively manufactured (AM) for demonstrating that tubular shaped-part geometries can be fabricated with use of AM tooling, while also meeting the 100 psi requirement for the resin transfer molding (RTM) process used to make the final part. The tubular shaped geometry was selected to be representative of environment control services (ECS) ducting for aircraft. These types of tubes, some much bigger and longer than the geometry used for this demonstration, are used to convey cooling air for electronics and A/C for passengers.

The first “demo tube” mold that was additively manufactured was for use of fabricating the Smart Tool or caul which would then be used for manufacturing the final tubular-shaped part. The tool set was named the “demo tube ***form*** mold” as it would be used to help re-form the Smart Tool after each part manufacturing cycle. This tool set was manufactured with the intent of having only vacuum pressure applied to the inner and outer mold surfaces during the vacuum assisted resin transfer molding (VARTM) process. To ensure stringent vacuum integrity leak rate requirements from the previously stated Task 1 requirements could be achieved, a tube vacuum bag was placed down the inside cavity of the assembled tool set which then tied into an envelope bag, thus providing an air-tight seal. The Smart Tool or caul produced from this mold was then used to manufacture the final part in the second “demo tube” tool set.

The second demo tube mold was manufactured and used as a cure mold. This tool set was referred to as the "demo tube ***cure*** mold". This tool set was to be uniquely designed for resin transfer molding (RTM) with use of AM tooling inserts. The tool was required to withstand internal pressure of 100 psi during the RTM manufacturing process. Through several tool design iterations, the team decided on using an aluminum coffin mold as clamshells to clamp the additively manufactured top and bottom tool halves together. The additively manufactured tool halves or inserts possessed the final net tubular-shaped part geometry. The aluminum coffin acted as the closed-mold system needed for the RTM manufacturing process while simultaneously incorporating AM tooling inserts that could be changed out and amortized over multiple different part geometries. A final tubular shaped part was able to be produced with use of the demo tube cure mold while also verifying the 100 psi criteria could be achieved.

Demo Tube Form Mold

The demo tube form mold CAD file was provided by SpinTech to serve as the demonstration piece that possessed tubular-shaped part geometry used to fabricate a duct on an aircraft. The toolset was designed for use during both the manufacturing and re-forming process of their Smart Tool. The Smart Tool was then to be manufactured through vacuum assisted resin transfer molding (VARTM). Vacuum pressure was the only acting force that the inner and outer surfaces of the toolset would experience. A tube bag stretching down the cavity of the toolset was to be used for consolidation of the inner surface of the Smart Tool. The tube bag then was to be connected to an envelope bag that applied vacuum pressure on the outside surfaces of the toolset.

The step file provided by Spintech was modified using SOLIDWORKS by UDRI to achieve optimal efficiency with cost, material, print time, and print quality on the Titan Atlas. Features such as O-ring grooves and bolt holes were added into the CAD so that the form mold could be clamped shut during the caul infusion process. O-ring grooves were added on the bottom half of the toolset to block resin from leaking into the bolt holes and locating pins. The toolset possessed dimensions of about 13.5" x 5.5". A print file and a machine-to file were both designed using SOLIDWORKS as shown in **Figure 14**. The print file for the Titan Atlas was used to print the toolset with added wall thickness that would account for the extra material needed during machining. The machine-to profile possessed the final net geometry for each half of the demo tube cure mold, including the necessary O-ring grooves, bolt holes, and locating pin features.

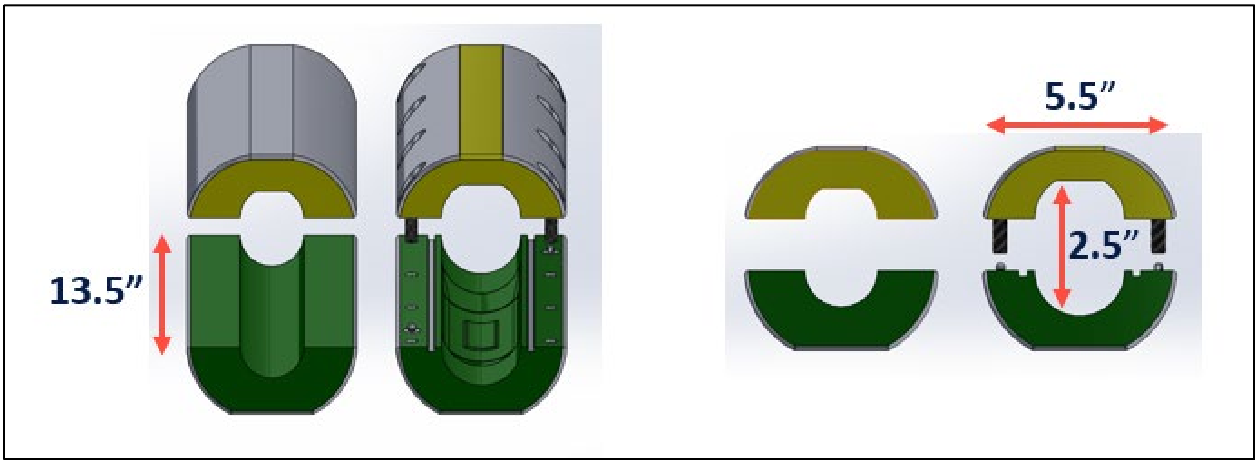


Figure 14. Demo Tube Form Mold Modified SOLIDWORKS Files

The top and bottom half of the toolset were printed on the Titan Atlas at the same time as shown in **Figure 15**. The tool print took about 9.5 hours to complete and used approximately 9.3 lbs of 20% carbon-filled Ultem (PEI) for the total toolset. The print included use of a 2mm nozzle for extrusion of the thermoplastic pellets and parameters of 1mm layer height followed by 7 contours of thickness.

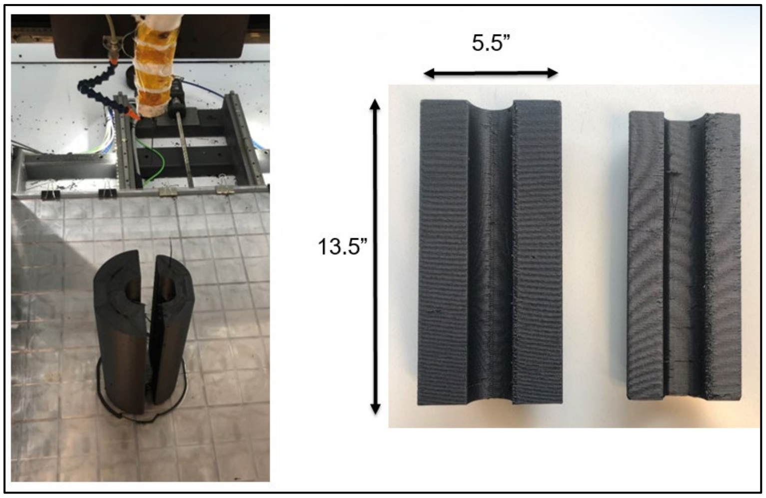


Figure 15. Titan Atlas Print of Demo Tube Form Mold

Following the print of the tool and an annealing stage, the machine-to step file was sent to the UDRI machine shop to have the net geometry machined into the halves, as shown in **Figure 16**, including the removal of the added ¼” of material.

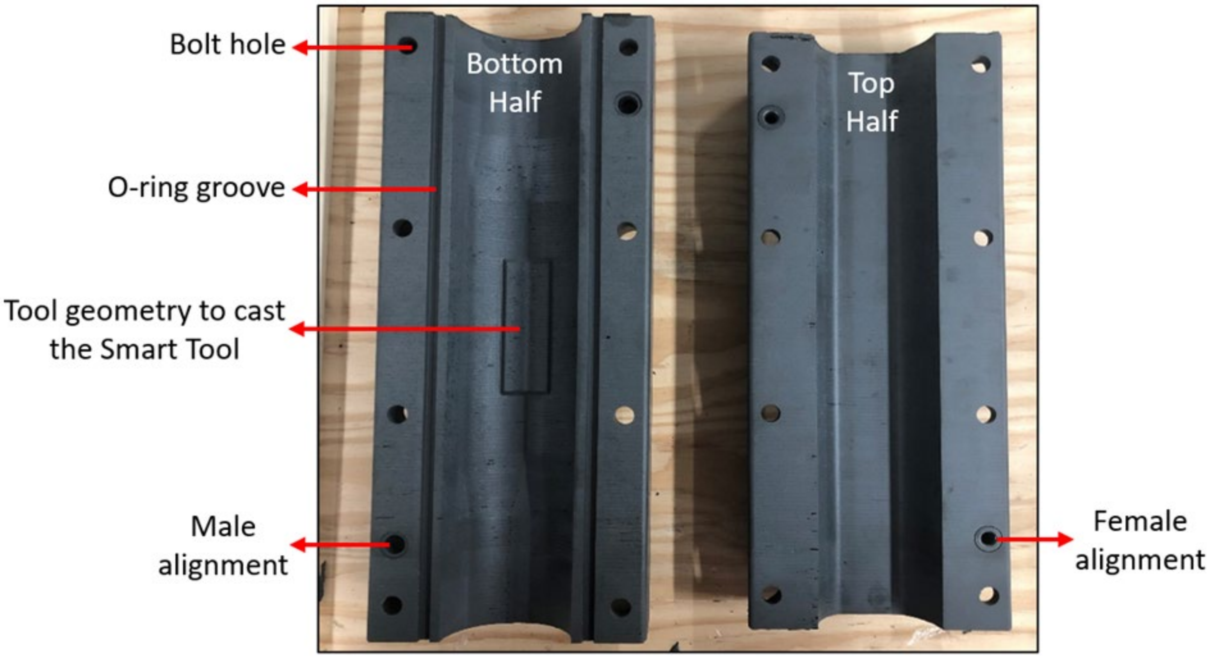


Figure 16. Demo Tube Form Mold Top and Bottom Half Post-Machining

Both halves of the tool were then benched through hand sanding to meet the surface finish requirement (Ra32). The tool was sanded with standard grit paper starting at grit size 120 and ending at grit size 320.

A dimensional scan was completed on both mold halves following benching, and then sealed with TruDesign epoxy sealer as shown in **Figure 17**. This was the same sealer used in the square trial panel study and it was applied following the same application procedure.

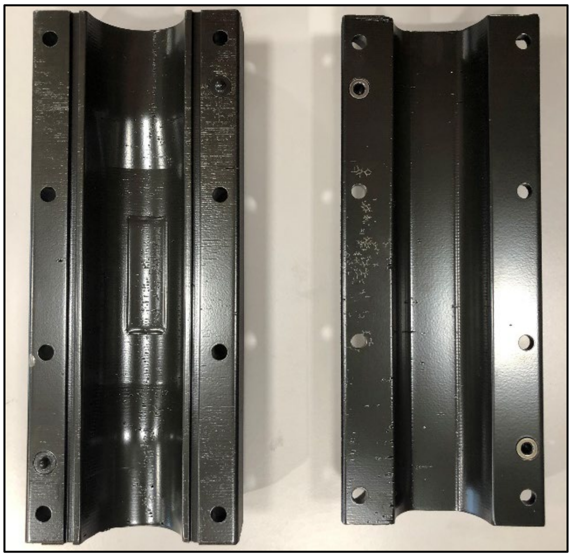
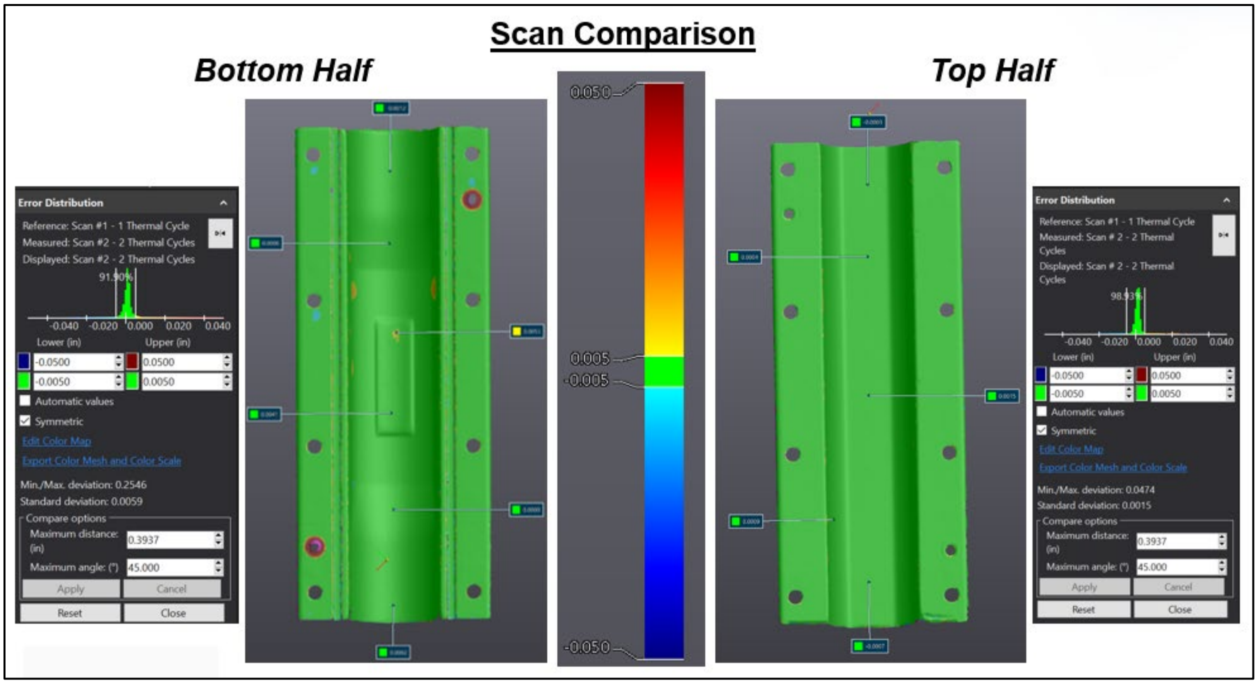


Figure 17. Demo Tube Form Mold Coated with TruDesign Epoxy Sealer

After both halves of the toolset were sealed, a dimensional scan comparison was completed on each mold half. The team felt confident, after the dimensional scan study was completed over 50+ thermal cycles on the larger bird bath tool, that this tool geometry should maintain dimensional stability over many thermal cycles. Only one-dimensional scan comparison was completed on both mold halves. This scan comparison was conducted on each half of the toolset after it was exposed to two initial thermal cycles. The first thermal cycle was completed after the tool was machined. The tool was ramped up to 392°F (200°C) and then cooled back down immediately upon hitting that set point temperature. The Tg of 20% carbon-filled Ultem (PEI) is approximately 423°F (217°C), so the first thermal cycle acted as an annealing stage for the toolset to allow for thermal relaxation. An initial scan was then completed after the first thermal cycle and considered the reference scan for this toolset. A second scan was then completed on the toolset after both halves were sealed and cured at 250°F for an hour.

As expected, both tool halves experienced no concerning movement. The best-fit scan comparison showed each mold half remained dimensionally stable as 91.9% of the bottom half and 98.9% of the top half remained within +/-0.005” from one thermal cycle to the next as shown in **Figure 18**. The heat map shows both halves of the tool to be predominantly all green which is a direct indicator of dimensional stability.



Error Distribution

Reference: Scan #1 - 1 Thermal Cycle
Measured: Scan #2 - 2 Thermal Cycles
Displayed: Scan #2 - 2 Thermal Cycles

Lower (in)	Upper (in)
-0.0500	0.0500
-0.0050	0.0050

☐ Automatic values
☑ Symmetric

Min./Max. deviation: 0.2546
Standard deviation: 0.0059

Compare options
Maximum distance: (in) 0.3937
Maximum angle: (°) 45.000

Error Distribution

Reference: Scan #1 - 1 Thermal Cycle
Measured: Scan # 2 - 2 Thermal Cycles
Displayed: Scan # 2 - 2 Thermal Cycles

Lower (in)	Upper (in)
-0.0500	0.0500
-0.0050	0.0050

☐ Automatic values
☑ Symmetric

Min./Max. deviation: 0.0474
Standard deviation: 0.0015

Compare options
Maximum distance: (in) 0.3937
Maximum angle: (°) 45.000

Figure 18. Demo Tube Form Mold Best-Fit Scan Comparison

Following the dimensional scan comparison, the toolset was delivered to SpinTech for the Smart Tool manufacturing process. SpinTech again used VARTM to manufacture the Smart Tool part as they did with the bird bath tool. The same cure part cure cycle of 365°F for 16 hours was used for fabrication of the Smart Tool. The Smart Tool was successfully fabricated and demolded off the toolset as shown in **Figure 19**.

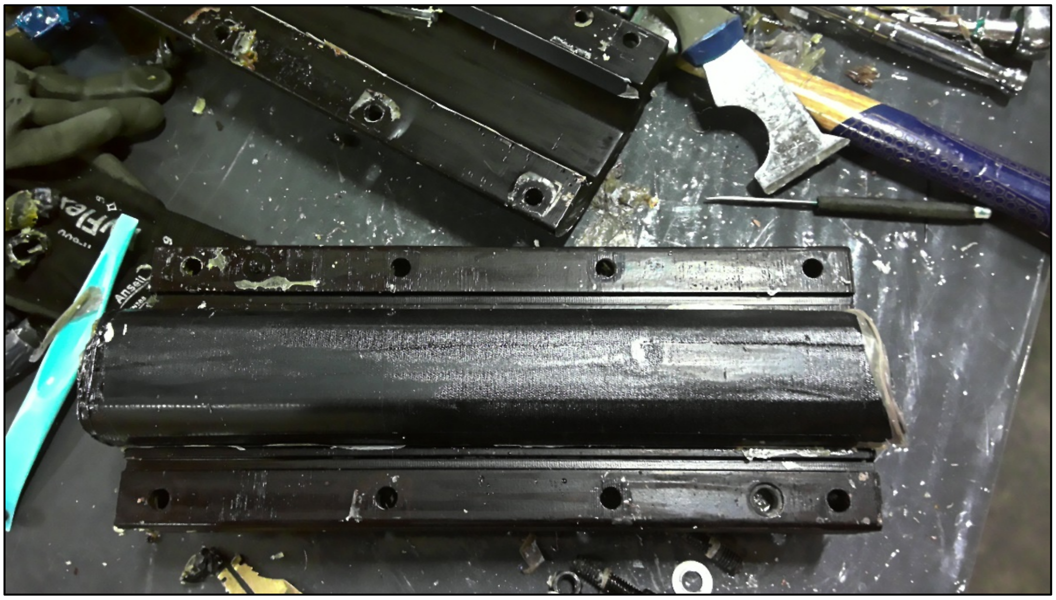


Figure 19. Demo Tube Form Mold Part Demold

The Smart Tool produced from the demo tube form mold reinforced the concept that tubular-shaped part geometry, with variable diameter features, could be successfully fabricated with use of AM tooling as shown in **Figure 20**. The Smart Tool part was visually inspected following the demolding process. The part appeared to be a little dry on the outside surface and possessed noticeable mark-off that had transferred from the contoured surface finish present on each mold half. The inner cavity surface of the tubular-shaped part had mark-off visually present from the consumables and vacuum bag that were consolidated to it during the cure. SpinTech determined what cosmetic mark-off was acceptable for the final Smart Tool. If they deemed certain mark-off unacceptable, either sanding or adhesive fillers were to be used as repair methodologies.

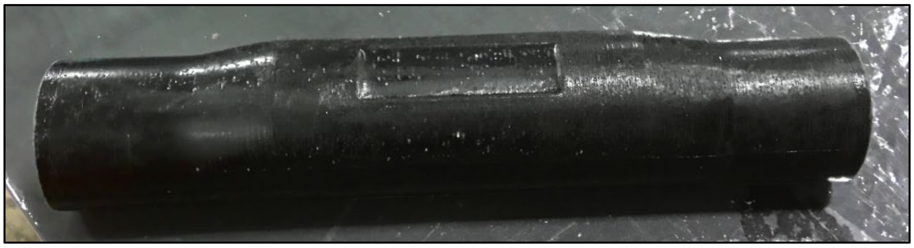


Figure 20. Smart Tool Produced from Demo Tube Form Mold

Inspection of the demo tube mold after use, shown in **Figure 21**, indicated the top mold half experienced shearing or cracking around several of the bolt holes. The cracks were most likely bead layer delaminations that were formed during the part cure. Selective reinforcement would be needed to prevent delaminations from occurring on future two-piece clamshell molds that are bolted together. It was also acknowledged that these delaminated bolt hole areas are what led to resin easily penetrating through the O-rings. These failures prevented the ability for the form mold to be used for a second reforming step.

In conclusion, it was determined that this mold was a viable option for fabricating a useable Smart Tool but would need modifications implemented into its structural design during print, specifically the surrounding areas of the bolt holes which experienced delaminations. For the mold to be cost effective it should be serviceable for several more forming and part manufacturing cycles than just the single cycle it experienced.

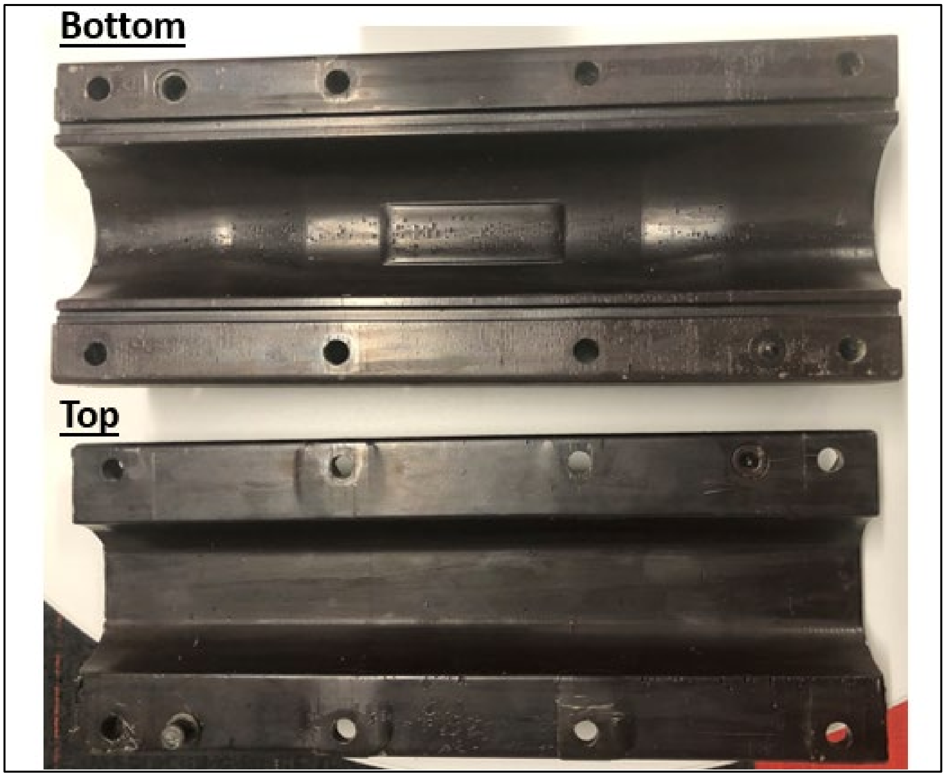


Figure 21. Demo Tube Form Mold after Part Cure

Demo Tube Cure Mold (RTM)

The original SpinTech demo tube cure mold, also referred to as their bond tool, was designed for manufacturing the tubular-shaped part that is representative of aircraft duct geometry. This tool was design to be used for resin transfer molding (RTM). The Smart Tool produced from the demo tube form mold was then to be used in tandem with the cure mold.

The demo tube cure mold CAD file was provided by Spintech and several modifications were made to allow for RTM to be possible with the use of AM tooling. An aluminum coffin design was chosen by the team so different AM tools or inserts could be amortized with the same aluminum mold halves, acting as a hybrid tool, as shown in **Figure 22**. The coffin strongback approach would provide the structural integrity needed for the AM inserts when being infused with moderate pressure levels during the RTM process. A stress analysis was completed by UDRI to confirm stresses occurring in the axial, circumferential, and radial directions on the inner cavity of the AM inserts were not going to fracture the polymer.

The additive inserts were designed to be geometrically constrained onto the cure mold halves. Coefficient of thermal expansion (CTE) management was considered when dimensioning the bottom mating face for each AM insert. With knowledge of the thermal expansion coefficients for both the polymer and aluminum tooling, the necessary dimensional tolerance was added to allow for expansion when exposed to the cure temperature of 350°F.

The bottom AM insert was designed with an O-ring groove on each side of the top face. These O-rings were to be used as resin dams during the infusion process. A second O-ring groove was to be used on each end plate to create a seal for the internal pressure occurring during part infusion. Two vacuum ports, an inlet and outlet, were added to the outside corners of the bottom aluminum mold half. The two mold halves and end caps were designed to be bolted together. A vacuum tube bag and sealant tape would then be passed through the inside of the demo tube Smart caul (form mold) tooling and sealed to the cure tooling. This configuration would create a vacuum barrier around the Smart caul tool and create a pocket that is pressurized following the installation of the end caps. Four pry points were added onto the side of the cure mold for demolding. The final dimensions of the CAD assembly ended up being 13.5” x 9.7” x 9” as shown in **Figure 22**.

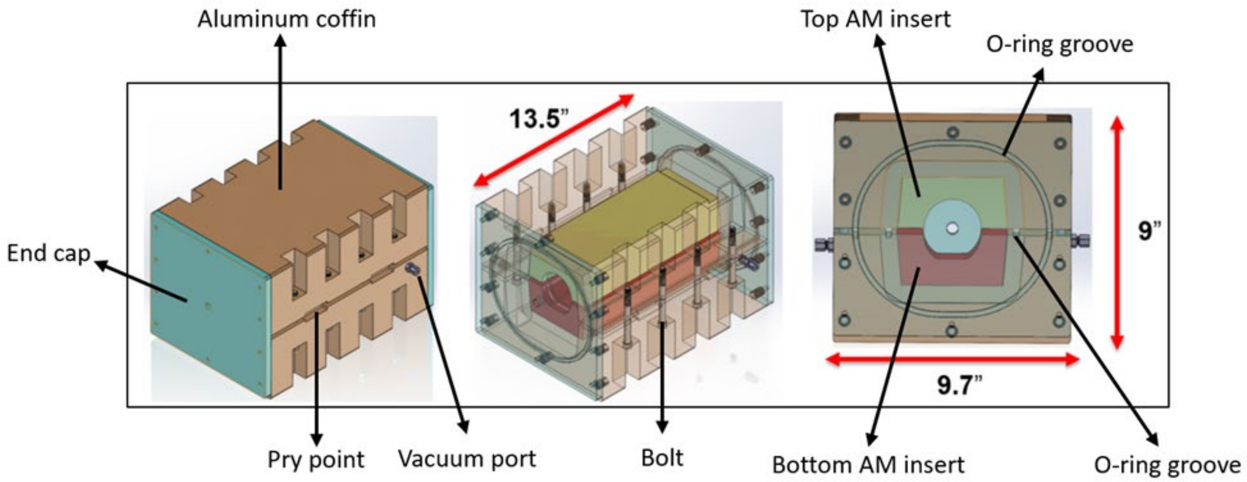


Figure 22. Demo Tube Cure Mold CAD Design

The team agreed to the final CAD design for the demo tube cure mold and then the coffin and AM inserts were fabricated. After machining, the bottom additive insert appeared to experience minor fiber tear out on the top surface. It appears that the surface defects resulted from internal porosity that was manufactured into the inserts during the additive process. When material was removed during machine finishing the internal porosity was exposed. EA 9394 epoxy adhesive was used to fill the areas with missing fibers from the porosity that was creating low spots. The AM inserts were then sealed with TruDesign HT Sealer and everything was assembled as shown in **Figure 23**.

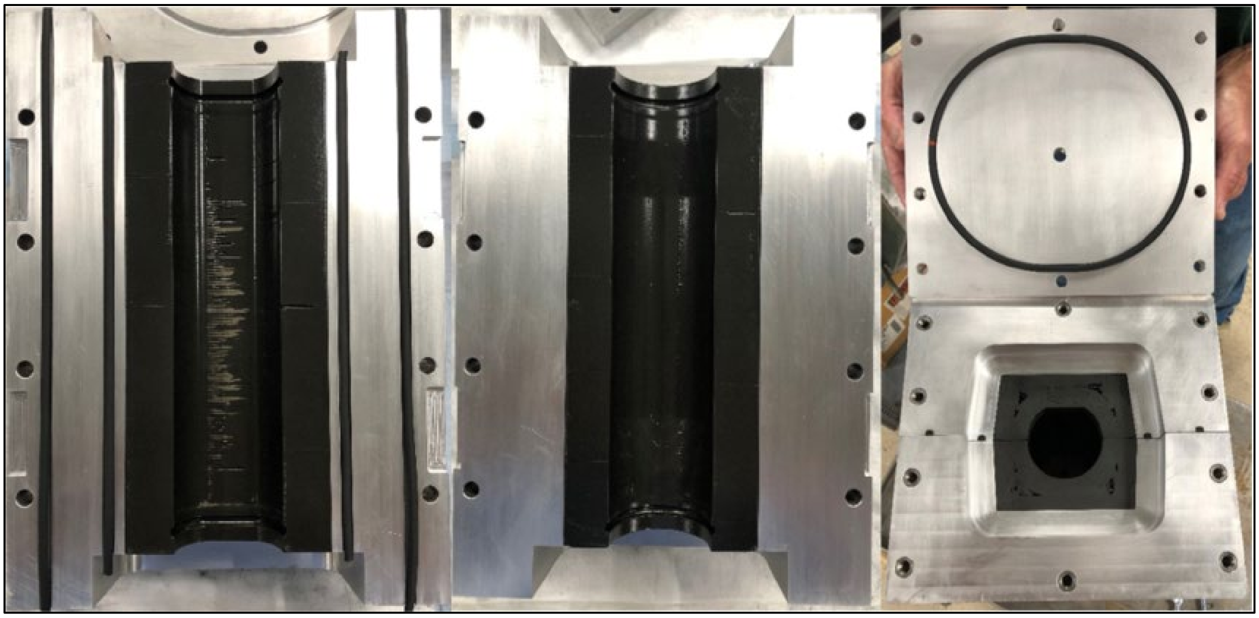


Figure 23. Demo Tube Cure Mold Final Assembly

The demo tube cure mold assembly was then delivered to SpinTech for part infusion. A good part quality was able to be produced, as shown in **Figure 24**, but some surface texturing transferred onto both the Smart Tool and the subsequent composite part from the surface porosity. The additive tool and coffin design worked and sealed without any processing issues. To try and minimize the impact of the surface finish and ensure composite part release, SpinTech coated the additive insert with Airtech Tooltec-CS5. If the bottom insert would have been smoother and possessed a more ideal surface finish, SpinTech had full confidence an even higher quality part could have been produced. SpinTech internally pressurized the cure mold to 60 psi during cure, but they felt confident that there would have been no issues at 100 psi as well.

Figure 24. Demo Tube Cure Mold Final Assembly

In order maximize the hybrid cure mold's usage, the team determined this mold would work best through amortization over several different part geometries by swapping out AM inserts while using the same aluminum coffin. The cost of making just one part geometry using the hybrid approach is more expensive than a CMC machined aluminum tool set and thus the AM approach would not provide an advantage. The benefits the hybrid cure mold could provide are a significant increase in throughput where someone could be simultaneously laying up the laminate or preform in the additive inserts while the aluminum coffin is heating up in an oven. The aluminum coffin could possibly never even have to cool down and the additive inserts could continuously be swapped out, demolded, and then new additive inserts rotated into the coffin. Multiple aluminum coffins could even be manufactured and used at once to significantly increase throughput even further.

Task 2: Complex Tool Demonstration

Having addressed tooling vacuum integrity, internal pressure capability, and thermal dimensional stability, the team turned to a more complex toolset design to be used for fabrication of a UAV wing trailing edge. The baseline toolset and application is shown in **Figures 25 and 26**. **Figure 25-left** shows the tool configuration used to reform three Smart Tool mandrels. The image on the right shows how the braid is applied to the three mandrels. The three internal elements are then over wrapped with an outer braid which is then positioned into an RTM tool shown in **Figure 26**. The finished aeroshell with mandrels removed is shown on the right hand side of **Figure 26**. The objective of this task was to determine if additive manufacturing could be applied to these tool sets while achieving a 50% cost savings.

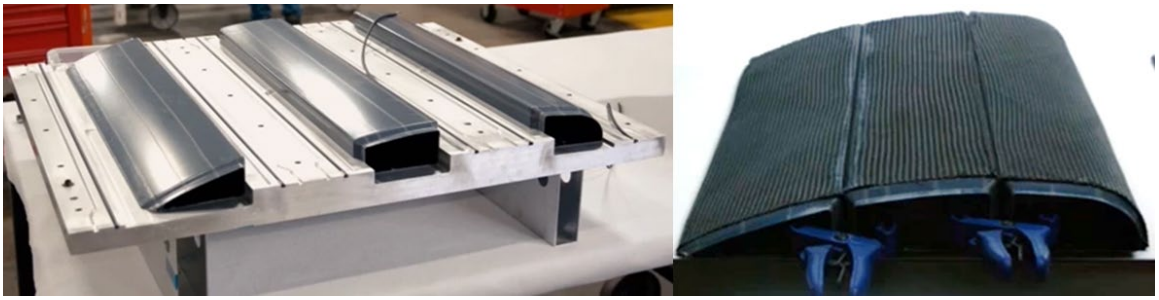


Figure 25. Trailing Edge Smart Tool Master Tool-set for Aeroshell Internal Structure

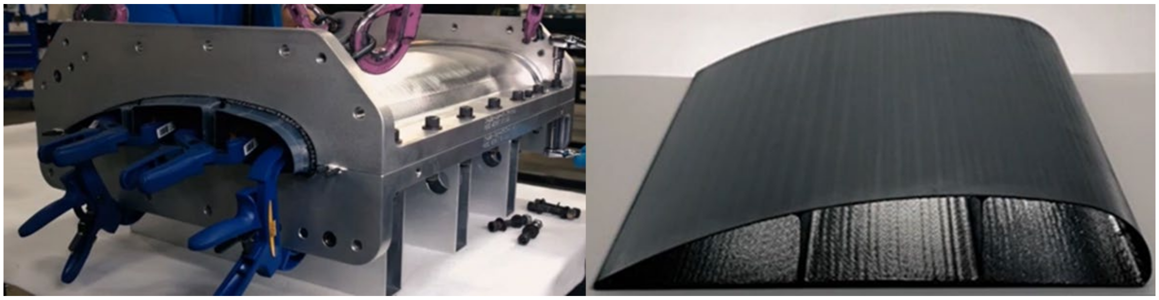


Figure 26. Trailing Edge Bond Toolset for Aeroshell Overwrap and Internal Structure Integration

Two, two-piece clamshell baseline tool CAD files were provided by SpinTech for evaluation. These files were named the "***trailing edge smart tool master***" and the "***trailing edge bond tool***". The tool files were modified in SOLIDWORKS with optimization of best printing practices garnered from Task 1 while considering the 50% cost savings that was sought to be achieved.

Due to the level of uncertainty regarding cost for an additive tool set to be produced at the larger dimensions that the trailing edge tool sets required, the team decided to complete all technical work and cost modeling as a paper study before any physical tools would be considered for additive manufacture. This approach allowed for a thorough cost evaluation of the additive tools versus the baseline tools.

Trailing Edge Smart Tool Master

UDRI received SpinTech's trailing edge smart tool master CAD file as shown in **Figure 27**. This original aluminum toolset was manufactured and used by SpinTech for an actual in-house demonstration. The baseline toolset was manufactured with M5 aluminum and was used by SpinTech as an RTM tool to manufacture their Smart cauls. The toolset possessed X-Y dimensions of 35.5" x 40.5".

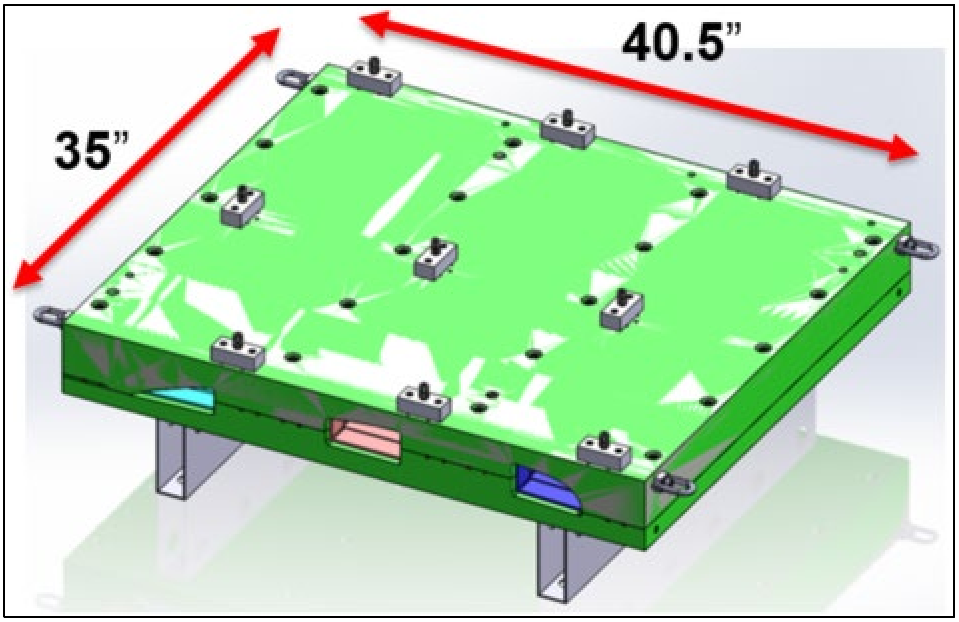


Figure 27. Original CAD File of SpinTech's Trailing Edge Smart Tool Master

The CAD file was modified in SOLIDWORKS to turn the original RTM tool into a tool that could be used as a VARTM tool where only vacuum pressure would be needed during the caul infusion process. The VARTM process was completed in the same manner as the demo tube form mold where a tube bag went down the three cavities and tied into an envelope bag. An oversized tool file for the additive print was developed along with a net shape file. Some new features were added onto the modified CAD file, such as bolt holes, O-ring grooves, pry points, and alignment pins as shown in **Figure 28**, but the modified tool's dimensions ultimately remained the same from the baseline tool file.

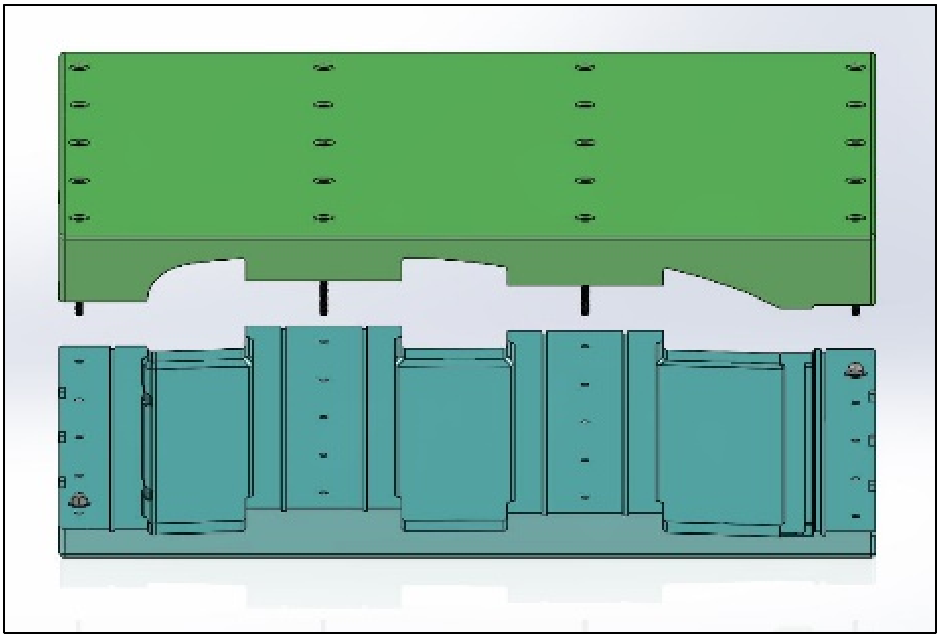


Figure 28. Modified CAD File of SpinTech's Trailing Edge Smart Tool Master

After the CAD file was modified, the team decided to also evaluate scaled tool files of 75%, 50%, and 25% of the full-size volume for the Smart tool master as shown in **Figure 29**. These files were developed for use in the Task 2 cost analysis section to compare how manufacturing costs of the baseline aluminum tool scaled in comparison with the costs of the additive tools.

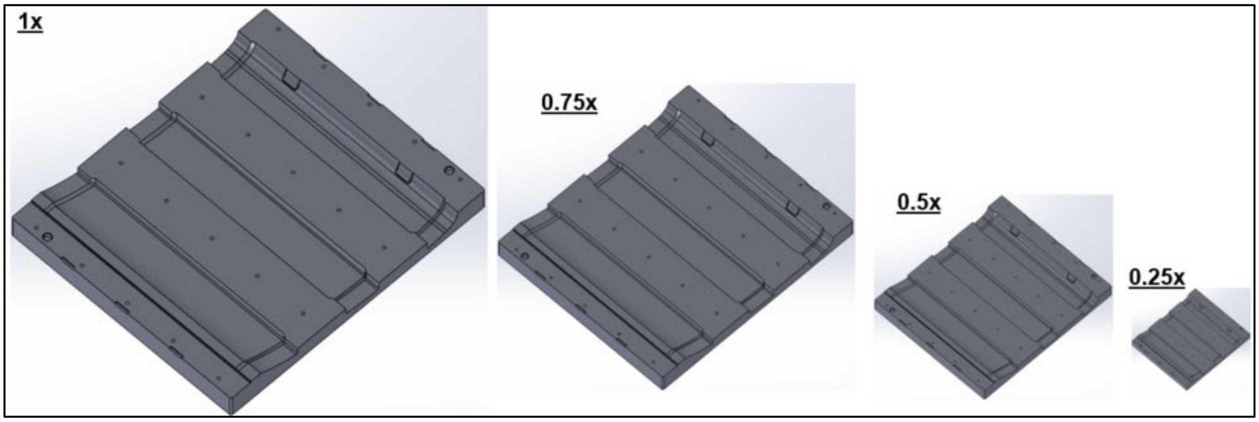


Figure 29. Trailing Edge Top Half Scaled CAD Files

Trailing Edge Bond Tool

The trailing edge bond tool CAD file was received from SpinTech. Their original tool was an aluminum RTM tool that possessed two clamshells and two end caps. That original tool was modified in SOLIDWORKS to be a two-piece clamshell tool that the final part would then be processed through VARTM in the same manner as the trailing edge smart tool master. **Figure 30** shows how the manufactured cauls (pink) from the trailing edge Smart tool master would then be used in the bond tool to manufacture the final trailing edge part (orange). The dimensions were relatively similar for each of the trailing edge tool sets, thus there was not much final cost variation expected between each tool file.

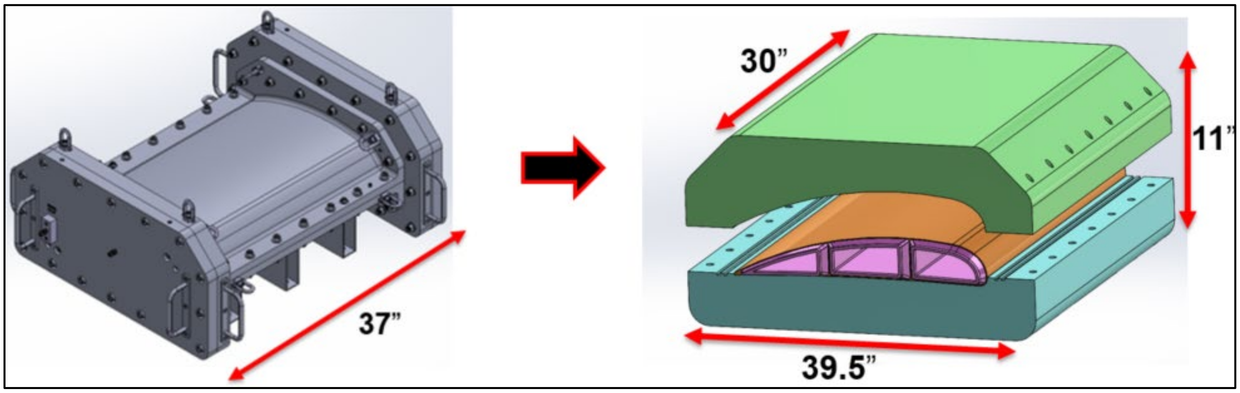


Figure 30. SpinTech's Trailing Edge Bond Tool CAD File Modified for AM

Task 3: Large Aero Fabrication Demonstration

Task 3 featured the use of AM tooling on another aerospace relevant component, a wing skin, as the part of interest for this specific task. The value proposition for using AM tooling for this specific part geometry was to be demonstrated by showing that a 50% cost reduction from the aluminum baseline tooling cost could be achieved. Given time and cost constraints the team decided to complete all technical work and cost modeling as a paper study without fabricating a physical tool. This approach allowed for a thorough cost evaluation of the additive tools versus the baseline tools.

Wing Skin Tool

The wing skin tool used for the study had dimensions of 21" x 16" x 1.25" and is shown in **Figure 31**. This tool represents a lower wing skin only, the upper wing skin was expected to have similar design and cost considerations due to having a similar geometry. The tool baseline was a steel tool used for compression molding, while the new tool would be designed for processing in the RapidClave. The design and cost evaluation details for this tool are presented in section 6.

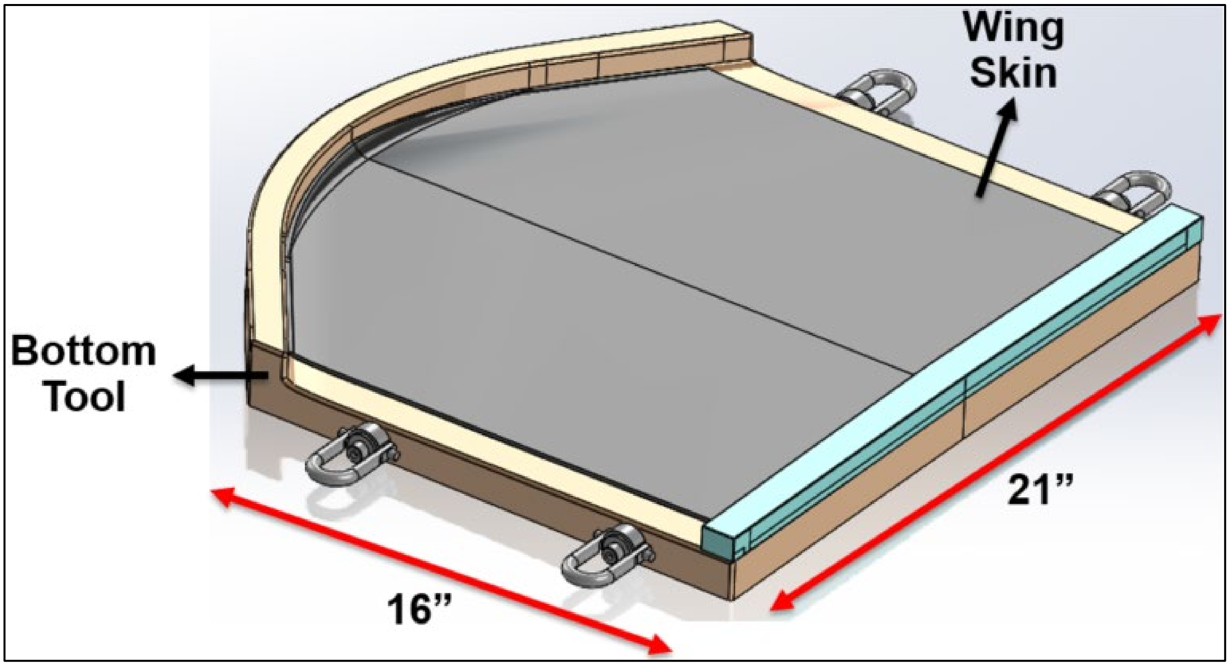


Figure 31. Bottom Wing Skin Tool

5. Cost Analysis/Benefits Assessment

Costs were tracked throughout the development of all additively manufactured tools. Pertinent costs were tracked during each task, such as labor or active time needed to complete a specific task, amount of time a machine was in use, and quantity of a specific material used. After compiling all costs needed for fabrication, a total price was able to be obtained and assigned to each AM tool. The cost of each AM tool was then compared against its metallic baseline tool that was produced using conventional manufacturing processes to see if a 50% cost reduction was able to be achieved.

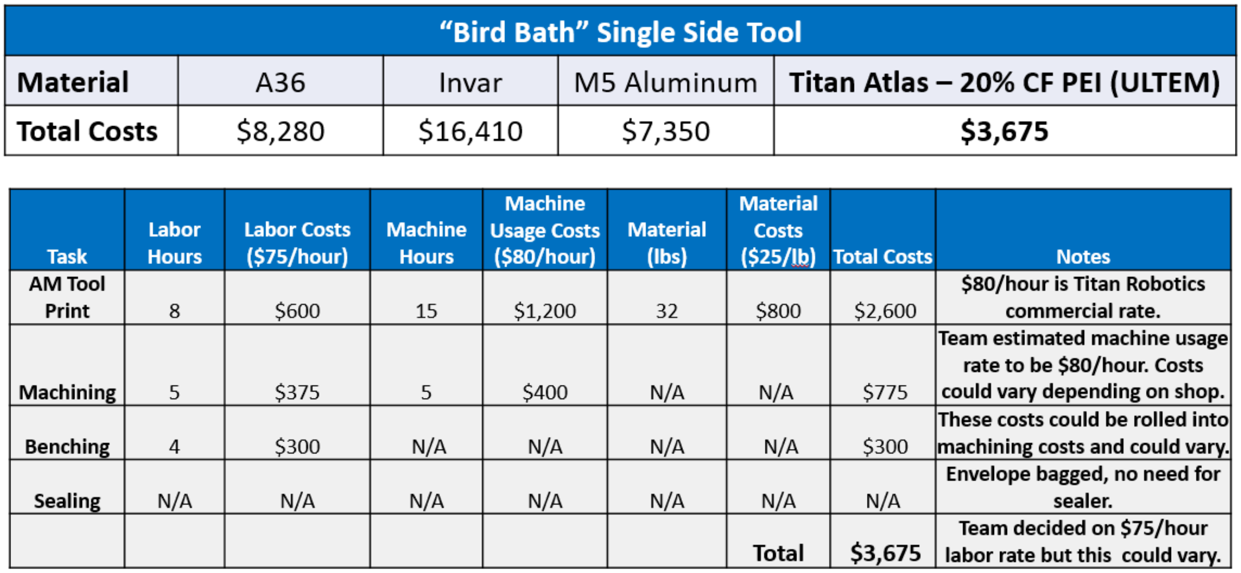
Cost summary tables were established for each tool to track total costs. Each task performed during the manufacturing process was timed from start to finish to determine how many labor or machine hours were needed. The team decided to use a baseline rate of $75/hour for a technician to perform the specific task at hand. An $80/hour rate was quoted from Titan Robotics as their standard commercial rate for 3D printing. Other tasks that were completed after machining to finish the tool properly were tracked and the costs were recorded. A total cost for each tool was then able to be determined and compared against the baseline.

Task 1 – Bird Bath Tool Cost Model

Costs were tracked at each step of the bird bath tool's development to determine if a 50% cost reduction could be achieved with use of additively manufactured tooling as compared to conventional processes. Baseline metallic tools were provided by SpinTech. These tooling costs were compared with the AM bird bath total tool costs.

After compiling all the costs to produce the final usable tool for Smart Tool manufacturing, a total tool cost was determined to be roughly $3,675, as detailed in **Figure 32**. This tool cost was able to achieve a 50% or more cost reduction in comparison to all the baseline metallic tool costs. It was concluded that this specific tool geometry allowed the use of AM tooling to be a viable solution to achieve significant cost savings while providing comparable performance of conventional processes that are needed for the tool to last for 50-part cycles. AM tooling proved to be a feasible option for this part geometry due to its ability to be envelope bagged to maintain vacuum integrity, an ability to maintain dimensional stability over 50+ thermal cycles and achieve significant cost savings of over 50%.

While AM offered beneficial aspects, such as in-house fabrication and light weight; with this specific tool geometry, the major drawback present was that an airtight seal could not be achieved unless an envelope bag was used. This could create potential issues during the liquid molding process if a release barrier or sealer is not present on the top surface of the tool as resin could be lost into the thickness of the tool.



"Bird Bath" Single Side Tool				
Material	A36	Invar	M5 Aluminum	**Titan Atlas – 20% CF PEI (ULTEM)**
Total Costs	$8,280	$16,410	$7,350	**$3,675**

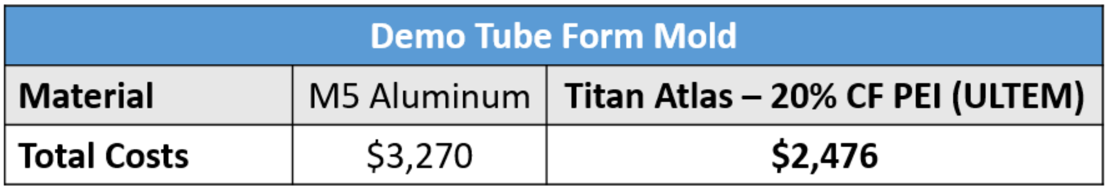
Task	Labor Hours	Labor Costs ($75/hour)	Machine Hours	Machine Usage Costs ($80/hour)	Material (lbs)	Material Costs ($25/lb)	Total Costs	Notes
AM Tool Print	8	$600	15	$1,200	32	$800	$2,600	**$80/hour is Titan Robotics commercial rate.**
Machining	5	$375	5	$400	N/A	N/A	$775	**Team estimated machine usage rate to be $80/hour. Costs could vary depending on shop.**
Benching	4	$300	N/A	N/A	N/A	N/A	$300	**These costs could be rolled into machining costs and could vary.**
Sealing	N/A	N/A	N/A	N/A	N/A	N/A	N/A	**Envelope bagged, no need for sealer.**
						Total	**$3,675**	**Team decided on $75/hour labor rate but this could vary.**

Figure 32. Bird Bath Tool AM Cost Model

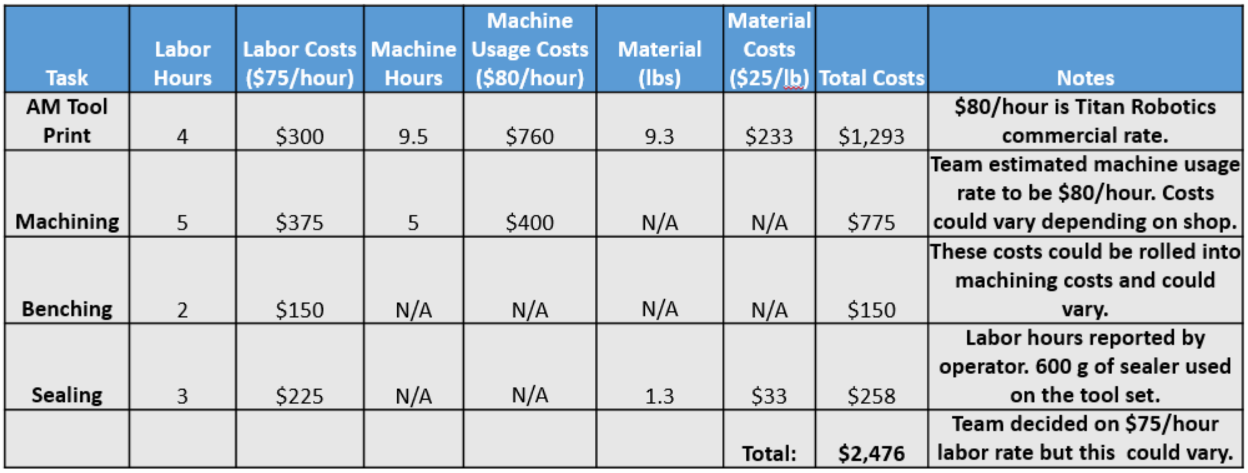
Task 2 – Demo Tube Form Mold

Costs were tracked at each step of the demo tube form mold's development to determine if a 50% cost reduction could be achieved with use of additively manufactured tooling as compared to conventional processes. Prototyping tools used by SpinTech, such as the demo tube form mold, are manufactured with use of M5 aluminum. The total costs for each step of the development of the AM demo tube form mold were tracked for formulation of a cost comparison model of high fidelity versus the baseline M5 aluminum tool.

After totaling up all the costs during the development of the AM tool, it was determined that the final price tag was $2,476, as detailed in **Figure 33**. A target cost savings of 50% was not able to be reached. Nevertheless, a significant cost savings of around 25% of the baseline metallic tool cost was achieved. More research is needed to determine if this AM tool set could also provide matched tool performance of the baseline metallic tool over 50-part thermal cycles. Early indicators show that with minor printing and machining improvements, AM tooling could be feasible option for production of the demo tube form based on its part geometry, ability to maintain dimensional stability, and significant cost savings.



Demo Tube Form Mold		
Material	M5 Aluminum	**Titan Atlas – 20% CF PEI (ULTEM)**
Total Costs	$3,270	**$2,476**



Task	Labor Hours	Labor Costs ($75/hour)	Machine Hours	Machine Usage Costs ($80/hour)	Material (lbs)	Material Costs ($25/lb)	Total Costs	Notes
AM Tool Print	4	$300	9.5	$760	9.3	$233	$1,293	**$80/hour is Titan Robotics commercial rate.**
Machining	5	$375	5	$400	N/A	N/A	$775	**Team estimated machine usage rate to be $80/hour. Costs could vary depending on shop.**
Benching	2	$150	N/A	N/A	N/A	N/A	$150	**These costs could be rolled into machining costs and could vary.**
Sealing	3	$225	N/A	N/A	1.3	$33	$258	**Labor hours reported by operator. 600 g of sealer used on the tool set.**
						Total:	**$2,476**	**Team decided on $75/hour labor rate but this could vary.**

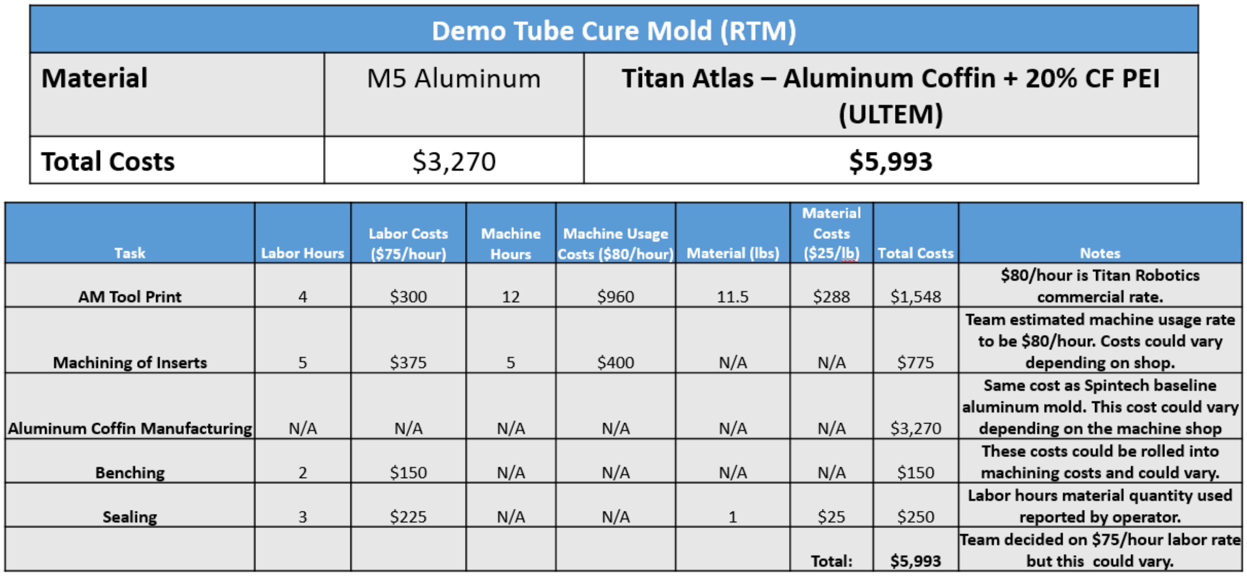
Figure 33. Demo Tube Form AM Mold Cost Model

Demo Tube Cure Mold (RTM)

The costs of each task completed during the fabrication process of the demo tube cure mold was tracked to determine if a 50% cost reduction could be achieved with use of AM tooling as compared to conventional processes. M5 aluminum was the metallic tooling material used by SpinTech for their in-house cure mold design. The cost of that tool set was considered the baseline tool cost and was to be compared against the AM tooling costs. The price for SpinTech's aluminum cure mold was the same as the demo tube form mold, priced at $3,270.

The original cure mold was designed as a matched metal tool for resin transfer molding (RTM). To incorporate the use of AM tooling into this cure mold design, the team decided to use an aluminum coffin that possess internal cavities to hold top and bottom AM inserts. The aluminum coffin was a four-piece mold that included two end caps and two clamshells. While the cost of this aluminum coffin could vary depending on the machine shop, for this cost study the price of the coffin was set equal to the baseline aluminum tool cost provided by SpinTech.

After totaling up all the costs during the development of the demo tube cure mold, it was determined that the final price for the tool set including the AM inserts for one part geometry was roughly $5,993 as detailed in **Figure 34**.



Demo Tube Cure Mold (RTM)		
Material	M5 Aluminum	**Titan Atlas – Aluminum Coffin + 20% CF PEI (ULTEM)**
Total Costs	$3,270	**$5,993**

Task	Labor Hours	Labor Costs ($75/hour)	Machine Hours	Machine Usage Costs ($80/hour)	Material (lbs)	Material Costs ($25/lb)	Total Costs	Notes
AM Tool Print	4	$300	12	$960	11.5	$288	$1,548	$80/hour is Titan Robotics commercial rate.
Machining of Inserts	5	$375	5	$400	N/A	N/A	$775	Team estimated machine usage rate to be $80/hour. Costs could vary depending on shop.
Aluminum Coffin Manufacturing	N/A	N/A	N/A	N/A	N/A	N/A	$3,270	Same cost as Spintech baseline aluminum mold. This cost could vary depending on the machine shop
Benching	2	$150	N/A	N/A	N/A	N/A	$150	These costs could be rolled into machining costs and could vary.
Sealing	3	$225	N/A	N/A	1	$25	$250	Labor hours material quantity used reported by operator.
						Total:	$5,993	Team decided on $75/hour labor rate but this could vary.

Figure 34. Demo Tube Cure AM Mold Cost Model

The project's primary cost savings target of a 50% reduction as compared to the baseline was not able to be reached for a singular part geometry. In order achieve max tooling cost savings, the team decided to complete a cost study to show the demo tube cure mold would work best by amortizing over several different parts through the swapping out AM inserts and using the same aluminum coffin. To model this, the manufacturing costs of the AM inserts were totaled individually. After printing, machining, and benching costs the AM inserts end up costing roughly $2,473. For SpinTech, a new aluminum tool would have to be made each time for a new part geometry. Staying in the realm of the same part geometry and for the purpose of this study, the estimated cost of a new aluminum mold each time for relatively similar part geometry of the demo tube would be $3,270, the same price as SpinTech's baseline tool cost.

It was found that after using the hybrid AM tool, also known as the demo tube cure mold, that the costs were comparable after using about 4-to-5-part geometries, as detailed in **Figure 35**. To achieve a 25% costs savings, about 25 different part geometries would have to be manufactured and used with the hybrid tool. With use of the cost model numbers from **Figure 34**, achieving a 50% cost savings would require hundreds of different part geometries. To feasibly achieve a 50% cost savings with use of the hybrid AM tool, the clamshell halves could be thinned out and the overall volume reduced. The additive inserts could also be thinned out in the same manner and even be printed with use of a larger nozzle, such as a 4mm nozzle instead of a 2mm nozzle to reduce the total print time and cost. The team felt confident that with a few of these design modifications implemented into the hybrid AM tool that a significant cost savings could be more quickly achieved with less part geometries needed. Until these design modifications are made and prove that they are a tenable solution, the associated risk far outweighs the reward of routinely using the hybrid AM tool versus the aluminum tooling approach.

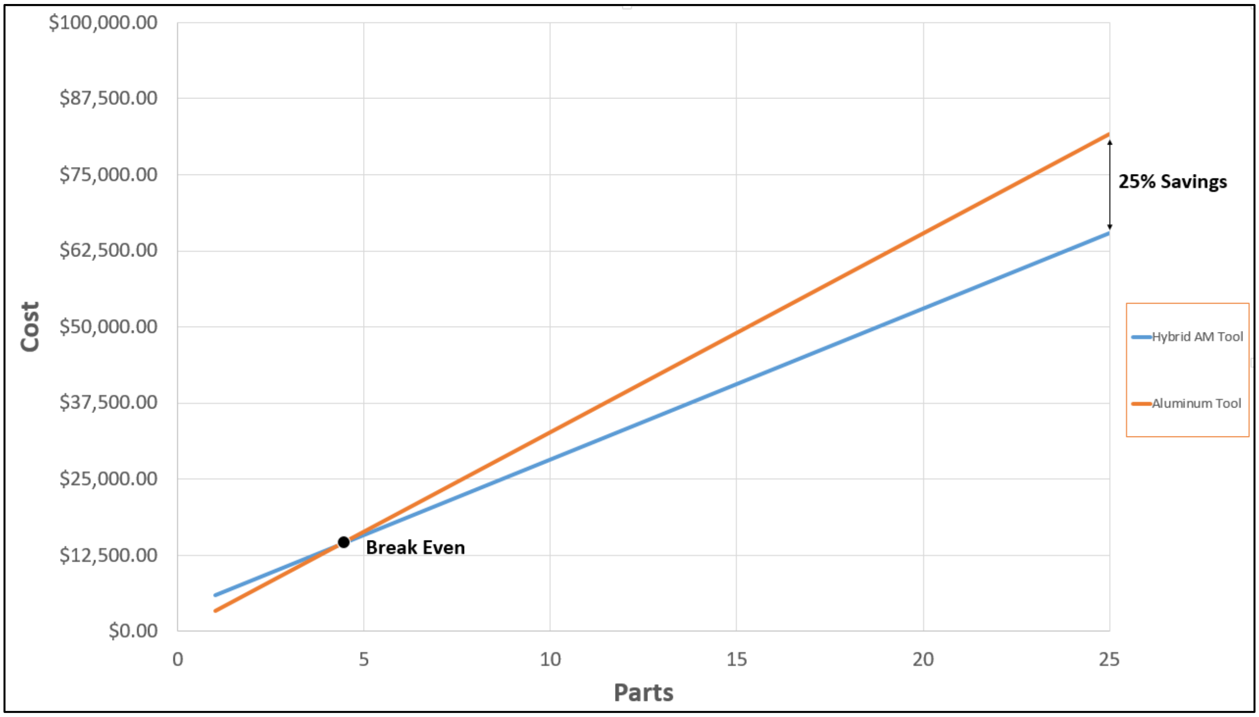


Figure 35. Demo Tube Cure Mold Cost Projection

Trailing Edge Smart Tool Master and Bond Tool

SpinTech's total manufactured tool cost for their aluminum trailing edge smart tool master was determined to be $14,200 while their bond tool was priced at $16,600. Due to the similar geometry of both trailing edge tool sets, the team decided to use the trailing edge smart tool master as the main toolset of interest for the cost analysis. Dramco Tool Co. partnered with UDRI for this cost study and quoted all CAD files for this specific toolset. Quotes were received for the manufacturing costs of the full-size top half tool along with the other scaled down versions as shown in **Figure 29**. These prices shown in **Table 4** reflected a billet of aluminum being machined into the final net geometry of the top half smart master tool. Dramco Tool Co. acknowledged that the total machining costs would be the same for both the top and bottom half for the smart tool master, hence double the price of one half for the total toolset cost.

Table 4. Manufacturing Costs for Trailing Edge Smart Tool Master

TE Smart Tool Master		
Material	**One Half**	**Total**
Spintech – Baseline	*N/A*	$14,200
Dramco – 1x	$7,900	$15,800
Dramco – 0.75x	$5,150	$10,300
Dramco – 0.5x	$3,200	$6,400
Dramco – 0.25x	$1,575	$3,150

To get representative commercial machining rate, Dramco Tool Co. also quoted the cost of machining the oversized additive tools to their final net shape as, **Figure 36**.

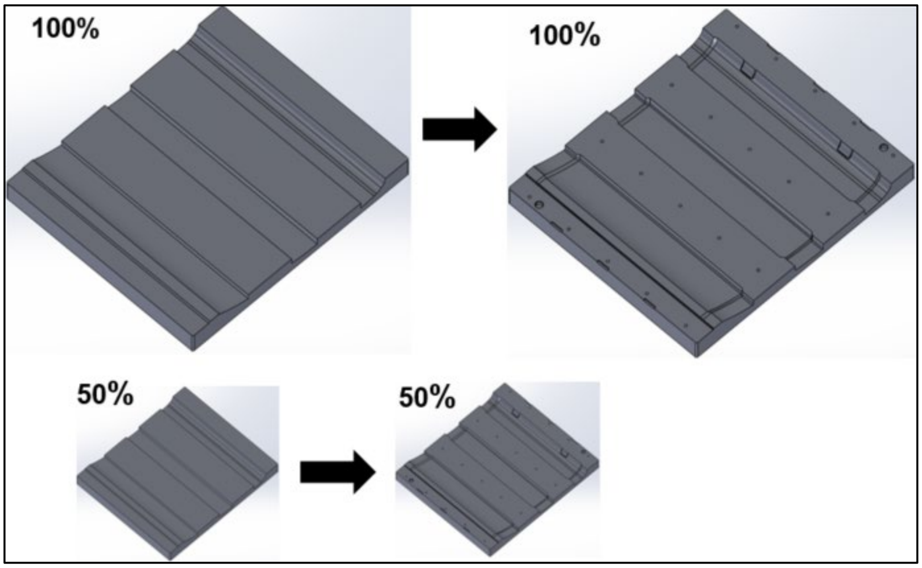
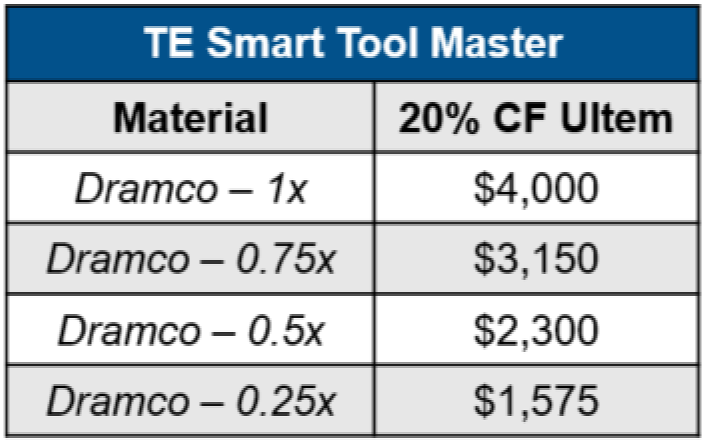


Figure 36. Oversized Tools Machined to Net Shape

The machining costs for the top half at the four different scaled sizes came back quoted as shown in **Table 5.** The scaled sizes were used to simulate different buy-to-fly ratios and to see how the associated machining costs scaled as the tool geometries decreased in size. The buy-to-fly ratio is the ratio of the mass of the starting billet of aluminum to the mass of the final, finished aluminum tool half.

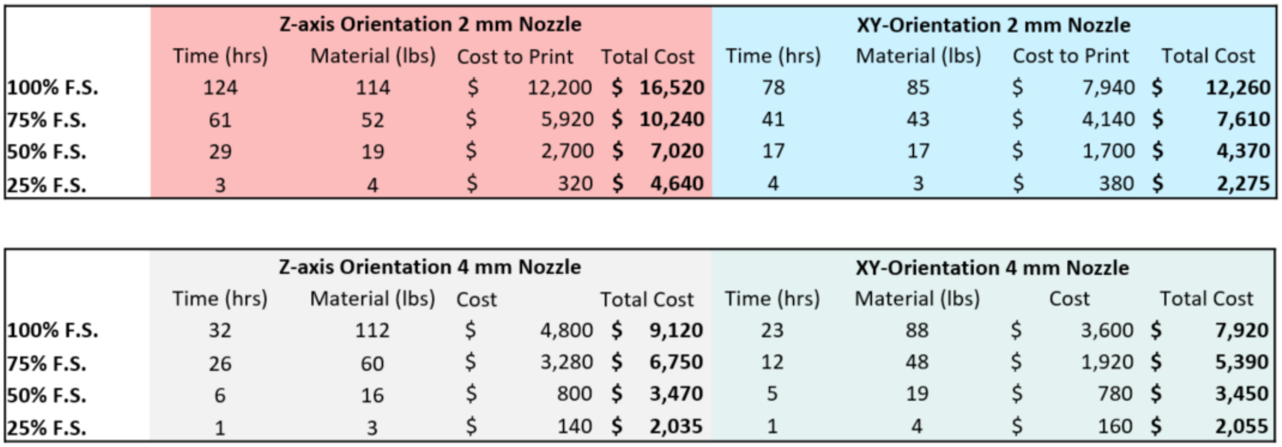
These costs provided rational representations of commercial machining rates with the given geometries of each tool. The total costs were able to be added to the total AM printing costs to get a final price for each scaled tool half.

Table 5. Machining Costs for Oversized 3D Printed Polymer Tools



TE Smart Tool Master	
Material	**20% CF Ultem**
Dramco – 1x	$4,000
Dramco – 0.75x	$3,150
Dramco – 0.5x	$2,300
Dramco – 0.25x	$1,575

With the known commercial printing rate that was provided by Titan Robotics LTD. and a commercial machining rate that was able to be obtained from Dramco Tool Co., a cost model was able to be constructed to reflect the different costs of the four different tool geometries. The cost model, as shown in **Figure 37**, included cost comparisons of 3D printing with both a 2mm and 4mm nozzle. The model also reflected if the tool was printed standing up (z-orientation) or flat (xy-orientation) on the printing bed. The total cost is the final price to both print and machine the top half of the trailing edge smart tool master. That total cost then can be doubled to determine the cost of the complete toolset.



	Z-axis Orientation 2 mm Nozzle				**XY-Orientation 2 mm Nozzle**			
	Time (hrs)	Material (lbs)	Cost to Print	Total Cost	Time (hrs)	Material (lbs)	Cost to Print	Total Cost
100% F.S.	124	114	$ 12,200	**$ 16,520**	78	85	$ 7,940	**$ 12,260**
75% F.S.	61	52	$ 5,920	**$ 10,240**	41	43	$ 4,140	**$ 7,610**
50% F.S.	29	19	$ 2,700	**$ 7,020**	17	17	$ 1,700	**$ 4,370**
25% F.S.	3	4	$ 320	**$ 4,640**	4	3	$ 380	**$ 2,275**

	Z-axis Orientation 4 mm Nozzle				**XY-Orientation 4 mm Nozzle**			
	Time (hrs)	Material (lbs)	Cost	Total Cost	Time (hrs)	Material (lbs)	Cost	Total Cost
100% F.S.	32	112	$ 4,800	**$ 9,120**	23	88	$ 3,600	**$ 7,920**
75% F.S.	26	60	$ 3,280	**$ 6,750**	12	48	$ 1,920	**$ 5,390**
50% F.S.	6	16	$ 800	**$ 3,470**	5	19	$ 780	**$ 3,450**
25% F.S.	1	3	$ 140	**$ 2,035**	1	4	$ 160	**$ 2,055**

Figure 37. Titan Atlas 3D Printing Costs for Trailing Edge Smart Tool Master

After the total cost was able to be determined for each of the scaled polymer top half tools, they were compared with the top half aluminum tool costs, **Table 6**.

Table 6. Cost of Manufacturing Aluminum Top Tool Half vs. Polymer Top Tool Half

	Aluminum	Z-Axis 2mm	XY-Axis 2mm	Z-Axis 4mm	XY-Axis 4mm
100% F.S.	$ 7,900.00	$ 16,520	$ 12,260	$ 9,120	$ 7,920
75% F.S.	$ 5,150.00	$ 10,240	$ 7,610	$ 6,750	$ 5,390
50% F.S.	$ 3,200.00	$ 7,020	$ 4,370	$ 3,470	$ 3,450
25% F.S.	$ 1,850.00	$ 4,640	$ 2,275	$ 2,035	$ 2,055

The costs were graphed and analyzed to show that the full-size trailing edge smart tool master would not make a good fit for AM, no matter the orientation or nozzle used for print. When scaled down to 25% volume of the original tool geometry, the total tool cost is similar as compared to the aluminum tool cost as shown below in **Figure 38**, but still unable to achieve the milestone of a 50% cost reduction.

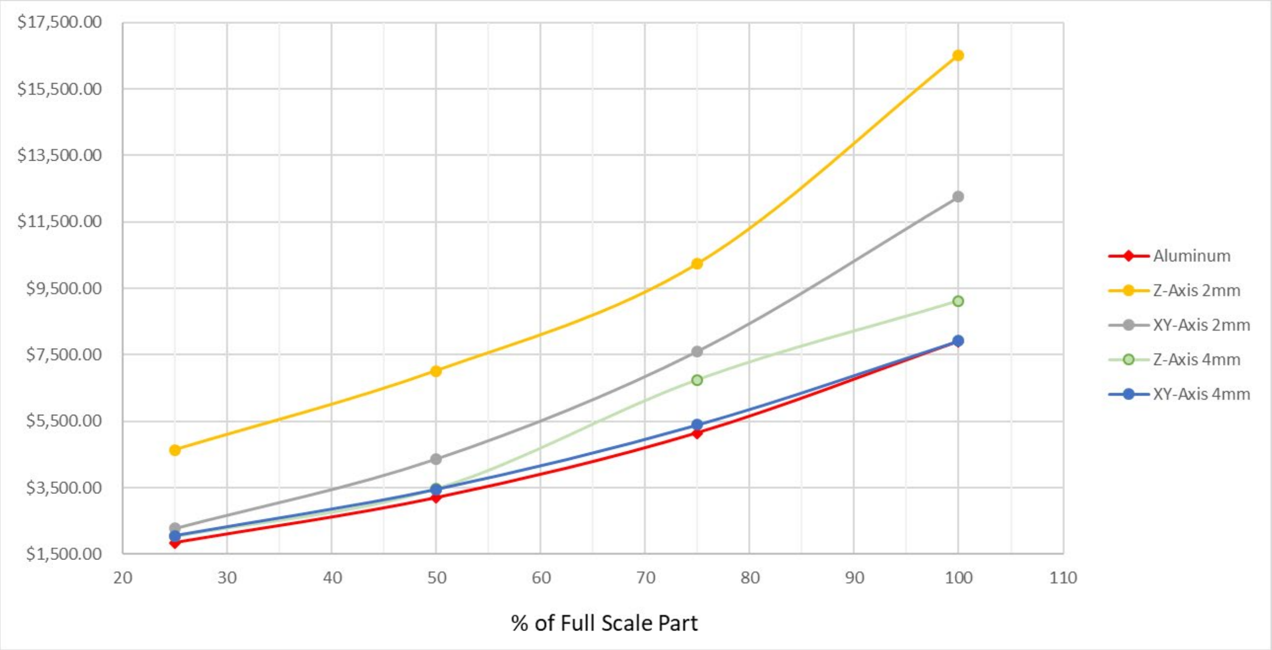


Figure 38. Graph Cost Comparison of Aluminum Top Half Tool vs. Polymer Top Half Tool

The team was able to determine from this cost study that aluminum is the cheaper and best long-term option for the original tool geometry of each trailing edge toolset. Cost was able to become more comparable when the part geometry is smaller, and a larger 3D printing nozzle is used. Printing parts flat (xy-orientation) on the Titan Atlas also is the favorable approach for reducing print time and total costs. The cost analysis showed that the use of AM is not viable for the trailing edge tool geometry, but may be applicable for other geometries, as shown earlier with the bird bath tool.

Costing was not necessarily an advantageous approach for this tool geometry because compiling costs with use of variables such as larger nozzle diameters or different print orientations that were not actually tested during the study could lead to unpredictable circumstances occurring during the tool print, directly impacting tool quality and total costs. Until these different variables demonstrate they can be used effectively on the Titan Atlas, the total costs modeled for this specific tool geometry should be used as nothing more than a rough projection.

Wing Skin Tool

Another paper cost study was completed for this milestone to explore the value proposition for use of AM versus metallic tooling. The wing skin tool was quoted by Dramco Tool Co. as both a steel compression tool and an aluminum layup tool. The manufacturing cost of the steel compression tool was quoted with use of H13 tool steel and came back with an estimated lead time of 12 weeks and a total cost of $42,500. The manufacturing cost of the layup tool was quoted with use of M5 aluminum and came back with an estimated lead time of 6 weeks and a total cost of $6,400. The aluminum layup tool cost was set as the baseline cost to investigate if a 50% cost savings could be achieved with use of AM.

The wing skin tool was modeled to print in both the z-axis and xy-axis orientation on the Titan Atlas, **Figure 39**. These two orientations printed in the same manner as previously described in this study with the xy-orientation being the more feasibly approach for time and cost savings.

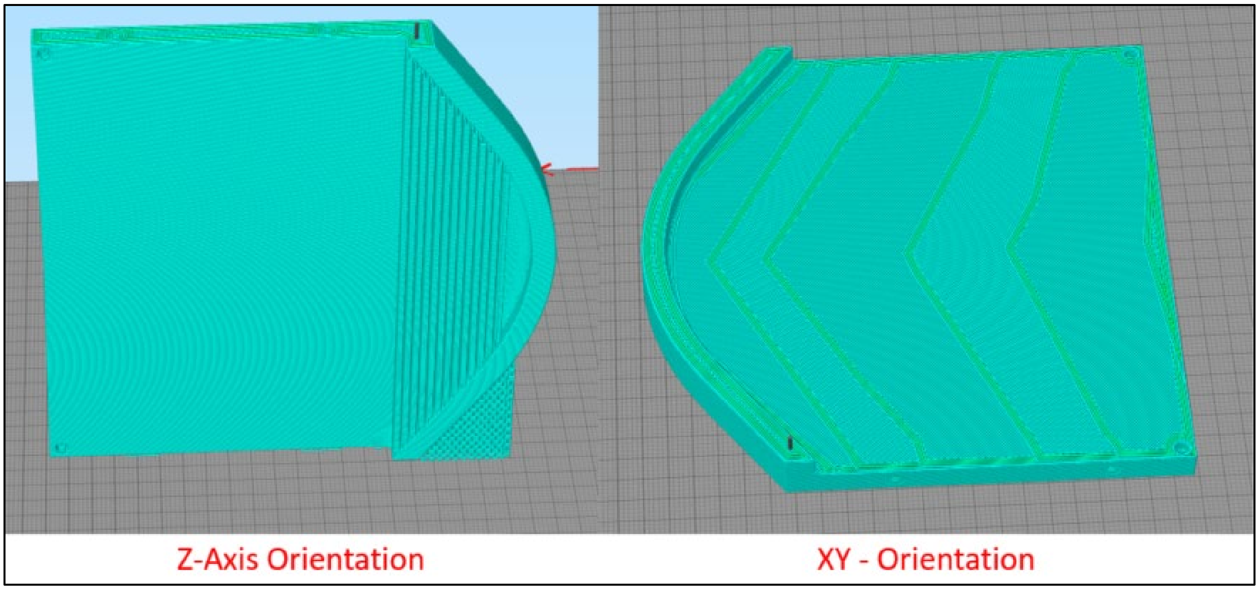
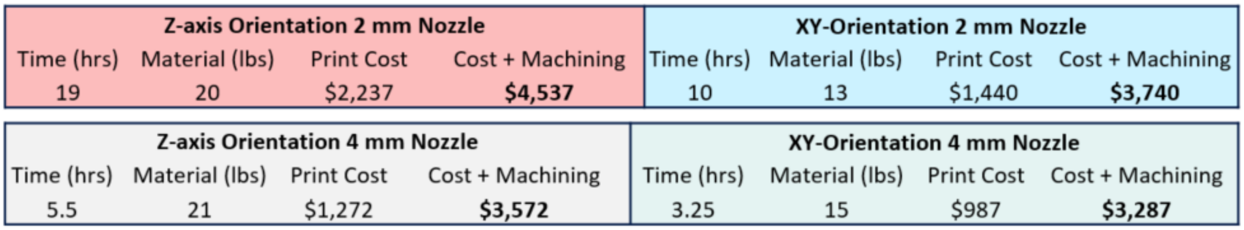


Figure 39. Wing Skin Tool Modeled for Print in Z and XY Orientations

Along with the different orientations, the tool was also quoted with use of both a 2mm and 4mm nozzle. The cost estimate completed by the team came back to reflect the data as shown in **Figure 40**. Again, the xy-orientation and use of 4mm nozzle ended up being the most cost-effective option. The xy-orientation along with the 4mm nozzle led to a 50% cost savings versus use of the M5 aluminum layup tool while only taking 3.25 hours to print. The other printing variations also proved to lead to roughly a 25-50% cost savings versus use of the M5 aluminum layup tool. While not as applicable as a layup tool, when compared to the steel compression tool cost, the AM approach led to an increase in savings by as much as a factor of 14. The team ultimately decided that the geometry of the wing skin tool seemed to be a good fit for using AM to decrease cost by as much as 50% and while decreasing the lead time by several weeks.



Z-axis Orientation 2 mm Nozzle				XY-Orientation 2 mm Nozzle			
Time (hrs)	Material (lbs)	Print Cost	Cost + Machining	Time (hrs)	Material (lbs)	Print Cost	Cost + Machining
19	20	$2,237	**$4,537**	10	13	$1,440	**$3,740**

Z-axis Orientation 4 mm Nozzle				XY-Orientation 4 mm Nozzle			
Time (hrs)	Material (lbs)	Print Cost	Cost + Machining	Time (hrs)	Material (lbs)	Print Cost	Cost + Machining
5.5	21	$1,272	**$3,572**	3.25	15	$987	**$3,287**

Figure 40. AM Wing Skin Tool Cost Estimates

6. Commercialization

Business partner SpinTech LLC was able to digest everything learned from the study and provide valuable insight to where they could or could not see a future for AM to be used for their in-house tooling operations.

During the study, all additive tools that were delivered to SpinTech required full envelope bagging and/or secondary assembly with a “coffin style mold” as a result of higher than acceptable porosity to achieve their vacuum integrity requirement. SpinTech’s tooling go/no-go criteria for resin infusion processes is unchanged at 0.2” Hg drop over a 30-minute period. While envelope bagging and coffin style tools proved to be functional during the study, they limited potential applications to either demonstrations or part families that have similar physical limits that fit within a single coffin style mold.

Despite machining after the additive manufacturing process, the additive tools still appeared to possess significant surface texturing that resulted in transfer for both the Smart Tool and subsequent composite parts. These surface defects resulted from internal porosity that is manufactured into the inserts during the additive process, which led to a surface finish that was not up to standard of SpinTech’s expected quality for their deliverable tooling.

Given the cost and quality of the demonstration additive tooling, SpinTech LLC determined that while additive manufacturing shows future potential for use it is not currently a value-added solution in comparison to their conventional metallic tooling. When the quality of the additive tooling has increased and the cost decreases where the additive tooling can meet the operational requirements for a lower price-point than the metallic baseline, SpinTech LLC will likely be able to find initial customers for deployment on low-volume applications, which showed the most promise during this study.

7. Accomplishments

A decision tree was developed in conclusion to this study for determining whether to choose AM or metallic tooling depending on the customer’s needs as shown in **Figure 41**.

An AM mold repeat use threshold was determined to be 50 or less part cycles as required by SpinTech LLC for their preforming and consolidation tooling. Anything above 50 parts needed was determined to be for higher volume manufacturing applications and would be best served to continue using conventional manufacturing approaches. If a mold was quickly needed, then AM provides the potential upside for short lead times. The volume of the tool then becomes the main driving factor for manufacturer to decide if AM provides a significant cost reduction versus metallic tooling. After cost modeling several different size toolsets during the study, the UDRI team determined that a small volume tool would be considered anything less than 50% of the Titan Atlas print envelope, and vice versa for anything larger. If the manufacturer determined that the mold needed was a smaller volume part, then the CAD would be optimized for print and sent to the Titan Atlas. At that moment, as a final check to make sure AM is the best approach from a value proposition standpoint, the cost of the CAD to be printed and machined to net geometry for delivery is quoted. If this price checks out as compared to conventional processes and with the customer, then the mold is printed and finished accordingly.

The bird bath tool discussed in this study was utilized as the ideal test case scenario for the decision tree. SpinTech identified that the tool would need to last for a total of 50-part cycles, which was identified through the thermal survey that was completed and would need to be manufactured quickly for immediate use. This tool geometry was less than 50% of the Titan print envelope, which was coined a small volume. After being optimized in SOLIDWORKS and cost modeled to ensure the AM process would be cost-effective compared to conventional manufacturing, the tool could then be printed and finished.

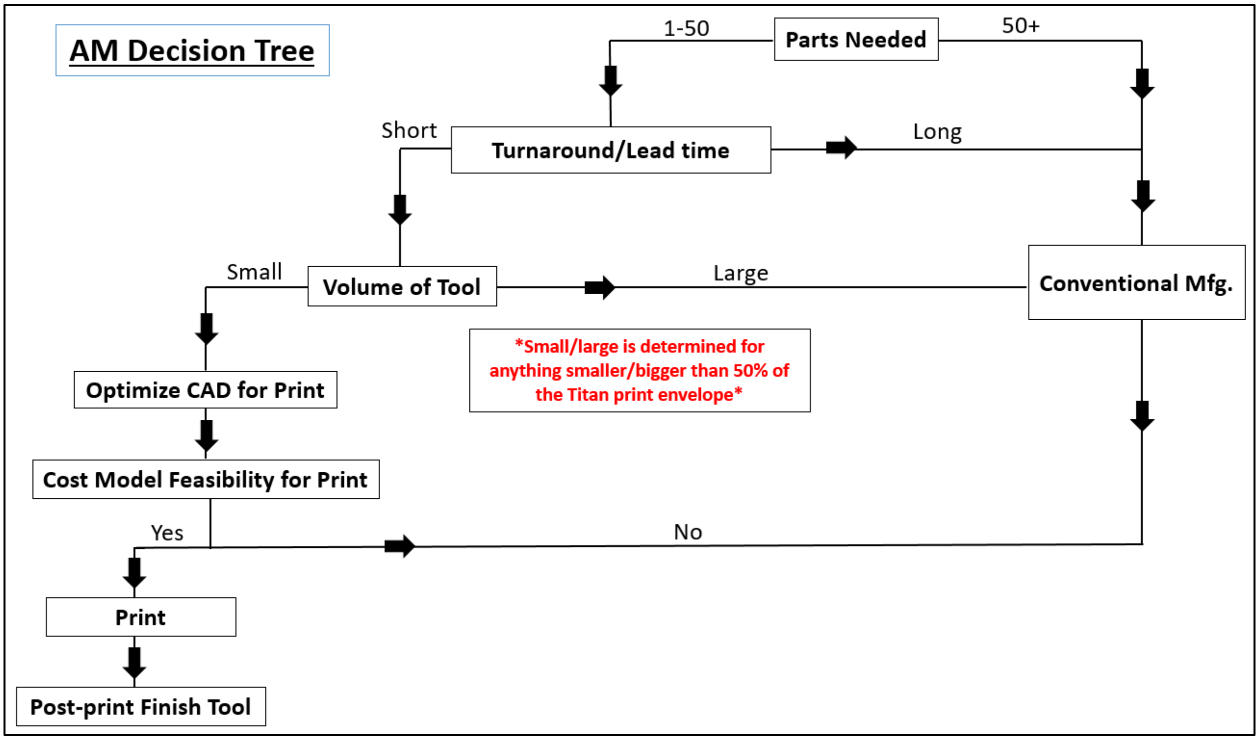


Figure 41. AM Decision Tree

8. Conclusions

AM tooling using a 20% carbon-filled PEI feedstock and the Titan Atlas FDM printer was able to be successfully used to produce toolsets for both preforming and consolidation while demonstrating a 50% cost reduction as compared to conventional processes. A general decision and design approach for AM tooling parameter and cost optimization was established and should serve as a guide for whether to choose AM versus using metallic tooling.

Preforming and consolidation tooling printed with 20% carbon-filled PEI feedstock was shown to be capable of key performance parameters to withstand more than 50 thermal cycles of 365°F (185°C) without significant tool movement while maintaining vacuum integrity necessary for stringent leak rate requirements. The toolsets printed during this study withstood temperatures and pressures that would be expected in or out of an autoclave, including SpinTech's liquid infusion processes.

Three different toolsets were manufactured for tool characteristic evaluation in this study. A one-piece airfoil shell (bird bath) or single-sided caul master, comprised of compound contours where male tooling would usually be trapped, was manufactured, and used to validate if AM tooling could meet SpinTech's performance requirements as expected of their conventional tooling approaches while also demonstrating more than a 50% cost savings. A two-piece clamshell caul master tool (demo tube form mold) and hybrid two-piece clamshell OML tool (demo tube cure mold) were both fabricated and used to show that AM preforming, and consolidation tooling could be used to manufacture a tubular-shaped part representing aircraft duct geometry. The demo tube form and cure mold were able to show significant cost savings while producing a high-quality final part. The team felt if the hybrid mold design was optimized to reduce material and manufacturing costs, then that concept would provide valuable upside to increase throughput while being amortized over several similar and interchangeable part geometries, such as a duct or propeller for urban air mobility vehicles. All three tools were able to achieve the target specifications sought out by SpinTech as traditionally used for their baseline tooling, giving them full confidence that AM tooling could be a reasonable solution for them to regularly use with these tool geometries.

As learned from the decision and design approach for AM tooling, larger geometry parts such as the trailing edge toolsets do not appear to be an economical solution for AM. Large print volumes yield an array of concerns that range from print time, material, and post-print machining costs. More research and prints are needed to determine if scaling up the size of the Titan Atlas printer nozzle, as large as 7mm, could help reduce larger geometry print times and total tooling costs to as much as 50%, as shown can be completed with smaller to medium sized geometries. Determining when to use AM tooling is not a "one size fits all process" as all decisions are based on the complexity and size of the tool being produced.

9. Recommendations

This program provided technical insights as to which tooling applications might benefit from emerging polymeric additive manufacturing. Cost of AM tooling was largely driven by print time and final machining. New advancements in the polymeric AM systems such as the Titan system used for this project are expected to reduce these cost drivers. These improvements include two extrusion heads and in situ CNC machining. We suggest these new updated technologies should be explored to determine the value proposition of printing larger volume parts on an expanded print envelope which now provides the ability to immediately machine the tool to its final net geometry. These new developments and printer updates from Titan Robotics LTD have the potential to dramatically reduce tool costs while providing historically low lead times and greatly improve the quality of the final machined part.

10. References

N/A

11. Appendices

SpinTech – smart tooling website
https://smarttooling.com/

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https://titan3drobotics.com/

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