



FDM Ancillary Tooling for Composite Fabrication

—
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FDM® has been proven to be a valuable and disruptive solution for composite fabrication tooling. In addition to lay-up mold tools, FDM technology offers significant advantages for ancillary tools used in secondary operations such as trimming, drilling, assembly, bonding and inspection. The benefits include reduced lead time and cost, design simplification, and ease of fabrication and use. Concurrently, FDM ancillary tools enable increased functionality and geometric complexity.

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Nearly all conventional composite parts require some sort of secondary processing such as trimming, drilling, bonding, surface preparation, and/or subsequent assembly. Depending on the application requirements, these operations can be done with hand tools or CNC machining. Regardless of the method, they require a variety of tools, which are used to efficiently and effectively process the part. These tools tend to be highly customized and tailored to a specific composite part. The materials and methods of manufacturing for ancillary tools will depend on the application and performance requirements. Any reduction in the manufacturing cost and/or lead time of these tools has the potential to dramatically disrupt the composites industry. This white paper will discuss the methods of designing, printing, and implementing (as well as performance characterization for) ancillary tooling for composite part fabrication.

DESIGN CONSIDERATIONS

Just as the design and construction aspects of traditional composite tooling vary depending on the material of construction (e.g., Invar vs. carbon/epoxy), there are factors and “key considerations” that are critical to the effective design and use of FDM for ancillary tooling. It is

important to consider the strengths and limitations for the manufacturing method when trying to minimize cost and lead time. Subtractive forms of manufacturing, such as machining, can constrict what’s possible, feasible, and practical. FDM is an additive process that minimizes waste by depositing material only where necessary. There are a few considerations when designing a tool for FDM:

- Selecting the correct material
- Style of tool
- Orientation of the tool while printing
- Addition of ergonomic features
- Incorporation of inserts

Requirements

The performance requirements of the ancillary tool will drive its design. In many cases, the primary function is to aid in some form of secondary operation, which can vary based on size, complexity, number of parts and accuracy requirements of the composite part. Ancillary tools are often an afterthought, which means it’s important to consider the application during design.

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Material Selection

Material selection will play a major role in dictating the properties and cost of the tool. Unlike composite lay-up tools, ancillary tools are typically not exposed to elevated temperatures, high pressures, or harsh chemicals, which means they can be made from a variety of materials ranging from wood to fiber-reinforced polymer (FRP) composites. There are a variety of FDM thermoplastics that can be used, but ASA is the recommended material for ancillary tooling because of its ideal combination of mechanical properties, UV resistance, high-quality printability, and cost. At 108 °C, ASA has a relatively low glass transition temperature (T_g), which means that inserts can be installed thermally via heat-staking. ASA also comes in a variety of colors and can be used for color-coding types of tools, which can improve efficiency. Table 1 lists FDM thermoplastics commonly used for tooling as well as their advantages, limitations, and best fits.

FDM thermoplastics and their properties commonly used for tooling.			
MATERIAL	ADVANTAGES	LIMITATIONS	BEST FITS
ASA	<ul style="list-style-type: none"> • Aesthetics • UV stable • Color-coded tooling • T40 tip compatible 	<ul style="list-style-type: none"> • Low flexural modulus • Low heat resistance • Poor chemical resistance 	<ul style="list-style-type: none"> • Nests and cradles • Kit boxes • Surrogate parts • Go/no-go gauges • Hand tools • Drill guides
PC	<ul style="list-style-type: none"> • Moderate temperature resistance • Moderate mechanical strength 	<ul style="list-style-type: none"> • Poor chemical resistance • Moisture sensitive 	<ul style="list-style-type: none"> • Drill guides • Surrogate parts • Dunnage trays • Hand tools • Thermoforming
FDM Nylon 12™	<ul style="list-style-type: none"> • High toughness • Best fatigue resistance • Mild chemical resistance 	<ul style="list-style-type: none"> • Lower aesthetics • Moisture sensitive • Lower flexural modulus 	<ul style="list-style-type: none"> • End effectors • Feeders • Metal tool guards • Machine Guards
FDM Nylon 12 CFT™	<ul style="list-style-type: none"> • Carbon fiber reinforced • Increased mechanical properties in-plane 	<ul style="list-style-type: none"> • Mechanical properties are not increased in Z-axis • Abrasive surface finish 	<ul style="list-style-type: none"> • Robotic end effectors (end-of-arm tooling) • Bracketry • Jigs & fixtures
ULTEM™ 9085 resin	<ul style="list-style-type: none"> • High tensile strength and modulus • High temperature resistance 	<ul style="list-style-type: none"> • Complexity limitations with breakaway support material 	<ul style="list-style-type: none"> • Thermoforming • End effectors • Lifting tools/aids • Drill guides
ULTEM 1010 resin	<ul style="list-style-type: none"> • Highest temperature capability • Lowest CTE • No VOC outgassing 	<ul style="list-style-type: none"> • Complexity limitations with breakaway support material • Lower impact resistance 	<ul style="list-style-type: none"> • Composite layup tools • High-temperature applications • Tooling that requires sterilization
PEKK ESD	<ul style="list-style-type: none"> • ESD Properties • High-temperature Resistance • No VOC's outgassing • Cleanroom compatible 	<ul style="list-style-type: none"> • Complexity limitations with break-away support material 	<ul style="list-style-type: none"> • Cradles • Trays • Clean room fixtures

Table 1

FDM Ancillary Tooling for Composite Fabrication

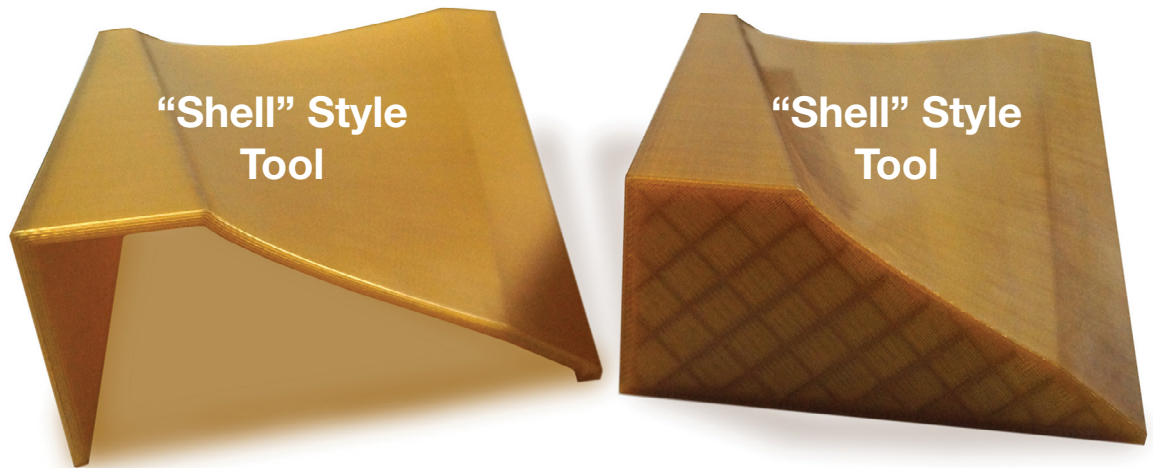


Figure 1. Shell and sparse style tools.

Tool Styles

Once the material has been selected, the next step is to establish the style of tool and if it is based off an existing design or not. In many cases, it's easier to design a new tool specifically for FDM because tools designed for other processes such as machining will have excess material and/or features that may not be optimal for FDM. The goal of designing for FDM is to minimize the amount of material being printed and to only include the critical features necessary to perform the secondary operation. The two design styles for FDM tooling are referred to as "shell" and "sparse." They were originally devised for FDM composite tooling, but can be translated to ancillary tooling as well.

Shell style tools are designed to use the least amount of material possible. This is done by thickening the tool surface by approximately 7 mm. Stabilizing legs can be added so the tool sits flat on a table, but they are not necessary. Shell style tools are lightweight and easily conform to complex shapes, which makes them ideal for trim and drill jigs. Sparse style tools are similar to shell style tools except they include an internal lattice structure known as a "raster" or "infill" pattern. The raster pattern provides additional strength and rigidity to the tool which makes them ideal for machining and assembly fixtures.

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Tool Build Orientation

The orientation of the tool during printing is extremely important because it will dictate the print time, cost, mechanical properties, surface quality, and the amount of support material required. The FDM process deposits beads of thermoplastic, layer-by-layer, in the Z-axis. The thickness of these layers is commonly referred to as the “slice height”, which has a fixed thickness and is based on the size of the extruding tip.

The properties of the printed tool will vary based on the orientation of the slice height. In general, inter-layer mechanical properties tend to be slightly less than in-plane. It is recommended to identify the loads that will be exerted on the tool and to orient it in such a way that the inter-layer strength will not compromise the areas of high loading.

In regard to surface quality, the fixed slice height will also dictate the surface resolution of the tool. A smaller slice height will have a finer resolution whereas a larger slice height will have a coarser resolution. The best orientation to maximize surface resolution, regardless of slice height, is to orient the tools vertically. The trade-off is that the vertical orientation may take longer to print even

if minimal support material is required. It's up to the user to determine the orientation of the tool by prioritizing the importance of surface resolution, mechanical properties, and/or print time. Figure 2 demonstrates the same tool printed in the horizontal and vertical orientations. The horizontal orientation required much more support material and had a coarse surface resolution compared to the vertical orientation.

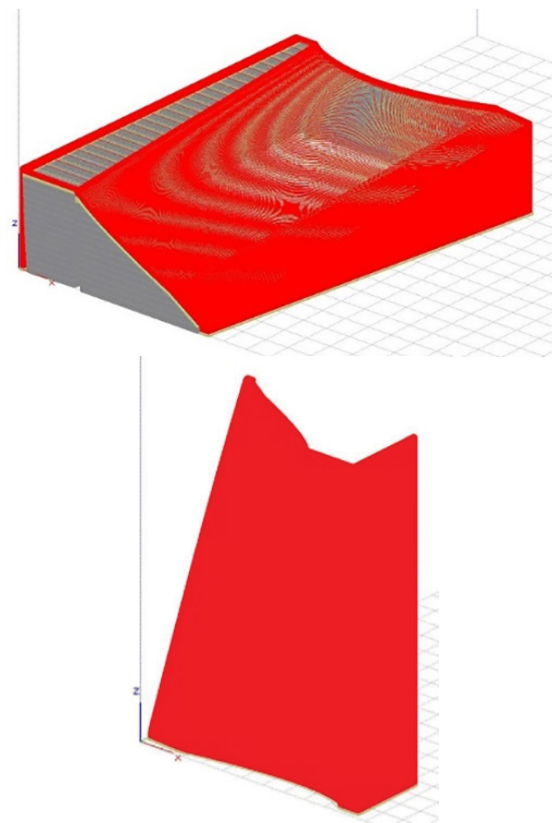


Figure 2. Tools printed in the horizontal orientation (top) and vertical orientation (bottom).

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2.5 Adding Ergonomic Features & Text

FDM allows for the tools to be highly customized and tailored to the operator. Ergonomic features such as handles and text can be easily incorporated into the tool design without dramatically increasing cost or lead time. The quality of text is dependent on the slice height, build orientation, font size, and depth. For large slice heights, fonts larger than 10mm printed in the vertical orientation will yield the best finish. Avoid text that contains fine features, such as Times New Roman, and opt for simple fonts such as Arial Bold.

Text can either be recessed or protrude from the tool surface by 1 – 3 mm, but it is recommended to avoid protruding text when printing in the horizontal orientation. Figure 3 demonstrates how the build orientation can affect text. Both images are of protruding text with the same font and size. The text printed in the horizontal orientation has a far worse quality and has a higher likelihood of delamination.

Sectioning and bonding large tools

Tools larger than the build envelope of the printer can be sectioned into multiple pieces, printed individually, and bonded together. There are multiple bonding methods for ASA, but the two



Figure 3. Protruding text printed in the vertical orientation (top) and horizontal orientation (bottom).

proven methods are to use either a compatible structural adhesive (e.g., Henkel Hysol EA 9394) or to filament-weld the sections together. Filament welding is the process of using a heat gun and thermoplastic filament to weld sections together. Unlike a structural adhesive, the bond will only be near the surface of the tool, but the bond is still strong. For more information on filament welding, refer to Appendix A of the Stratasys [“FDM for Composite Tooling Design Guide.”](#)

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Aligning features should be incorporated into the design of each section. Commonly used joint designs, such as dovetails, mortise-and-tenon, and lap joints are acceptable methods. Butt joints and pins should be avoided for FDM tools because they have a higher incidence of failing compared to other methods. It is recommended that an approximately 0.13 – 0.25 mm gap be designed into the joint to allow for a proper bond line and adequate clearance during assembly.

Inserts

Inserts, such as bushings, can be easily incorporated into any FDM ancillary tool. The inserts can either be heat-staked or bonded with any compatible structural adhesive. Inserts designed for plastics are recommended and both methods are viable techniques depending on the application requirements.

A test was performed to evaluate the dimensional stability of inserts after thermal cycling. Metallic bushings were heat-staked into a coupon made out of ULTEM 1010 resin, printed in the vertical orientation (noted as X-axis in Figure 4), and subjected to eight thermal cycles ranging from 20 °C to 121 °C. The coupon had a thickness of 5 mm, 10 mm, and 15 mm, to evaluate if the length of the bushing had an effect. Upon conclusion

of the cycling, dimensional scans showed that bushings deviated by no more than 0.18 mm in the Y-axis and 0.01 mm in the X-axis. The length of the bushing and the thickness of the substrate did not appear to have an effect in this particular evaluation, but further tests may be required for other bushing materials and temperature combinations.

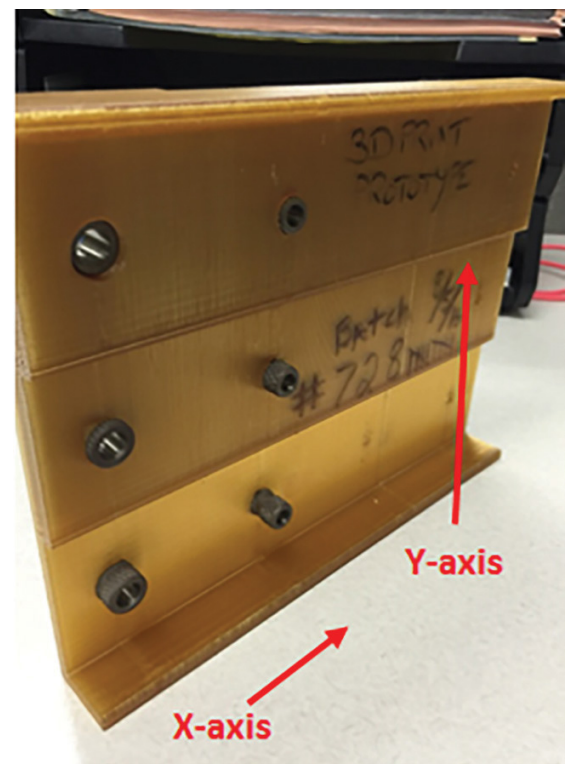


Figure 4. Bushings inserted into an ULTEM 1010 resin coupon of varying thicknesses.

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APPLICATION EXAMPLES

The following examples demonstrate how FDM technology for ancillary tooling is currently being applied in the composites industry.

Profile trimming jig

A combination trim and drill tool was created for the pan skin of a thrust reverser blocker door. The approximate size of the composite part to be trimmed was 36 cm x 25 cm x 5 cm. The tool was designed as a shell style and printed with ASA. Ten pilot holes were drilled along the perimeter of the tool to accept metallic bushings, which were heat-staked into the tool. The tool was printed in the horizontal orientation to minimize support material use. The outer edge of the tool is where the composite part would be trimmed so the middle section was removed to further reduce the amount of material required. The tool was produced on a Fortus 900mc™ and took three



Figure 5. Trim and drill jig printed with ASA.

hours to print at a cost of ~\$160 (material cost and build time).

CNC Machining Fixture

A CNC machining fixture for a composite panel was printed using FDM. The tool was based off of an existing design and modified for FDM using design-for-additive-manufacturing (DFAM) principles. A sparse-style design was selected over shell style to add rigidity. The tool was sectioned into three separate pieces (the primary body of the fixture and two brackets for attaching to the mill bed) and measured 117 cm x 48 cm x 20 cm when assembled.

Various bushings and tooling balls were inserted into the tool surface for dimensional inspection and to act as locating features. Double-sided tape was used to secure the composite part to the tool surface for the initial evaluation. This technique appears to be a viable method for low-volume production, but fasteners, such as toggle clamps, may eventually be incorporated. The tool was printed in a Fortus 900mc and all three sections printed simultaneously.

The finished tool was completed in 48 hours at a cost of \$4300 (material cost, build time, and inserts). An added benefit of FDM is that the tool

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weighs less than 11 kg, which means it can be easily moved by a single operator. The existing tool, made out of FRP material, weighed 78 kg and required an assisted-lifting device (forklift, overhead crane, or similar) to position on the CNC mill.

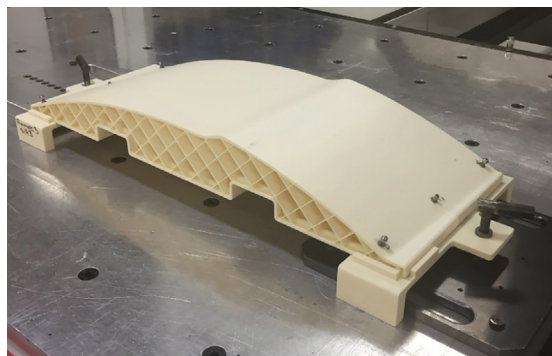


Figure 6. FDM machining fixture secured to the CNC platen.

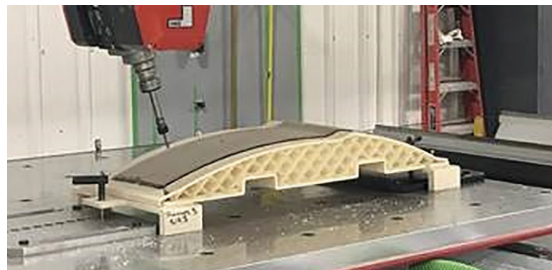


Figure 7. Composite panel being machined using the FDM fixture.



Figure 8. Original machining fixture made out of FRP composites.

Vacuum holding fixture used for CNC machining

The machining fixtures shown in Figure 9 take advantage of the inherent porosity of FDM parts. Instead of using double-sided tape, vacuum is used to firmly secure the composite part to the tool. The FDM parts are inherently porous, due to the physical limitations of the extruded material beads. Figure 10 shows the cross-section of toolpaths for an example build layer and the cross-section of extruded bead profiles, illustrating the porosity. This phenomena may be desirable or undesirable based on the application. In the case of FDM ancillary tooling, it can be used as an advantage.



Figure 9. Mirrored halves of the FDM vacuum fixtures upon completion of printing.

The tool was modeled off an existing tool design, which was manufactured by bonding sheet metal together to form a hollow cavity. A vacuum hose

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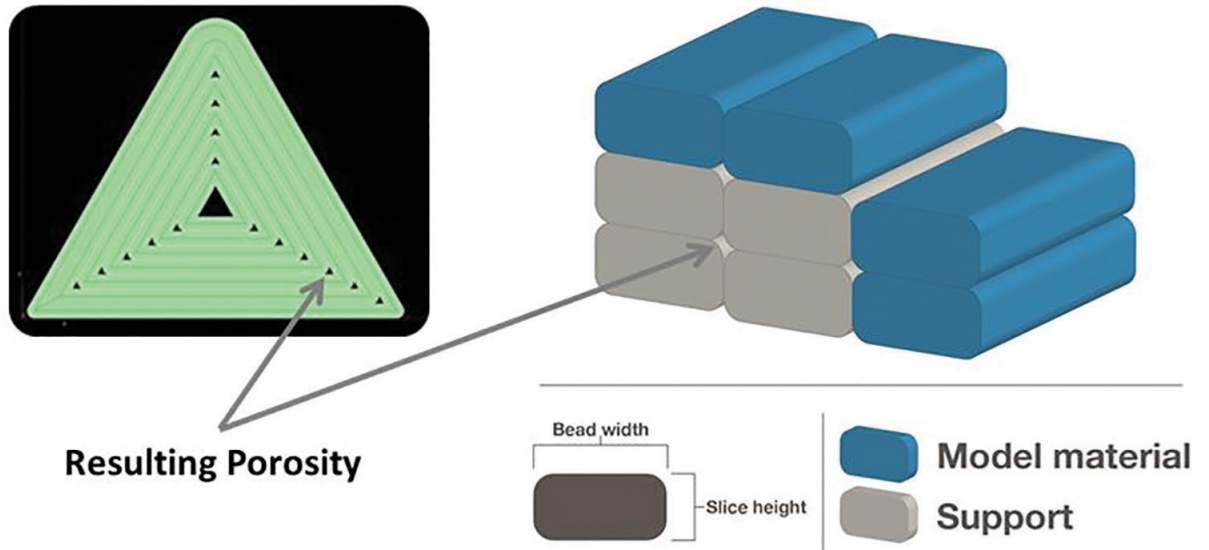


Figure 10. Top view of a toolpath (left) and cross-section of bead profiles (right) demonstrating the inherent porosity of FDM parts.

is connected to the tool, which creates a negative pressure inside the cavity. Holes on the tool surface allow for proper suction to ensure the composite part is held firmly in place.

The FDM machining fixture was designed to perform in a similar manner. The tool measured 92 cm x 61 cm x 16 cm and was designed as a sparse style tool. It incorporated a large infill spacing to promote maximum porosity inside the tool. The external surfaces needed to be sealed in order to achieve sufficient vacuum. Otherwise, the vacuum source would pull air through every surface, which may not be adequate to secure the composite part.

Initial trials sought to prove if this concept was a viable solution. Spray paint was used as the sealer and applied to every external surface of the tool, except where the composite part would rest. A plastic release liner was placed over the tool to visibly indicate that the tool was able to direct sufficient suction to the tool surface as shown in Figure 11.

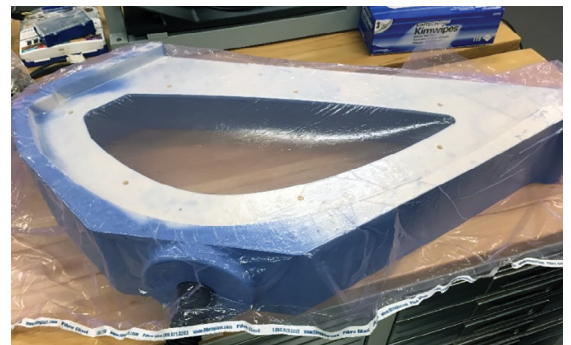


Figure 11. Test setup to evaluate the effectiveness of using spray paint to effectively seal the edges of the vacuum fixture.

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The results were favorable so a second tool was printed, but used an epoxy to seal the outer surface. Though epoxy increases cost and labor time, it delivers a more robust and thorough sealing of the tool. The tool was printed with ASA material on a Fortus 900mc and took 28 hours to print plus one hour of labor to seal the external surfaces, for a total cost of \$1700.

Ergonomic Tool Cradle

Stratasys participated in the evaluation of FDM composite tooling for the Air Force Research Lab responsive tooling program. A combination of lay-up mold and support cradle were printed with FDM. The layup tool was designed as a shell-style tool and printed with ULTEM 1010 resin to meet the required 176 °C / 0.68 MPa autoclave cure-cycle parameters.

Due to the curved shape of the layup tool, an ancillary holding cradle was designed and printed to provide stability while the part was being laid up. The cradle measures 69 cm x 38 cm x 18 cm and was printed in the vertical orientation to achieve the best surface resolution, which allowed the layup tool to properly nest inside the cradle. The cradle would not be subjected to the elevated temperature or pressure of cure cycles so it was

printed out of ASA material to reduce cost. It was built on a Fortus 900mc in 17 hours and cost \$1100 (material cost and build time).

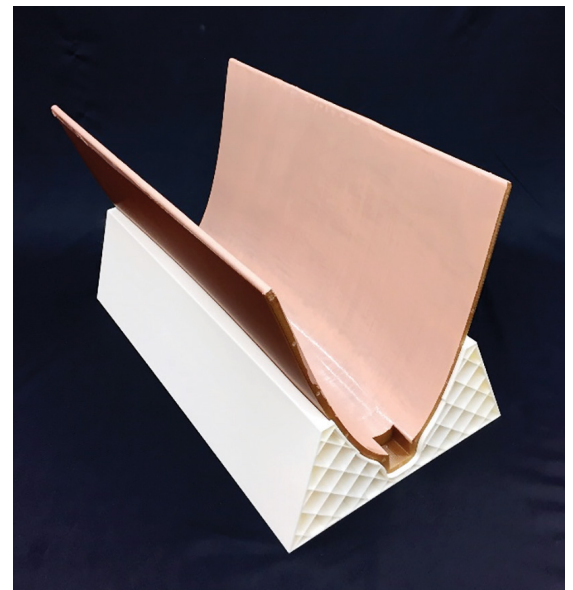


Figure 12. ULTEM 1010 layup tool nested into ASA cradle.

CONCLUSION

FDM is a proven additive manufacturing technology used to create tools for the composites industry ranging from high-temperature lay-up tools to ancillary tools used for secondary processes. These tools can be printed with a variety of available high performance thermoplastic materials and can be tailored to the application requirements. FDM ancillary tools are compatible with common inserts and can be built in segments and subsequently bonded together for tools larger than the build envelope. Unlike subtractive manufacturing methods, FDM allows for highly complex and customized tools to be printed in a matter of hours or days and typically at a fraction of the cost.

The reduced cost, lead time, and increased customization enables optimization during the design and manufacture of composite parts and has the potential to truly disrupt industries invested in composite fabrication.



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