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5.5 Hybrid Additively Manufactured Tooling for Large Composite Structures

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Hybrid Additively Manufactured Tooling for Large Composite Structures

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LIST OF ACRONYMS

UDRI	University of Dayton Research Institute
LFAM	Large Format Additive Manufacturing
CTE	Coefficient of Thermal Expansion
AM	Additive Manufacturing
AES	Additive Engineering Solutions
CFRP	Carbon Fiber Reinforced Polymer
BAAM	Big Area Additive Manufacturing
DoD	Department of Defense
PEI	Polyetherimide
CMM	Coordinate Measuring Machine
EOP	End of Part
ASF	Automated Stiffener Forming

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1. EXECUTIVE SUMMARY

This program sought to lower tooling costs for tightly toleranced, large composite aerostructures by using large format additive manufacturing (LFAM). LFAM tooling has the potential to lower tooling costs, but the large and unpredictable thermal expansion of polymer-based tooling did not previously allow for the production of large structures made with high performance resins requiring 350 deg F cures. Geometric tolerance issues and demolding concerns continued to arise.

The proposed approach for this work was to print a thin shell via additive manufacturing that would be used as a scaffold for a conventional tooling prepreg. The prepreg would be laminated and cured onto both sides of the shell, creating a tool with a sandwich construction. The cured prepreg would then be machined and serve as the tooling surface. In addition to providing a clean, pit-free surface, the prepreg stiffness and low thermal expansion would physically restrain the AM shell and prevent it from expanding during thermal cycling, thus preventing any geometric mismatch between the nominal and actual part dimensions.

A stair-step approach was taken to prove out this approach. Coupon level testing was done to ensure a good bond was possible between the AM shell and the tooling prepreg. These samples were also used to determine the amount of prepreg needed to achieve the desired coefficient of thermal expansion (CTE). The project team than progressed to a subscale tool measuring two feet in length. The geometry used was a C-section spar from Airbus' Wing of Tomorrow program. A hybrid tool, using the AM shell and tooling prepreg, was made, and a composite part was fabricated with the tool. Dimensional scans of the tool and part indicated that the desired CTE was achieved with the tool.

A second tooling approach was taken to reduce risk. In this approach, a subscale tool of the same geometry as previously mentioned was created, but the tool was entirely constructed of the tooling prepreg. AM was used to print a "master" that was then used to fabricate the tool by creating a splash off of the master using tooling prepreg. The innovation was that the master was not machined, but rather, was used right off the printer after a small amount of surface preparation. Removing this machining step was thought to make this approach economically viable when compared to conventional master fabrication. As before, the tool was used to fabricate a part and tested for dimensional accuracy.

For the conclusion of the program, a ten-foot tool was created using the hybrid tool approach. The geometry also came from the Airbus C-section spar previously mentioned. Some difficulty arose in accurately predicting the geometry of the tool after laminating the tooling prepreg, resulting in multiple material additions and a tool geometry change. A part was fabricated in an autoclave using the tool.

A cost savings of almost 50% was achieved on the subscale tool in both the hybrid and master-style tool, but the savings dropped considerably as the tool length increased in the full-scale tool. Given the less than expected cost savings and added complexity of the tool construction, it is suggested that the master-style tool is best for immediate commercialization for larger tools (although it may be appropriate for smaller, table-top size tools). Since its construction is very similar to conventionally made composite tooling, there already exists a broad supply chain for building the tool, and project partner Additive Engineering Solutions (AES) is well acquainted with the design and build of the AM master needed.

2. INTRODUCTION

The focus of this work was to develop a new tooling approach for composite manufacturing, with an emphasis on lowering tool cost. The target application was large aerospace composite structures, such as wing C-spars, that would benefit the most from lower cost tooling options, considering their extremely high, current tool costs. The project team further refined their scope to prototyping and pre-production applications that require tight geometric tolerancing but do not have the benefit of large production numbers to amortize the high tooling costs.

This work focused on large format additive manufacturing (LFAM) as a means of producing the tooling. A quick internet search yielded dozens of sources detailing the high potential for cost savings with AM versus traditional tooling approaches. Also documented, however, are several shortcomings of additively manufactured (AM) tooling that would become particularly problematic for the geometry of tools being investigated in this work[1]. The most notable deficiency is the high coefficient of thermal expansion (CTE) of the tooling material. Matching the tool CTE to the composite part CTE as closely as possible is important for maintaining geometric tolerancing. Invar and carbon fiber-reinforced plastic (GFRP) tooling, considered the gold standard in aerospace tooling, are within a couple parts per million per degrees Celsius (ppm/deg C) or better to the part being made on the tool, typically at 2 to 3 ppm/deg C. AM tooling can come close to matching this CTE in one direction, but because the carbon fiber contained in the printing feedstock preferentially aligns in the print, or flow, direction, the cross-flow direction exhibits CTE's exceeding 50 ppm/deg C.

Industry has made attempts to lower AM tooling CTE, or at the least, make it more isotropic and easier to predict. Equipment modifications, feedstock development, and modeling attempts have made modest improvements, but all approaches to date still result in unacceptably high CTE values that require a compensation factor be placed on the tooling so that when the tool is at temperature, the geometry is within an acceptable tolerance. This does little to address female cavity tools with trapping features because the tool contraction on cooldown can severely damage the composite part contained in the tool. Also, very large tools with high aspect ratios, such as a commercial aircraft C-spar, would have inches of compensation needed down the length which could not accurately be accounted for by simply reducing the tool length.

The project team's approach to solving this problem was to additively manufacture a near-net shape shell that followed the contour of the molded part. The shell was then laminated with traditional tooling prepreg, forming a sandwich structure tool wall. The tooling surface was lightly machined to meet surface finish and geometry requirements. This approach used the strengths of AM, namely its ability to inexpensively form complex geometries, and offset its weaknesses by using conventional materials to physically restrain the AM core and limit its thermal expansion.

Using the above approach, it was estimated that certain tool geometries would see a 50% decrease in tool costs compared to Invar or CFRP tooling. At the prototype and pre-production level, this represents a huge cost savings since these tools would only be used for a very limited number of cycles before being retired. In addition, lower tool costs allow manufacturers to do more design cycles before committing to a final part geometry, ultimately allowing more part refinement in terms of cost, strength, and weight. Lastly, production runs that require accelerated ramp-ups but relatively low total numbers, could benefit by having multiple replicates of a tool manufactured at the same cost as one metallic tool.

This technology directly benefits commercial aviation manufacturers, but it could also have a profound impact in attritable defense aircraft systems and urban mobility platforms, both of which will likely require accelerated production schedules and are extremely cost sensitive. To make this technology available to these sectors, this program involved the entire supply chain necessary to commercialize the technology. SABIC and Hexcel supplied the AM feedstock and tooling prepreg, respectively. LFAM machine building Cincinnati, Inc consulted on print designs while LFAM service bureau Additive Engineering Solutions (AES) printed the tool. Visioneering, a tool builder familiar to the aerospace industry, was subcontracted to machine and assemble the final tool. Northrop Grumman, a Tier 1 aerospace manufacturer and OEM, and Airbus, also an OEM and the part end user, evaluated the final tool and parts yielded off of the tool.

With the conclusion of this project, part manufacturers are able to contract directly with Visioneering to procure tools with this construction. Visioneering could perform the tasks done on the project by UDRI, namely the laminating of the AM print with tooling prepreg. They have ample experience in composite lamination and have the equipment to support. The AM prints could be procured directly from Ohio-based AES.

3. BACKGROUND

The incumbent tooling techniques for composite manufacturing can be categorized into two families: metallic and CFRP tooling. Metallic tools start as thick billets of material that are machined to the desired geometry. Large, relatively flat shapes may be made by forming a thin sheet of metal and welding on a backing structure, referred to as an eggcrate, to the underside of the tool. Invar, steel, or aluminum may be used in the construction of these tools. Invar has a low CTE, on the order of 2 ppm/deg C, but it comes with a very high price and is usually reserved for full production tools requiring tight geometric tolerances. Steel is more moderately priced and is extremely durable, but its CTE is approximately 12 ppm/deg C. Parts that can accommodate slightly wider tolerances and that can be made on tooling conducive to CTE compensating can use steel tooling. Aluminum is a soft material with a CTE double that of steel. It is typically reserved for prototype tooling with very generous tolerance windows.

CFRP tooling is an alternative tooling approach. Its CTE matches the composite part almost exactly and requires no compensation factor. Like Invar, it is quite expensive. CFRP tools begin as blocks of tooling board that must be bonded together. After curing, the blocks are machined to the negative of the part to be produced. The “master” as it is now called, is hand sanded, cleaned, and laid up with tooling prepreg. The prepreg is cured, demolded and trimmed. A supporting eggcrate, previously laminated, cut, and bonded together, is bonded to the backside of the tool. Lastly the tooling surface is machined one final time and hand-sanded to achieve the desired finish and tolerance.

Additive manufacturing is a relative newcomer to composite tooling. It had limited applicability until recent feedstock releases and, more notably, the advent of LFAM in the form of Cincinnati Inc.’s Big Area Additive Manufacturing (BAAM) equipment propelled its use into aerospace-relevant applications. Most commercial and defense aerospace manufacturers, as well as Department of Defense (DoD) agencies, are now investigating this tooling approach. For the reasons stated in Section 2 of this report, along with uncertainty regarding tool life, its adoption is still limited.

This program sought to overcome the challenges with AM tooling to allow wider adoption and ultimately allow composite manufactures to capitalize on the potential cost savings of the technology. This program took a stepped approach that allowed for early coupon-level successes to build into sub-scale and full-scale demonstrations. Initial coupon-level trials had to demonstrate an isotropic CTE of 6 ppm/deg C and an ability to survive 10 thermal cycles without damage. This success rolled into duplicating this performance on an actual Airbus geometry but with a reduced, two-foot tool length. In addition, the tool had to show less than 0.010” movement through thermal cycling and maintain vacuum integrity of less than 1” Hg drop over five minutes. With this achieved, the final milestones focused on repeating this on a full-scale, ten-foot-long tool.

The team assembled to support this work had extensive experience in composite manufacturing and tooling. Airbus tooling engineers in their Spain office contributed to initial plans and tool design, led by Pilar Muñoz, a composite and tooling expert with 20 years of experience. Northrop Grumman’s Chief Engineer at their Clearfield, Utah location, Vern Benson, was a heavy contributor and offered 35 years of direct composite tooling and manufacturing experience. UDRI’s Principal Investigator, Scott Huelskamp, has led composite-based research programs for almost 15 years, a portion of which was spent designing and installing composite tooling lines for Spirit Aerosystems, Cessna, SpaceX, Karem Aircraft, Kongsberg, and others.

4. RESULTS AND DISCUSSION

The project was divided into three main tasks: design and model of the tool; fabricate and validate sub-scale tool; and fabricate and validate full-scale tool. The technical approach, test method, and subsequent results are divided by task below.

4.1 Design and Model of Tool

The first activity of the program was to select a part geometry to be used for the final tool. The part geometry would determine how the tooling would be approached. Airbus provided a C-spar tip geometry being used by their Wing of Tomorrow program (Figure 1). This part was already being made with traditional tooling materials, so a reference baseline was readily available. The part was ten feet long and 15 inches wide at the root end of the spar.

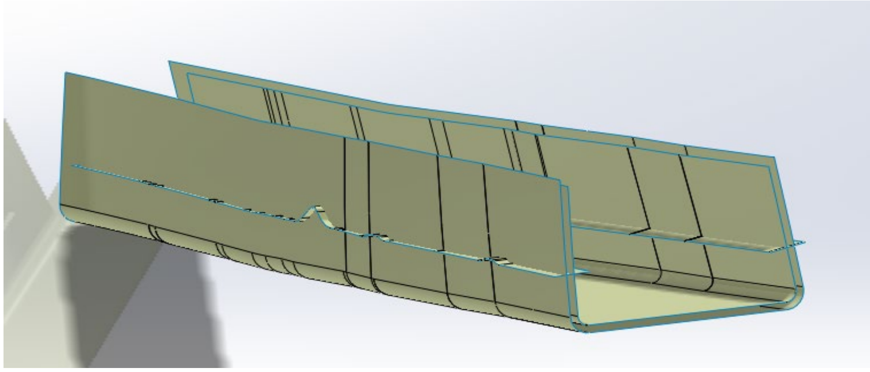

Figure 1. Outer mold line of Airbus Wing of Tomorrow c-spar

The metallic mold was slated to be a female cavity tool, so the same approach was taken for this project. A complicating factor to this geometry was that the spar caps had a negative draft that created jig lock between the part and a single-piece tool. Using this geometry required the team to pursue a split tool configuration. This added risk and complexity, but the team felt these challenges could be overcome.

An initial tool configuration was designed that used an eggcrate-type backing structure to reinforce a shell tool (Figure 2). The tool would be made in halves, with a tool surface and a backing structure for each half. This yielded four parts, each printed and laid up with tooling prepreg to control CTE. After cure, the surfaces would be secondarily bonded to their respective backing structure.

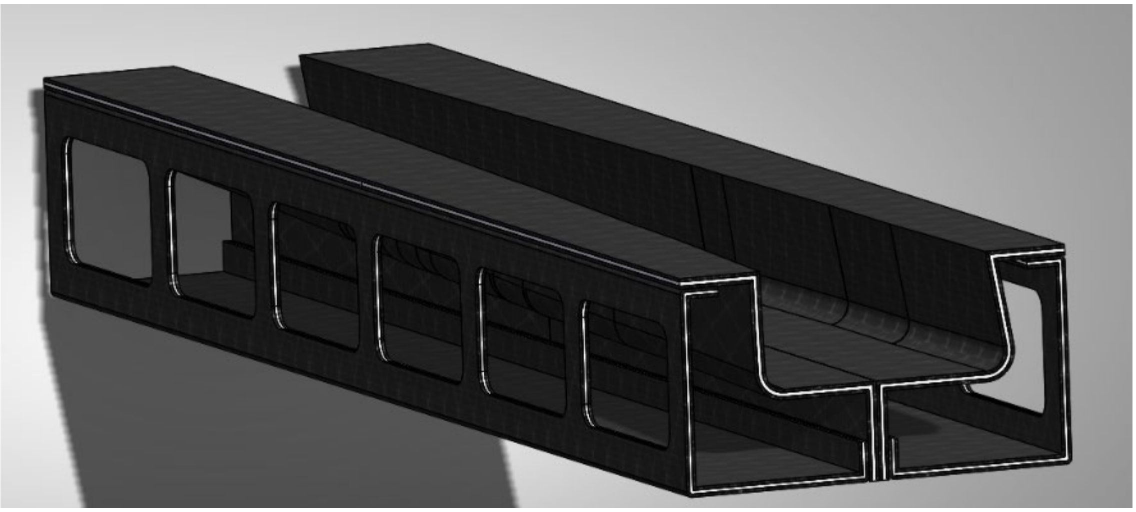

Figure 2. Initial c-spar tool design

This initial tool design yielded two concerns. First the eggcrate offered only moderate accessibility to the joining hardware that would need to be used down the length of the mating flange of the tool. Having to work through the eggcrate when assembling and disassembling the tool would be difficult. Secondly, the eggcrate would require a surface bag be used to seal the part since an envelope bag would crush the eggcrate and likely tear. Having no experience in sealing a multi-piece AM tool, the team was nervous to proceed with a design that eliminated the ability to use an envelope bag in the event that the tool would not seal with a single-sided bag.

A second tool design iteration was done to eliminate these concerns (Figure 3). In this design, the backing structure was removed. The wall thickness of the tool and the flange width were increased to provide more stiffness to the tool in the absence of the eggcrate. The general concept of 3D printing a core and laminating it with tooling prepreg remained unchanged from the previous design. This tool iteration simplified the construction of the tool, provided better access to the mounting hardware, and was ultimately selected to move forward with.

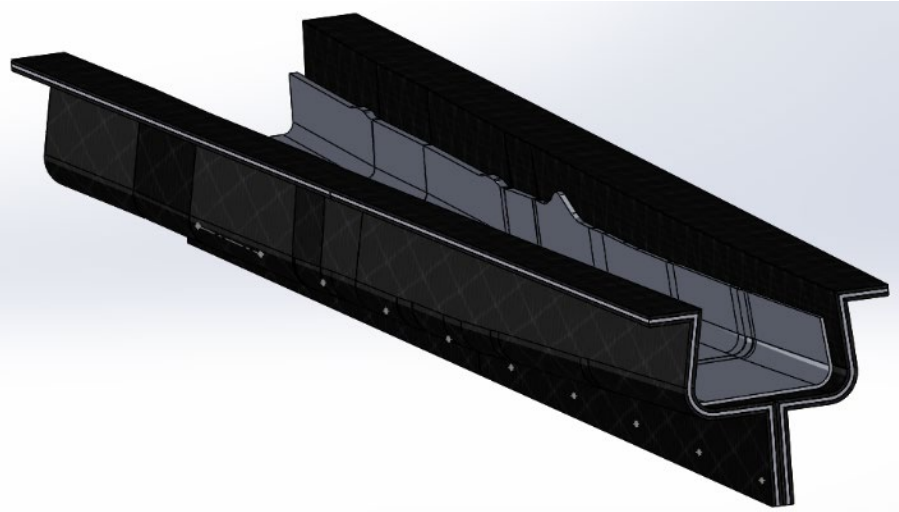

Figure 3. Second iteration of c-spar tool

In parallel to the tool design, the team selected a printer feedstock and tooling prepreg for tool fabrication. A 20% carbon fiber-filled polyetherimide (PEI) (Thermocomp™ EX004EXAR1 Ultem®) feedstock was selected due to the researchers' familiarity with the material and its proven ability to withstand typical autoclave cure cycles when used in composite tooling. SABIC, a material supplier to the project and the manufacturer of the material, supplied the feedstock pellets. A polycarbonate feedstock was briefly considered, but at the cure temperatures of the parts being made on the tooling, it was deemed too unstable to move forward with.

Hexcel's Hextool™ M81 epoxy tooling prepreg was selected for lamination of the AM shell. The material is a 2000 grams per square meter mat made of chopped carbon fiber impregnated with Hexcel's 8552 toughened epoxy system. The material boasts nearly isotropic properties that allows for post-machining without tool movement due to residual stress relief during the machining process, which was a driving factor in its selection for this project. It is also a proven material for composite tooling that Northrop Grumman was familiar with and comfortable using for this application. A bismaleimide matrix version of Hextool was also available, but with the limited expected lifespan of this tooling, the extra cost for this material was deemed unwarranted.

Plaques were cut from printed flat panels of the PEI feedstock and laminated with the Hextool material (Figure 4). The panels were printed by Cincinnati, Inc. at their Harrison, Ohio headquarters. Four surface preparation techniques were evaluated for durability. They are as follows:

- As-printed
- As-printed with a b-staged epoxy interface
- Sanded flat
- Sanded flat with a b-staged epoxy interface

Figure 4. Surface prep coupons. “Flat” refers to sanded samples while “ribs” refers to as-printed surface.

The epoxy selected for the interface was BJB Enterprise’s TC-1614 epoxy. It was used as a sealer for PEI AM prints and is known to adhere well to the material. The epoxy was only b-stage cured prior to the addition of the tooling prepreg plies to encourage chemical bonding between both epoxies. The four panels were subjected to ten thermal cycles up to 350 deg F. The sanded sample with the epoxy interface delaminated during the cycles, but the other three appeared unaffected. The lowest cost option, the as-printed variant, was selected to move forward with (Figure 5).

Figure 5. As-printed coupon cross-section after heating

Initial modeling and hand calculations predicted that five plies of Hextool on each side of the AM shell would be sufficient to restrain the thermal expansion of the tool to a target range of less than 6 ppm/deg C. Specifically, modeling predicted an in-flow CTE of 3.9 ppm/deg C and a cross-flow CTE of 5.0 ppm/deg C (Figure 6).

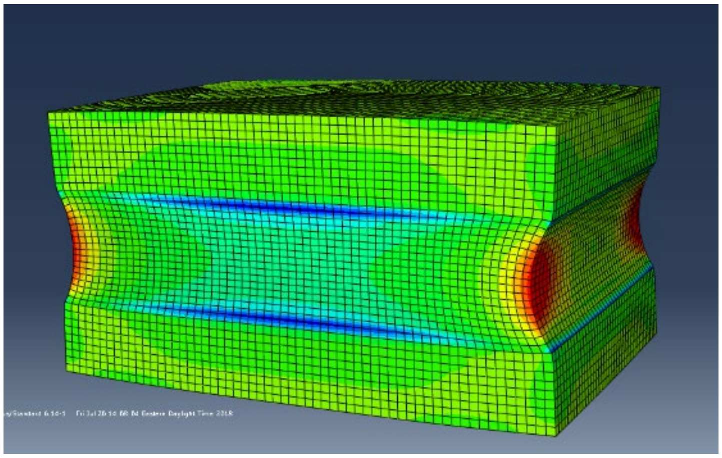

Figure 6. FEA model of interlaminar stress between face sheets and AM core

Two additional PEI panels were cut from the larger AM print and laminated with Hextool (Figure 7). One panel was laminated with five plies and the other was laminated with 6 plies. Both panels were cured according the Hextool M81 datasheet.

Figure 7. Laminated tooling panels for CTE check

After cure, tooling pins were inserted into the test panels. X and Y measurements were taken between the pins at room temperature and recorded. The panels were then allowed to soak in a 350 deg F oven until reaching a steady state temperature, confirmed with mounted thermocouples. The distance between pins was measured again at the elevated temperatures. This was done quickly, while monitoring the thermocouples to ensure no more than a five degree drop in temperature was seen. With the dimensional change and temperature delta known, the CTE could be calculated in both directions for each panel using Equation 1.

$$\delta L = L_o \, \alpha (T_F - T_o) \tag{1}$$

As shown in Table 1, the addition of the tooling prepreg had a profound effect on the resulting CTE of the panel. The as-printed material was severely anisotropic and had a cross-flow CTE of 57.1 ppm/deg C, more than double that of even aluminum. With the addition of the tooling prepreg, this value dropped by an order of magnitude, down to 6.3 ppm/deg C with five plies of prepreg. The flow-direction CTE was also reduced, down to 2.6 ppm/deg C.

Table 1. Calculated CTE values of PEI panel as printed and with the addition to tooling prepreg.

		PEI Tool (as-printed)	**PEI Tool** (with 5 plies HexTool)	**PEI Tool** (with 6 plies HexTool)
CLTE_{177C} ppm/C	flow	5.8	2.6	2.4
	x-flow	57.1	6.3	5.4

At the conclusion of this task Milestone 5.5.2.1, Milestone 5.5.3.2 and Go/No-Go 5.5.1 requirements were successfully met and the project progressed into the next main task. Note that the original milestone and Go/No-Go listed an anisotropy requirement and an accuracy requirement based on percentage. The team agreed to drop these since the actual magnitude was very low and a better predictor of tool performance than percentage.

Milestone 5.5.2.1 Achieve a design predicted to have a global CTE of less than 12 ppm/°C and exhibits CTE anisotropy of less than 25% demonstrated in-plane.

Milestone 5.5.3.2 Achieve predicted CTE of tool within 25% through actual measurements.

Go/No-Go 5.5.1 Optimized design that shows a global CTE of less than 6 ppm/°C and exhibits CTE anisotropy of less than 10% demonstrated in-plane.

4.2 Fabricate and Validate Sub-scale Tool

After validating at the coupon level that the tooling approach would successfully lower the CTE of the tool and survive thermal cycling, fabrication efforts moved to a sub-scale tool measuring two feet in length (Figure 1). A section of the full-size tool described in Section 5.1 was selected for fabrication. It contained the same joining hardware and flange seal expected to be used on the full-scale tool.

Figure 8. Subscale c-spar tool solid model

For ease and cost of manufacture, the preferred printing direction for the AM shell was a vertical build. At the subscale level, this was not a concern. However, a full-scale tool could not be printed to its full length in this orientation. The research team elected to split the tool down the length so that a method of bonding the tool could be established at the subscale level. The tool was also split into left and right sections to allow for the negative draft mentioned in Section 5.1.

The tool sections were printed back-to-back to be more efficient during the print (Figure 9).

After printing, the pieces were cut and the two right sections were bonded together as a butt joint (Figure 10), followed by the two left sections. Loctite EA9394 (Henkel) epoxy adhesive was used for the bonding.

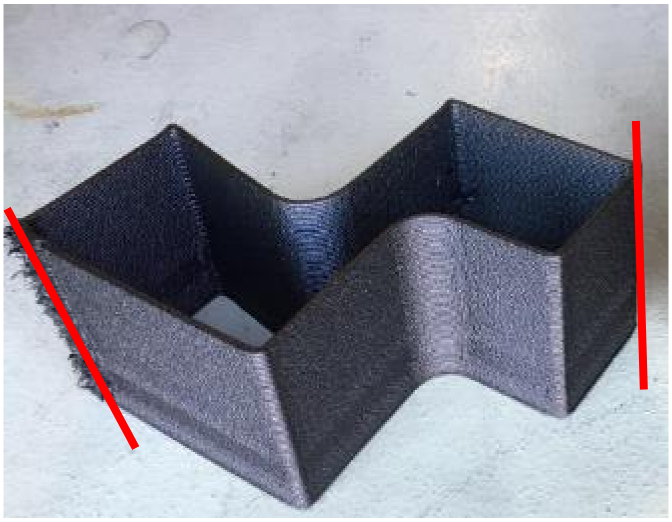

Figure 9. Right half of the subscale tool BAAM print. Red lines denote cut lines after printing.

Figure 10. Right half of BAAM print after bonding, approximately 24 inches tall

After bonding, each tool half was laid up with Hextool without any machining of the BAAM print (Figure 11). The backside of the tool, which would remain unfinished, was laid up with 5 plies of Hextool. The top side was laid up with 9 plies to allow for extra material to be removed during machining. Hot debulks (one hour soak at 200 °F) were performed after ply 1, ply 4, and ply 7. Silicone sheets and metal plates were used to more evenly apply pressure during the debulks and provide a more consistent surface for later machining (Figure 12). The pregreg was cured using the "High Temperature/Standard" cure cycle provided by Hexcel (ramp to 250 ºF, hold for 60 minutes, ramp to 350 ºF, hold for 120 minutes with 100 psi pressure) (Figure 13).

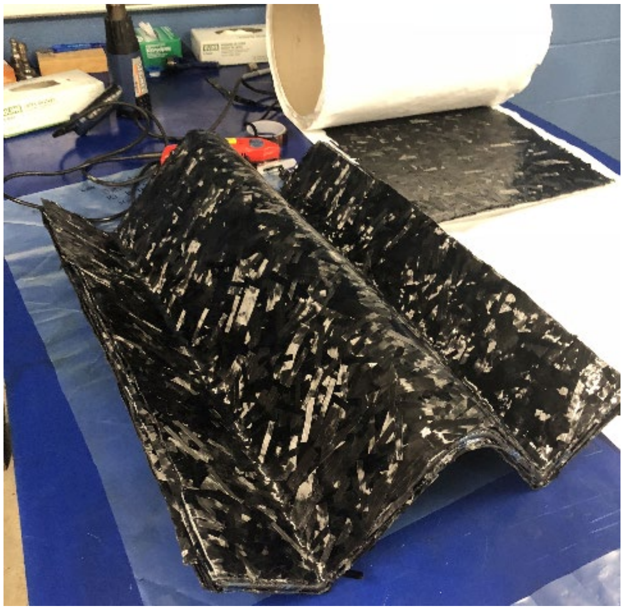

Figure 11. Hextool laid up onto AM core

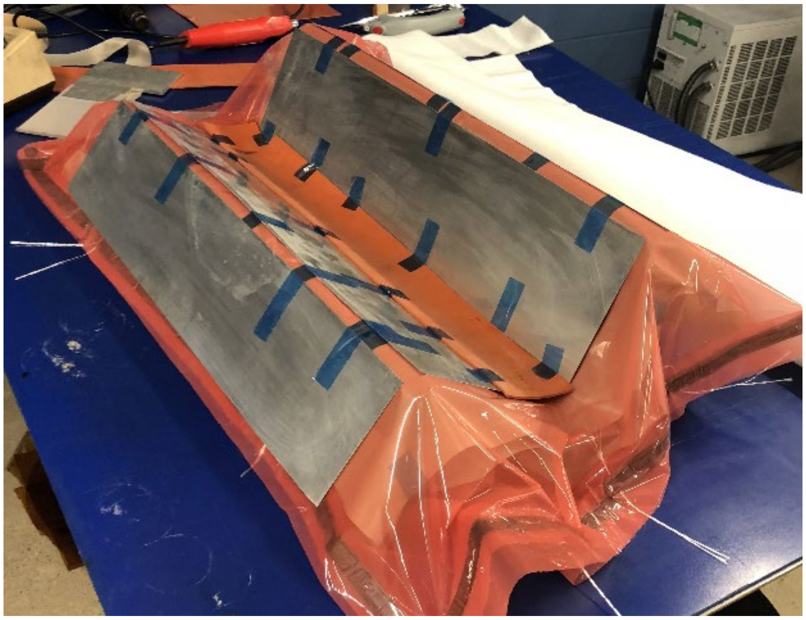

Figure 12. Release film and caul plates installed prior to cure

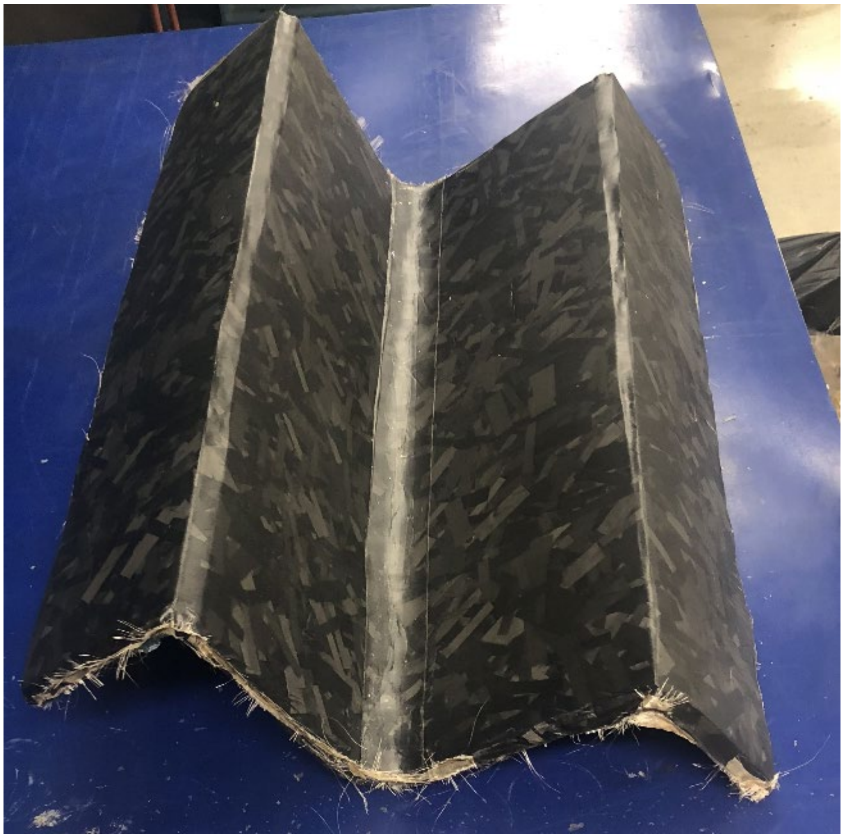

Figure 13. Cured tool half

After cure, the tool was sent for machining at Visioneering in Auburn Hills, Michigan. Prior to shipping to UDRI, Visioneering heated the tool to 350 deg F in an effort to measure the thermal expansion of the tool, similarly to what was done previously on the coupon level. Upon cooldown, delamination between the facesheets and 3D printed core occurred, as shown in the circled region of Figure 14.

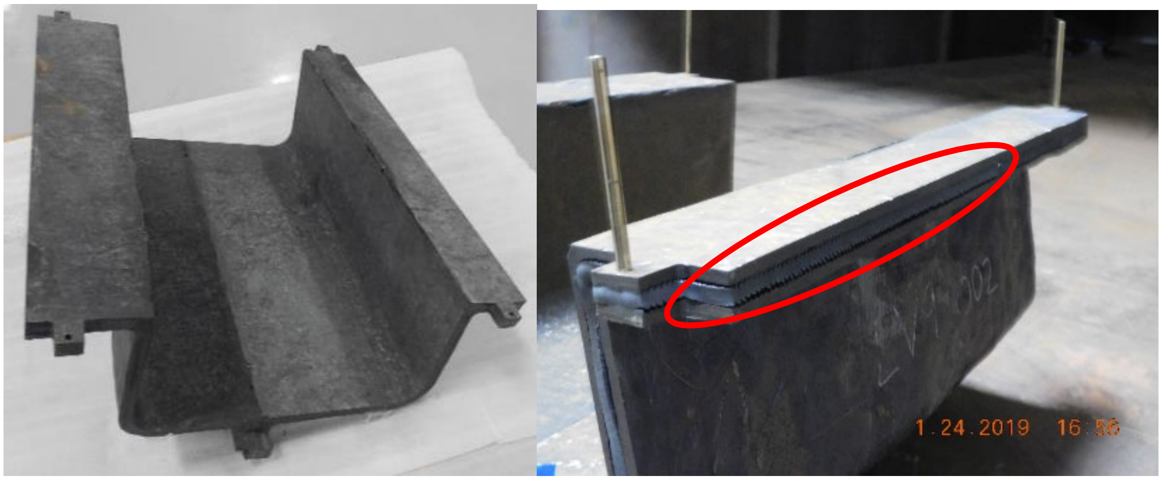

Figure 14. Machined subscale before (left) and after (right) thermal cycling

The team met and discussed ways to improve the interface between the facesheets and core. An option was selected, and a second sub-scale tool was fabricated. (Due to the proprietary nature of the solution, it cannot be discussed in the body of this report.) Pre-machining inspection of the tool indicated a risk of cutting into the core if a full surface clean-up was done due to thin areas in the prepreg facesheet. These areas were primarily isolated to the male radii and were a result of pressure intensification that thinned out the prepreg during cure. The decision was made to machine as deep as possible without risking a punch-through of the laminate. After machining, the areas that were not fully cleaned up were filled in with a high temperature tool filler and reworked to get the desired finish (Figure 15).

Figure 15. Machined subscale tool, assembled (top) and single half (bottom). Circle indicates area where tool filler was applied

The completed tool was inspected with a Coordinate Measuring Machine (CMM) probe to confirm that the required profile tolerance was achieved. A machined surface of + / - 0.25 mm (0.010”) from nominal was confirmed on the layup surface (Figure 16).

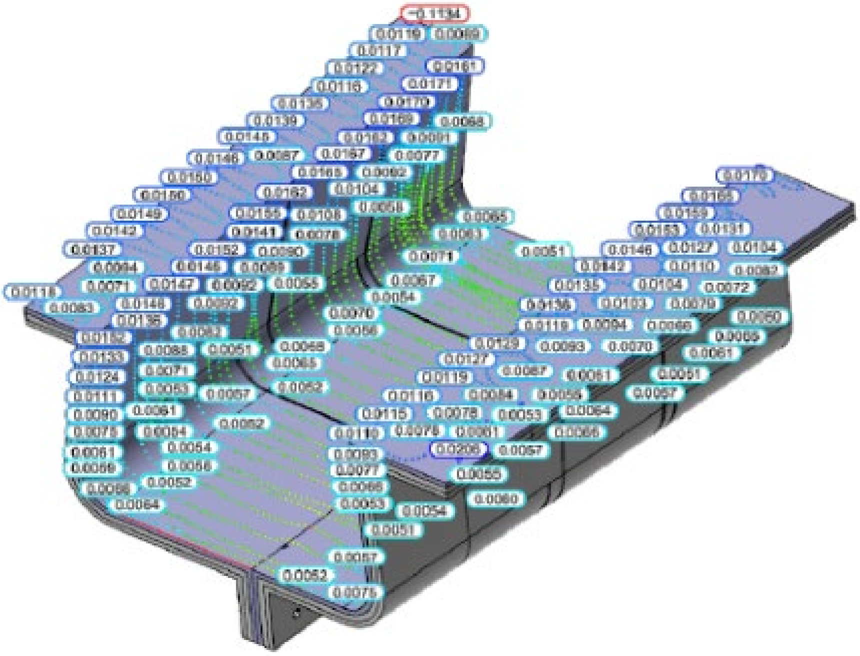

Figure 16. CMM scan map of subscale tool showing deviation from CAD model
(shown in inches)

After the dimensional check, the tool was probed with a FARO® arm at room temperature to determine overall length and width at four discrete pick-up points. The tool was then placed in a 350 °F oven and allowed to soak until reaching steady-state. It was removed from the oven and the four pick-up points were quickly probed to determine the tool’s length and width at elevated temperature. The tool was also inspected for physical damage, most notably delamination between the face sheets and core, of which, none was found. The two sets of measurements allowed for the change in width and length, and subsequently, the linear coefficients of thermal expansion, to be calculated (Figure 17).

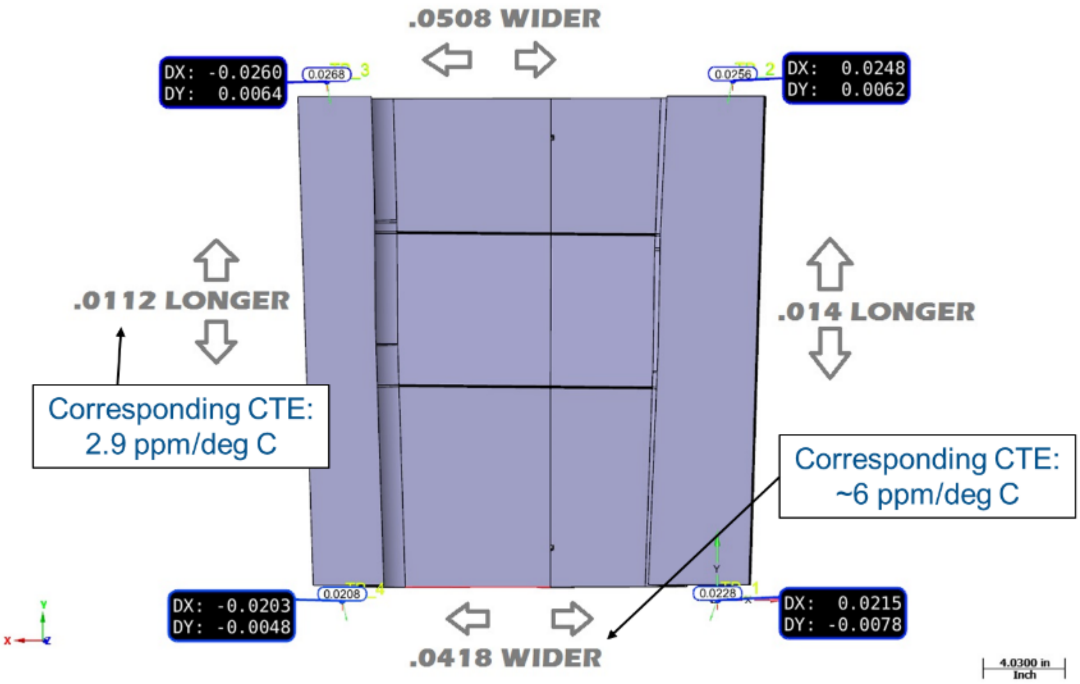

Figure 17. Physical measurements of tool expansion and calculated CTE values

Down the length of the tool, the CTE was calculated to be 2.9 ppm/deg C, while the calculated CTE in the transverse direction was 6.0 ppm/deg C. The transverse direction of the tool was also the flow direction of the underlying BAAM print. The unreinforced BAAM print was shown to have a CTE of 5.8 ppm/deg C, already less than what was being measured on the actual tool. It is suspected that residual stresses in the tool were causing a springback condition, causing the top flanges to move further away from each other. This artificially inflated the calculated CTE value in this direction. The actual transverse CTE is expected to be 3 ppm/ deg C or lower, although this was not confirmed.

A leak check was performed on the tool. Initially, a surface bag was applied that tied into the silicone o-ring cordstock seal at the mating surfaces between the two tool halves. The tool exhibited excessive vacuum loss, and it was determined, through the use of dye penetrant, that the leak was across the cordstock. Given time constraints, the decision was made to envelop bag the entire tool and improve the cordstock seal at a later date.

A section of the C-spar lay-up was applied to the tool surface. Unidirectional carbon fiber/epoxy prepreg (M21E/34%UD194 IMA12k, Hexcel) was laid up across the tool surface with a ply drop at the midpoint of the tool. The root section of the lay-up was 54 plies while the tip end reduced to 38 plies. The ply distribution was as follows: 0 deg = 26%, +/-45 deg = 48%, 90 deg = 26%. The part was debulked and cured according to Hexcel's M21 datasheet[2]. It demolded easily from the tooling (Figure 18).

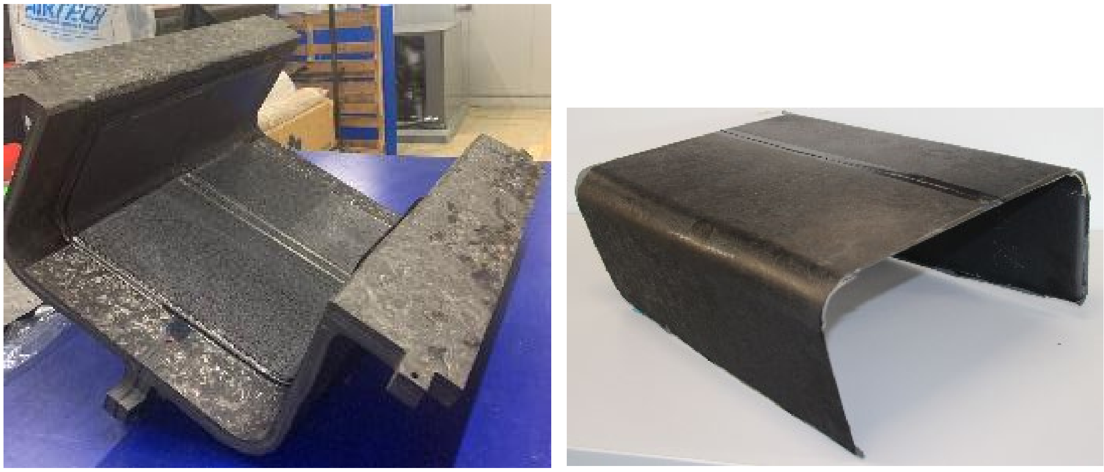

Figure 18. C-spar laminate laid up on tool (left) and after demold (right)

After cure, the part was demolded and the tool was subjected to further cycling to test durability. The tool was vacuum bagged (without prepreg) and cycled in an autoclave so that it experienced the same ramps and high temperature soaks that would be present during actual part cures. A pressure of 100 psi was maintained on the tool during the cycling. Ten total cycles were run. A second C-spar lay-up, identical to the first, was fabricated on the tool at the conclusion of the "dry" cycles.

A surface scan was performed on the first part fabricated on the tool and the second part that was made at the conclusion of the thermal cycling (Figure 19). The part surfaces are within +/-0.005" of each other, indicating almost no tool movement after thermal cycling. In the surface scan, green denotes areas within +/-0.001" while red and blue show areas up to +0.005" and -0.005", respectively.

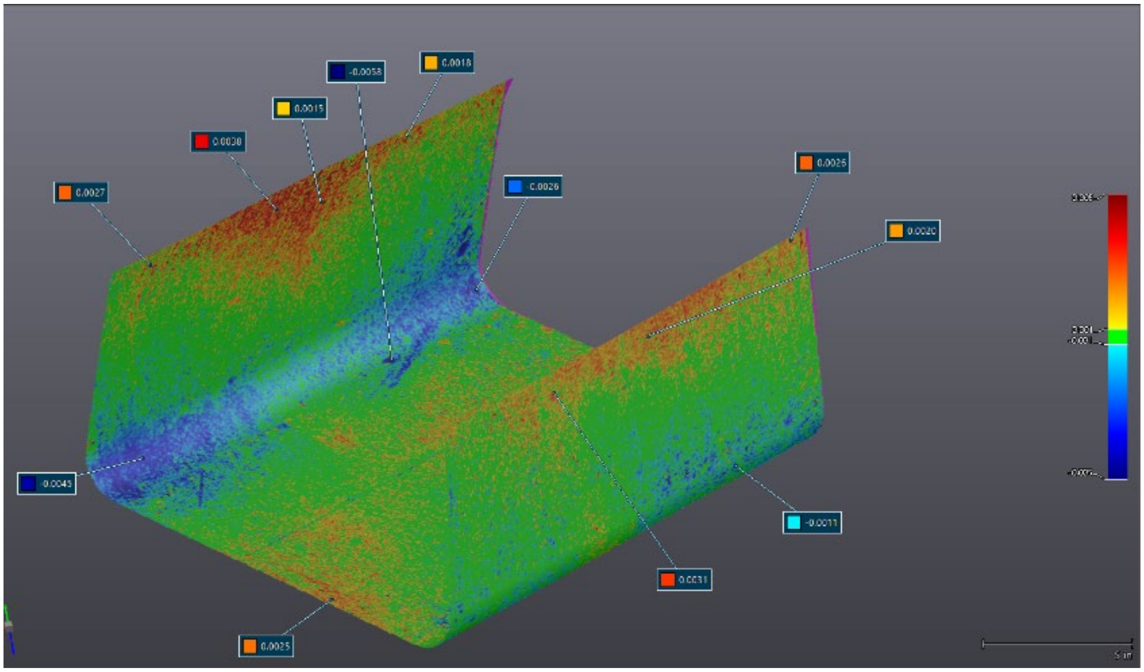

Figure 19. Dimensional comparison of Part 1 to Part 2

The surface scan of the first part was also compared back to the nominal geometry to ensure that the final part was achieving the desired geometric accuracy. Airbus had requested a profile tolerance of +/-0.020” from nominal. Figure 20 shows this comparison for the left half of the tool. In this scan comparison, the acceptance threshold was set for +/-0.020” and areas displayed as green indicate that those areas are within the limit. The cap region of the spar is shown to be outside of this limit, but this was expected. During tool design, the team agreed to neglect springback and not attempt to apply a compensation factor to account for it to simplify the design effort. As such, the spar cap regions of the cured part sprung out after demolding and were outside the tolerance limit. This phenomenon is not unique to this project’s tooling and would be addressed with a compensation factor in the future, exactly how it is handled with conventional tooling.

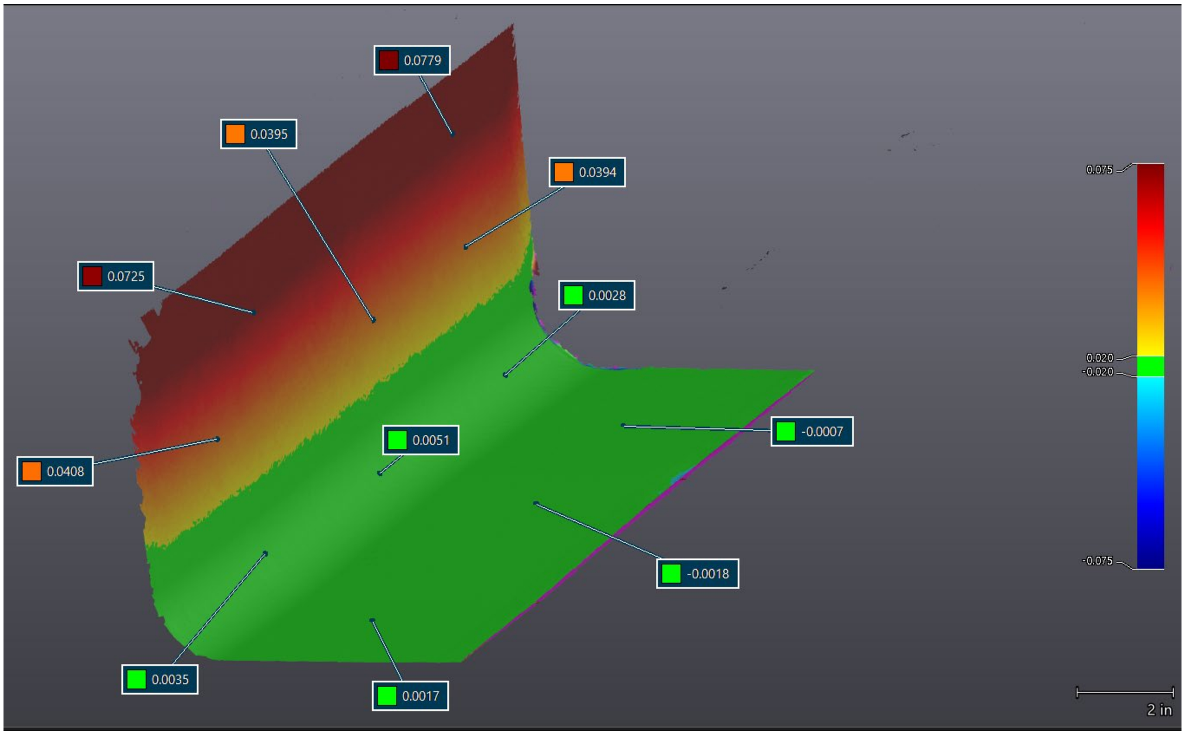

Figure 20. Scan comparison of subscale part to nominal geometry (left half shown)

A vacuum leak check was redone on the tool at this point, with the goal of improving the mating flange seal so that a surface bag could be used. This was especially important in advance of fabricating a full-scale tool. The o-ring cordstock was increased in size from the designed-for 5.33 mm diameter stock to the next bigger stock size of 5.7 mm. The material was also switched to Viton® to improve the adherence of the vacuum tape to the cordstock. These changes resulted in a leak rate of less than 1.0” Hg in five minutes and gave assurance that with these modifications, a full-scale tool would also seal well. The location of the cordstock channel can be seen in Figure 15.

While the second tool was being constructed, the project team agreed that a risk mitigation plan needed to be in place in the event that the modification to the tool did not correct the delamination issue. It was decided to fabricate a 100% CFRP tool using a BAAM print as the master for fabricating the tool. Although this has been done in the past by AES’s customers, the team hoped to demonstrate the ability to do this on an unmachined BAAM print. Typically, the BAAM master must be machined to an acceptable finish prior to layup of the tooling prepreg. Then the resulting laminate is machined again to the desired tolerance. These two machining steps, plus the cost of the BAAM printing, often push the cost beyond taking a conventional approach. By skipping the initial master machining step, the team felt that the cost of the tool would be much more favorable.

The design was modified so that the reduced tool wall thickness could be reinforced with an eggcrate structure (Figure 21). A BAAM master was designed and printed to allow for fabrication of the shell. Ten plies of Hextool material were laid up on a BAAM print heavily coated with mold release and cured according to Hexcel’s instructions. Despite the “corduroy” pattern on the tool side of the cured laminate, it demolded very easily from the BAAM master (Figure 22).

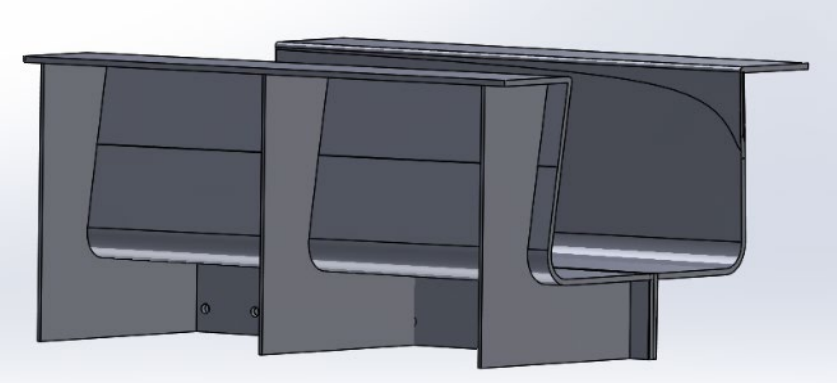

Figure 21. Subscale tool using master approach

Figure 22. Cured tool half demolded from BAAM master

Flat panels of Hextool material were fabricated and waterjet cut to the shapes needed for the eggcrate. They were bonded in place using Loctite 9394 adhesive. Overplies of carbon fabric and tooling epoxy were applied to reinforce the connection between the eggcrate and the tool skin (Figure 23).

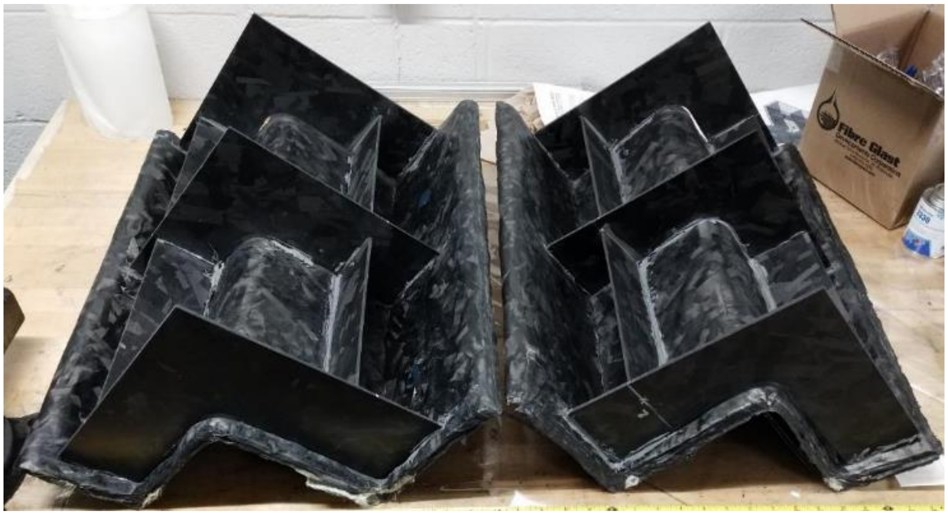

Figure 23. Subscale tool (master approach) with eggcrate installed

After completion of the tool, a composite part was laid up on the surface of the tool and cured. The ply schedule matched the two parts made on the hybrid tool previously described in this section. The resulting part qualitatively appeared to be of equal quality as the previous parts, validating this tooling approach as an acceptable back-up if needed for the full-scale part (Figure 24).

Figure 24. Cured c-spar part made from master-approach tooling

The conclusion of this task met the requirements needed on Milestone 5.5.3.1, Milestone 5.5.3.3, and Milestone 5.5.4.2.

Milestone 5.5.3.1 A completed sub-section of the full tool design (approximately 2 feet in length). A tooling surface proven to survive 10 thermal cycles without a loss of vacuum integrity (defined as < 1.0" Hg drop over 5 minutes) demonstrated on flat panels at room temperature and at 180 C.

Milestone 5.5.3.3 Show tool survival--defined as permanent tool movement less than +/- 0.010" profile movement—and maintained vacuum integrity of less than 1.0" Hg drop over 5 minutes.

Milestone 5.5.4.2 Produce composite part within +/- 0.020 profile tolerance.

4.3 Fabricate and Validate Full-scale Tool

Before proceeding with full-scale part fabrication, some design changes were made to the tool to account for lessons learned in the sub-scale trials. First, scribe lines were added to denote the end-of-part (EOP) of the cured C-spar. A double o-ring groove was added to give additional confidence in achieving a good seal in the finished tool. Alignment pins were added on the mating flange to drive repeatable alignment between both tool halves. Lastly, 6.35mm (0.25in) bushings were added on the top flange of the tool halves (four total). Actual centers of these bushings were measured and denoted. During fabrication, these bushings would aid in tool alignment during part lay-up, as well as serve as pick-up points for confirming tool CTE.

The full-scale tool core was printed in two pieces, split at roughly the midspan, to accommodate print height restrictions on the BAAM printer. The left and right half was combined into a single print for each of the two pieces to allow for more efficient printing. The two pieces were bonded together with Loctite EA9394 and clamped together with pipe clamps prior to cutting out the left and right halves (Figure 25). After the adhesive had set at room temperature, the left and right halves were cut apart to accommodate for the parting line on the final tool.

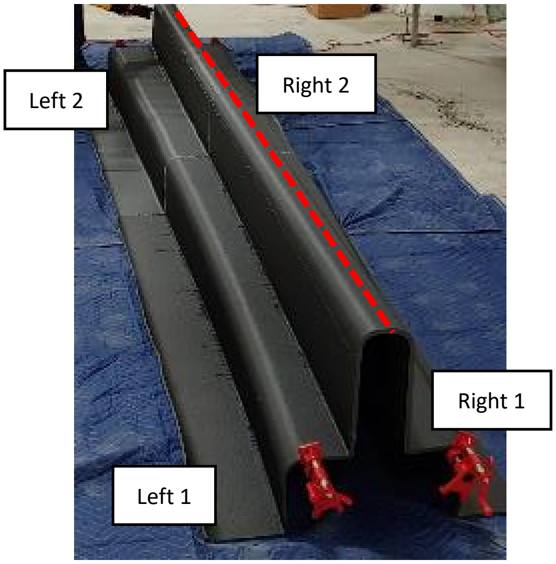

Figure 25. Full-scale tool, clamped for bonding. Red line denotes split line, cut after bonding.

The two tool halves were scanned and the surfaces were compared to the nominal geometry to confirm that the 3D structures hadn't sprung out of shape when cut out of the main structure. Both tool halves showed isolated areas of excessive movement as compared to the CAD model. These areas were locally heated with a heat gun and manipulated so that they better conformed to the original design intent.

The two halves were laid up with Hextool prepreg, with a slight modification from the subscale tool. The prepreg was redistributed so that four plies were added to the backside and 10 plies were added to the topside (layup side). In addition, an extra strip of prepreg was added on all male radii. These two modifications allowed for more face sheet thickness on the tool surface for machining. As before, hot debulks were done after plies 1, 4, and 7, and the tool was cured using the "High Temperature/Standard" cure cycle. This work occurred within Northrop Grumman's facility in an area off limits to cameras, so no photographic documentation was captured.

After curing the facesheets, a dimensional scan of the tool was done by Visioneering to ensure enough stock was present for machining. It became evident that the tool deflected during the cure and created low areas that could not be machined to the tool geometry without cutting into the core. This deflection was likely caused by residual stress buildup in the structure due to the dissimilar materials being bonded together. To compensate for this, additional tooling prepreg was added to the tooling surface and cured so that more stock would be available to the machine shop.

The tool was scanned a second time, which indicated that there were areas that may not fully clean up during machining. The project team agreed to adjust the geometry of the tool to match that of the physical tool. A point cloud of the physical tool was generated, then offset by 0.25" to provide the cut surface (Figure 26). Given the bumpy nature of the Hextool, this resulted in an irregular surface of the tool, but it was deemed acceptable given that the performance of the tool, rather than the actual part geometry, was key to the investigation.

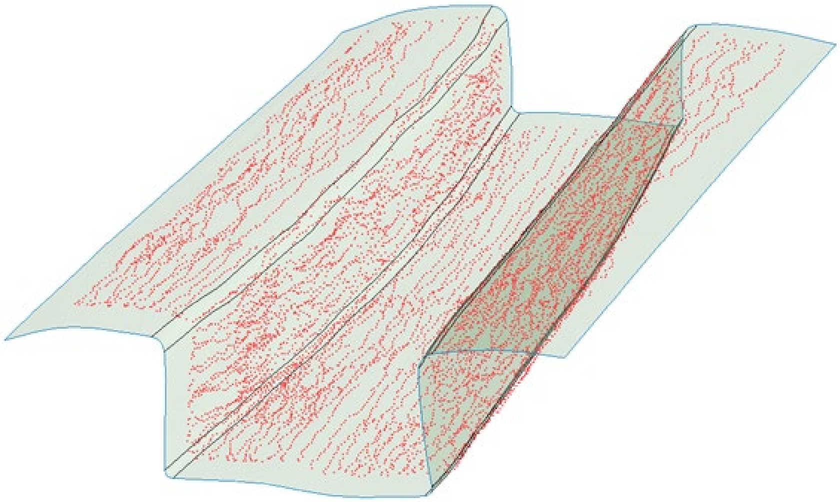

Figure 26. Point cloud of physical tool prior to finish machining

The tool was machined to this surface, and upon inspection, there were still isolated areas that did not machine. This indicated that there remained areas that were too low. The decision was made to accept the tool as-is, given the time constraints of the program, and that these low areas could be filled with high temperature tooling putty at a later date. If these areas are omitted, scans of the tool indicated that the surface was within +/-0.010" and met Milestone 5.5.4.1 (Figure 27).

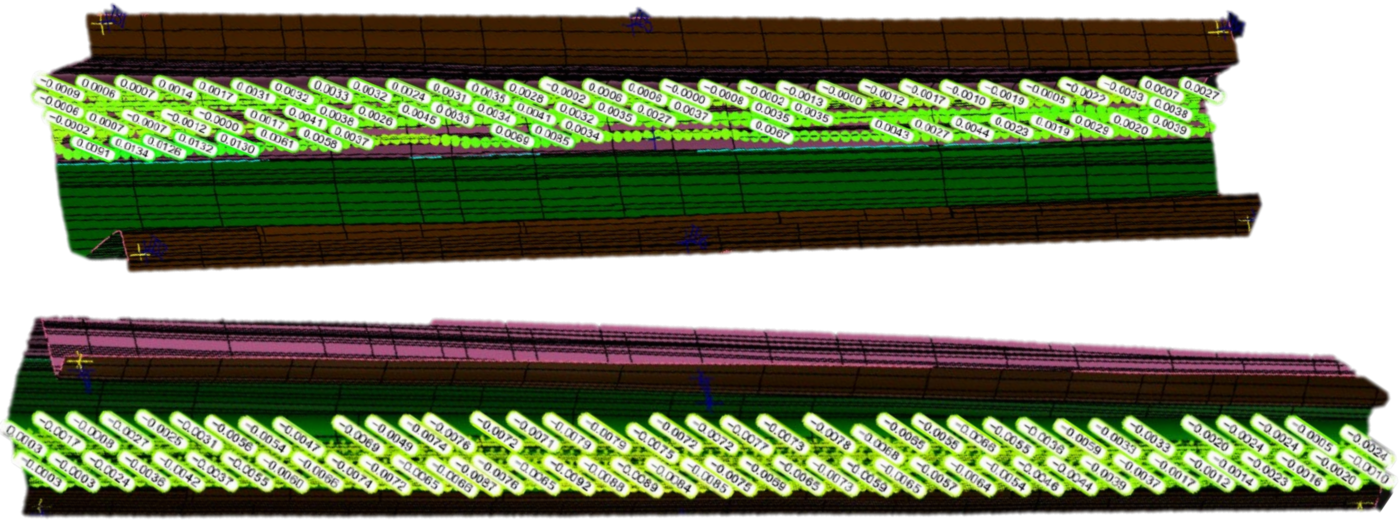

Figure 27. Scan of full scale c-spar tool

Once machined and the initial scan was taken, the tool was measured in length at room temperature. From the tool ball locations, the tool length was measured as 123.0 inches. The tool was placed in a 350 deg F oven to measure tool length at temperature, but tool temperature had dropped to 280 deg F by the time the tool was removed from the oven and scanned. At this temperature, the tool expansion was measured to be 0.036". The CTE of the tool was then calculated to be 2.46 ppm/ deg C, very similar to the CTE calculated for the subscale tool.

After scanning, the tool was returned to UDRI. To provide a better release surface, adhesive-backed Teflon film was applied to the tooling surface (Figure 28).

Figure 28. Machined tool with release film applied

The c-spar part was laid up with the same material and ply stack as done on the subscale tool (Figure 26). To conserve material, the thicker root end was omitted and the entire lay-up was kept at 38 plies. The part was cured and easily demolded from the tool.


Figure 29. Lay-up of c-spar tool

The tool was bagged and shipped to Northrop Grumman's facility to be cured that day. The M21E cure cycle was followed, although a reduced sandwich-core pressure (50 psi) was used due to concerns of the vacuum bag popping. Bag vacuum was lost at 125 minutes, indicating a bag pop. According to the M21 datasheet, the resin viscosity should have advanced significantly by that time. The failure was noted, and the cure was allowed to progress. The part and tool were shipped back to UDRI for demolding (Figure 30).

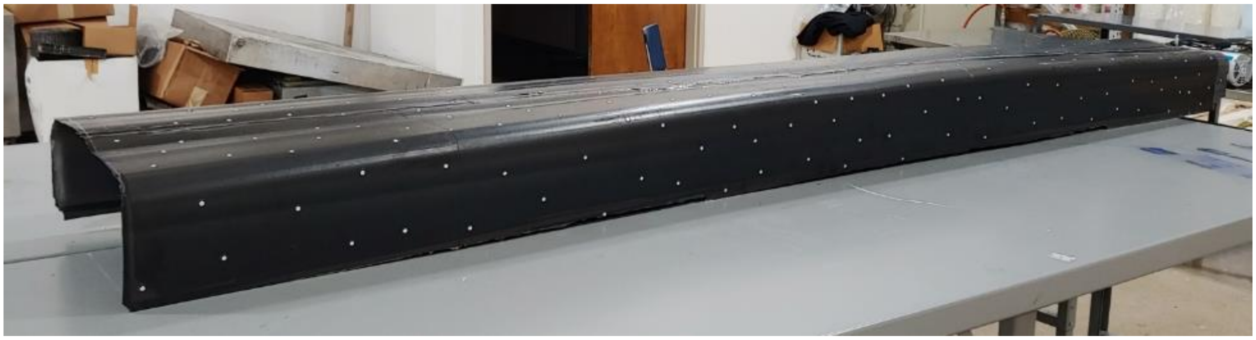
Figure 30. Demolded C-spar

The conclusion of this task fulfilled the requirements for meeting Milestone 5.5.4.1 and Go/No-Go 5.5.2.

Milestone 5.5.4.1 A completed, full-sized tool with +/- 0.010" profile tolerance of the nominal tool geometry.

Go/No-Go 5.5.2 Successful achievement of Milestones 5.5.4.1 and 5.5.4.2 will dictate the ability of this technology to be further scaled during follow-on work to 30-40', which is desired by Airbus and would be required to implement in turbine blade applications.

4.4 Further Work

The movement of the full-scale tool during fabrication caused significant problems that added cost and significant lead time. This unpredictability in the tool would not be tolerated by a tool builder. To fully mature the hybrid approach, a different approach is needed to stabilize the BAAM core during lamination. A thicker core could be used, but this adds additional cost and thermal mass to the tool, as well as increases the amount of polymer that needs to be restrained during heat up.

A preferred approach would be to laminate the core with Hextool while it is in a larger structure and cut out the tool pieces after lamination. In the case of the C-spar tool geometry, the core would be laminated while still in the configuration shown in Figure 25rather than after cutting apart the right and left half. Some fixturing may still be needed to further stabilize the laminated core during cure. Taken even further, the lamination could occur while the core pieces are still in a box configuration as shown in Figure 9 so that the print does not spring open due to cutting before being laminated.

Also, Northrop Grumman expressed an interest in evaluating the full-scale tool in their Automated Stiffener Forming (ASF) process to ensure that the tool could accommodate their automated processing. This may occur in 2021 outside of the project.

5. BENEFITS ASSESSMENT

After demonstrating performance equivalency, the most important aspect in this research was showing a significant cost reduction in the fabrication of this hybrid tooling when compared to traditionally machined invar tooling. The team estimated the need for a 50% cost savings for manufacturers to embrace this tooling method and deviate from the usual norms. Costs of the hybrid tool were recorded as the tool was being manufactured. Actual quotes from AES and Visioneering were used to capture the printing and machining costs, respectively. Industry-average labor rates were used to approximate labor costs so that university research labor rates did not skew the data. After compiling, the total cost of the tool was $24,200. Costs were roughly split equally between machining costs and printing/lamination costs. By comparison, Visioneering provided a quote to reproduce an identical tool using invar. This came to $46,775, for a cost savings of almost 50%. The sub-scale tool made using the BAAM master came in at almost the same cost, yielding roughly equivalent cost savings.

The full-scale AM/prepreg tool was estimated to cost $70,000 if the additional rework hadn't been needed. The corresponding invar and CRFP tool was quoted by Visioneering as $86,000 and $100,000 respectively. This represented a much more modest cost savings. The difference in cost savings can be explained by machining economies of scale. The printing costs (machine time) and material costs (feedstock and tooling prepreg) is mostly a linear function to tool length. These costs are roughly five times as much in the ten foot tool as compared to the two foot tool. Costs associated with the final machining of the tool were not linear. The cost to machine the two foot tool was $12,000, while the cost to machine the ten foot tool was $24,000. This is only double the cost of machining the subscale tool, not five times the cost as might be expected.

For smaller tools, the economics play out in favor of the AM/prepreg tool and offers manufacturers a significant opportunity to reduce tooling costs in pre-production tooling. Further trials are needed to certify that the tooling will survive in higher rate applications, but it is reasonable to assume that they will perform well beyond the 10 cycles already demonstrated, considering GFRP tools made from Hextool can run for hundreds of cycles. Further cost reduction work is likely need on larger tooling before it is ready for implementation.

In tooling applications that do not require elevated temperature cures or are otherwise unconcerned with CTE issues, the tooling approach taken in this program could also prove beneficial. The prepreg used in the hybrid tooling approach was shown to provide a pit-free surface able to maintain vacuum integrity without additional sealing or coating. AM tooling alone often suffers from significant vacuum loss at cure temperatures and pressures, stemming from internal porosity exposed during machining. Additional filling rework and surface coatings are required to improve this, although coating failure through thermal cycling is common and often results in the premature scrapping of the tool. Using the tooling prepreg surfaces negated these concerns.

6. COMMERCIALIZATION

Aerospace tooling is mostly subcontracted out to tool builders external to the aircraft manufacturer and/or its Tier One suppliers. Rarely are large production tools manufactured internally. When a part manufacturer sends out this work, it may be done as a “build-to-print” job, meaning that the part manufacturer’s tooling engineers have already designed the tooling needed and the tool builder simply needs to build what is contained on the prints. Alternatively, the part manufacturer may simply supply an engineering drawing of the final part and subcontracts the design of the tool to the tool builder as well. In the first case, individual tooling engineers across the industry need to be made aware of this project’s tooling technology and have to be convinced of its merits. This would require a concerted marketing effort.

The second method has a much more simplified commercialization approach. Only a single tool builder must adopt the technology. Given the cost savings of the approach, the tool builder’s quotes will routinely undercut their competition and clients will preferentially send their tooling jobs to the tool builder using this project’s technology. As part builders become more exposed to this type of tooling, they will begin to specify this type of construction for their tooling, generating more and more interest.

At the conclusion of this program, Visioneering is interested and able to build this type of tooling. They will serve as an immediate source for the final tool product. They are able to process the tooling prepreg and perform the machining, and will outsource the additive manufacturing back to AES. At this time, AES does not have the facility and/or experience to handle the prepreg portion of this work. Given that AES and Visioneering already have this relationship, there is no further work needed on the supply chain.

7. ACCOMPLISHMENTS

This work was highlighted in a journal article presented at the virtual 2020 SAMPE Conference, originally scheduled to be hosted in Seattle, Washington. Titled "Hybrid Additively Manufactured Tooling for Large Composite Aerostructures", it was presented virtually to the SAMPE audience and was followed by a panel discussion that included the project's Principle Investigator and paper author. The journal is included in the conference proceedings.

The composite industrial trade magazine CompositesWorld also ran an editorial on this project. The article, "Large Format Hybrid Tooling: Lighter, Faster, Less Costly Molds for Big Parts" ran in their December 2020 issue.

8. CONCLUSIONS

Both the hybrid tool and the master-style tool both were shown to produce high quality aerospace components at a cost savings, when compared to other low-CTE tooling options., specifically, Invar or CFRP. However, the hybrid tool proved to be difficult to implement, due to the movement of the thin AM core and the unpredictability of the final tool shape after laminating. Although a different approach to the core printing could remedy this, such as laminating the core while it is still in a box shape to provide better stability, the hybrid tool still requires a large education effort for tool builders to be able to produce this type of tooling. The master-style tool construction is familiar to tool builders and can be implemented seamlessly. In fact, after AES or another AM service bureau provides the master to the tool builder, there is no difference in the tool construction. Also, the master-style tool offers almost the same cost savings as the hybrid construction. When duplicate tools need to be made to meet rate demands, the master-style tool outcompetes the hybrid tool since the 3d printing does not need to be repeated.

As noted previously, the innovation in the master-style tool was the finding that the machining step typically done on the master after printing could be eliminated without detrimentally affecting the final tool. Removing this step allows the master-style tool to compete favorably, cost-wise, to CFRP tooling made on conventional masters.

Another advantage of the master-style tool approach is that it can be implemented after a CFRP tool has already been designed. This means that when a part manufacturer has already designed a conventionally-made CFRP tool and has released a print to the tool builder, the tool builder can easily elect to 3D print the core and use the master-style approach without requiring any deviation from the tool print. This allows for broader more broad implementation without the need to educate tool designers across the industry.

9. RECOMMENDATIONS

Regardless of whether the hybrid or master-style approach is taken, the cost of the tooling prepreg and its processing dominates the cost of the final tool. The raw material costs are high, and the need for an autoclave cure drives up processing costs. Tool builders cannot easily move away from this because tooling is required to last hundreds of cycles without cracking and leaking. High quality prepreg and autoclave-quality laminates are a requirement.

The need to drive out cost in composite manufacturing has given rise to a wide range of low-cost prepregs that feature industrial-grade carbon and oven-processible resins. Although these materials would not likely survive hundreds of cure cycles, they could be sufficient for the low volumes targeted by the tooling in this program. Not only would significant cost be removed if these prepregs could be implemented, but the supply base would greatly increase. Many tool builders have large ovens for heat treating their metallic tools, but few have large autoclaves. These ovens could be used to cure the composite tooling. If costs were lowered enough, multiple tools could be made of the same geometry to extend the production volumes or to support surge production needs. This is especially true if the master-style approach is utilized since the printing cost is a non-recurring expense.

10. REFERENCES

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