Demonstration of Additive Manufacturing (FDM) for Production Composite Tooling at Dassault Falcon Jet

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White Paper

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FDM® (Fused Deposition Modeling) technology from Stratasys has been used for years to produce cost-effective composite mold tooling for the aerospace industry in a fraction of the time of traditional tooling. However, printed tooling has primarily been used to produce prototype or development tooling, repair tooling and master patterns to produce final production tooling. The technology has consistently demonstrated its value for these applications. Leading the way in moving beyond development tooling, the Manufacturing Tooling team at the Completion Center for Dassault Falcon Jet worked closely with the Composite Solutions team at Stratasys to demonstrate the viability of the technology for production-grade tooling – from lay-up molds to machining fixtures. This paper outlines the development and evaluation effort from the initial design phases through final composite part production and provides associated results and lessons learned.

Dassault Falcon 2000LX

Introduction

Dassault Falcon Jet is a division of Dassault Aviation, an international French aircraft manufacturer of military, regional and business jets with nearly 90 years of aviation experience. Dassault conceived and launched their first purpose-built business jet, the Mystère-Falcon 20, over 50 years ago. Twenty different models have followed in the years since and presently, more than 2,250 Falcons have been delivered to 82 countries around the world. Dassault Falcon Jet's facility in Little Rock, Arkansas, is the site of the main Completion Center for all Dassault Falcon jets worldwide. Current production model Falcons are manufactured in France, then flown in "green" condition to the Completion Center where optional avionics and custom interiors are installed, and exteriors are painted. It is at this facility where the Manufacturing Tooling team has introduced additive manufacturing technologies with the objective of addressing current production challenges as well as continuing to position the company as an innovative industry leader.

FDM is a Stratasys-patented additive manufacturing technology that builds parts layer by layer by heating and extruding thermoplastic filament. FDM builds in a wide range of standard, engineering-grade, and high-performance thermoplastics, such as ABS, PC, and ULTEM™ resins. For years, the technology has been used for rapid production of high temperature (>180 °C), low-volume composite lay-up and repair tools. Relative to traditional tooling materials and methods, FDM offers significant advantages in terms of lead time, tool cost and simplification of tool design, fabrication and use while enabling increased functionality, greater geometric complexity and significant tool mass reduction.

To enable successful implementation and use of FDM composite molds and mandrels (referred to as "composite tooling" or "composite lay-up tooling" herein), Stratasys has developed a comprehensive Design Guide to address best practices for printed tooling, as well as to provide numerous examples of effective tool designs[1].

Background and Purpose

At the Falcon Jet Completion Center, the team at Dassault receives the aircraft in its basic, green state and adds exterior paint, systems and wiring, cabinetry and upholstery. The cabinetry incorporates a high degree of composite structures (laminates and sandwich structures) to provide performance, durability and custom geometries in addition to significant weight savings. The Process, Methods & Tooling team is responsible for all required tooling and the necessary manufacturing operations to produce such structures.

The methods used to produce the majority of current mold tooling at Falcon Jet are both time- and labor-intensive, as will be discussed in more detail in Current Falcon Jet Tooling Approach. Even for what are considered "small" structures (less than approximately 1,500 mm in length), it is not uncommon to have a 10+ week lead time. This lead time can be manageable for some parts and programs, but the Falcon Jet team also offers its customers a high level of potential customization that creates a high product mix and necessitates quicker response times. This high mix and the need for reduced lead times led the Falcon Jet tooling team to engage the Composite Solutions team at Stratasys to support evaluation of FDM production tooling.

Scope and Contents

The teams at Falcon Jet and Stratasys collaborated to evaluate FDM mold tooling and machining fixtures for use in producing interior composite structures. The structures were generally classified into "small" (less than approximately 1,500 mm in length) and "large" (greater than 1,500 mm in length and up to 5,000 mm). This paper provides an overview of the evaluation project, primarily focused on small tools. Information will also be provided on the large tool geometries evaluated as well, but more depth will be provided on that project in future publications. For small tools, the development and evaluation effort from the initial design phases through final composite part production will be covered as well as associated results and lessons learned.

As noted, Stratasys has developed a comprehensive Design Guide on FDM composite tooling, the purpose of which is to provide engineers, designers and manufacturers of composite structures with the information and knowledge to effectively design, produce and use FDM composite tooling. This paper provides a demonstration of the methods used in the Design Guide, although it will not contain the depth or detailed design aspects provided in that document.

Requirements

The first step in the development project was to review the basic requirements and assess the needs of the application relative to the capabilities of FDM technology. The general requirements for interior structures at Falcon Jet and commentary on the ability of FDM to meet them are provided in Table 1.

As noted in Table 1, the cure temperature requirements for Falcon Jet applications are between 121˚C and 138˚C. At this temperature, there are multiple FDM materials that could potentially be used. However, Stratasys recommends and uses ULTEM 1010 resin for such applications as it provides superior temperature resistance (Tg 215˚C) and provides the lowest coefficient of thermal expansion, or CTE (47 μm/m·°C), of currently available FDM materials.

Falcon Jet Requirement	Stratasys FDM Compatibility
Materials Fiberglass and carbon fiber / epoxy laminates and honeycomb core sandwich panels	FDM is commonly used for such materials and structures.
Process Vacuum-bag, oven cure – > 635 mm-Hg Carbon fiber cure temperature – 138 ˚C Fiberglass cure temperature – 121 ˚C	This temperature range and consolidation method is well suited to the capabilities of ULTEM 1010 resin FDM tools.
Part Volumes (and tool life) Typical – 300-500 parts Desired – cost-effective low volume production, < 50 parts	ULTEM 1010 resin FDM tooling is typically used for low-volume (< 50 parts) production. At the required temperature/pressure combination, longer tool life is anticipated.
Part Tolerances Part length < 800 mm – ± 2 mm Part length > 800 mm – ± 2.5 m	FDM has consistently demonstrated the ability to exceed these requirements, particularly for tools smaller than 1 meter in length. Capabilities for larger, multi-segment tools require further assessment.

Table 1. Application requirements and FDM compatibility assessment.

Current Falcon Jet Tooling Approach

For the majority of current mold tooling, the Falcon Jet tooling team uses fiber-reinforced polymer (FRP) composite materials. Such tools are very effective at producing the typical 300-500 part volumes required for many interior structures. However, as shown in Figure 1, the process to produce such tooling is time- and-labor intensive, resulting in high costs and long lead times. The basic steps start with the creation of a master mold, typically CNC-machined out of a tooling board material. From the master, the final mold (or machining fixture) is hand laid-up out of fiberglass/epoxy or similar materials, cured and then assembled with a backing or support structure. Additional trimming, machining and hole drilling operations are typically required.

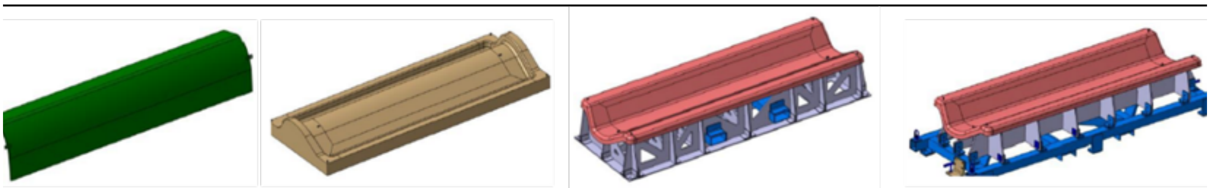
Lead time for Falcon Jet's standard FRP tooling can often exceed 10+ weeks. For the high level of customization that Falcon Jet offers their customers, quicker response times are a necessity which lead to their tooling team engaging with Stratasys to evaluate FDM tooling.

FDM Composite Tooling Overview

Conventional manufacturing methods for composite structures typically use mold tooling made of metallic materials (aluminum, steel or invar alloys) or specialized FRP materials. Regardless of material, tool fabrication requires significant labor and machining, leading to high costs and long lead times. As a whole, the composites industry is continually pushing for innovative tooling solutions to address these challenges, as well as to enable new use cases and product improvements. FDM technology allows rapid production of effective composite mold tooling across a broad range of tool sizes and complexities, and while not required for the applications discussed herein, are capable of performing at cure temperatures in excess of 180 ˚C in typical autoclave cycles (consolidation pressures exceeding 0.7 MPa).

Key Considerations

From a functional perspective, the use of FDM composite mold tooling is not drastically different from using conventional tooling. Just as design and construction aspects of conventional lay-up tooling vary depending on the material used,



Curved Panel — (Renshape 5008) — (Fiberglass sandwich panel) — (Fiberglass, alum structure

Costs/Times

	Master Mold	Lay-Up Mold	Machining Fixture
Small Tools	$20K / T0 + 6 weeks	$25K / T0 + 10 weeks	$20K / T0 + 16 weeks
Large Tools	$40-60K / T0 + 8 weeks	$45-65K / T0 + 13 weeks	$35-65K / T0 + 17 weeks

Figure 1. Current Falcon Jet tooling approach (FRP tooling) and associated costs/lead times.
Note – In Figure 1 above, T0 refers to the point in time at which the purchase order is placed.

there are a number of considerations to keep in mind for effective design and use of FDM composite tooling. The primary considerations for FDM composite tooling include cure temperature, coefficient of thermal expansion (CTE), process parameters and anticipated use/tool life. Each of these considerations is covered in greater detail in the Stratasys design guide.[1]

Design

FDM composite tools are primarily classified as “shell” or “sparse” style (cellular) tools. The basic differences are as shown in Figure 2. Fabrication process and cure cycle parameters, particularly cure pressure and vacuum bagging method, impact the design of FDM composite tools.

While effective for many applications, shell style tools are typically used where build time is critical and the intended part volume is very low, such as repair tools and “one-off” prototype structures. Sparse style tools tend to have greater overall rigidity and stability and as a result, are used for higher volume and production-oriented applications.

Tool Preparation (Post-Processing)

The FDM process inherently produces some level of internal porosity due to physical limitations of the extruded material beads. A representation of this porosity can be seen in Figure 3, which shows the cross-section of tool paths (extruded material) for an example build layer.

The FDM process also produces perceptible build layers, which vary based on the shape of the part and the layer thickness. As a result, to ensure a high-quality surface finish and vacuum integrity, post-processing of FDM tools is typically required. There are a range of methods to address tool preparation which have been discussed in previous papers[2] as well as in the Stratasys Design Guide. Common methods include manual abrasion, application of release films and CNC machining.

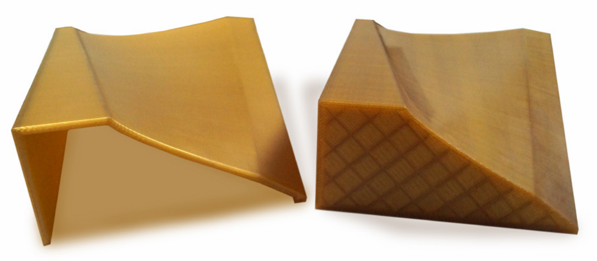


Figure 2. FDM tool construction styles.

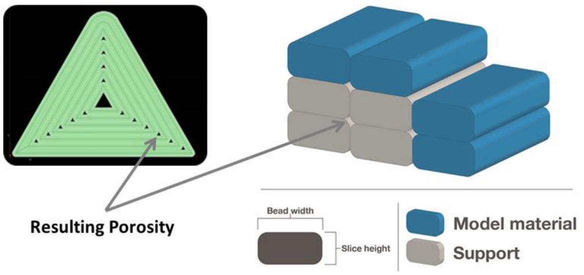


Figure 3. This cross-section of FDM tool paths illustrate the inherent occurrence of porosity (from Stratasys Insight software).

Ancillary Tooling

Composite parts are subjected to numerous secondary operations, such as trimming, machining, drilling, bonding, painting, inspection and assembly. All of these operations require tooling – drill jigs, machining fixtures, bond fixtures and many other manufacturing aids – to ensure high-quality final parts are produced. FDM is well suited to produce the entire tooling string in many cases and typically provides significant design, cost, time and weight benefits.

Falcon Jet
Tool Evaluation

The Tooling Engineering team at Dassault Falcon Jet identified multiple candidate geometries for evaluation with FDM tooling. Specifically, two part geometries classified generally as “small” and one classified as “large” were identified. The evaluation started with the smaller structures for the sake of simplicity and so that lessons learned could be applied to the higher-value, higher-cost large part. After identifying the structures of interest and establishing the requirements for the application (refer to Requirements section), the Composite Solutions team at Stratasys developed multiple design concepts for each geometry along with the associated cost, build time and physical characteristics. The teams then worked collaboratively to refine the designs and build initial prototypes for evaluation, as well as to identify desired changes (e.g., size, shape and thicknesses, etc.) and key areas of additional testing required to finalize the tool designs. The primary testing in this case was an assessment of the thickness required to provide stability for bushings, Section 5.1. A summary of the process/design concepts for each part are provided in the following sections.

Preparation and Testing

To establish the necessary thickness for the “facesheet” of the FDM mold tool required for tool bushings, the Dassault Falcon Jet-Stratasys team built a basic test panel as shown in Figure 4. The thickness was varied across the test panel, along with undersized holes that were subsequently reamed to the final diameter after printing. Inserts were heat staked into the geometry and a FARO arm scanner was used to measure the location of the bushings before and after eight thermal cycles at 121 °C ± 5.5. Table 2 shows the measurement data for before and after thermal cycling. This simple study shows bushing locations remained within 0.18 mm of their initial location after eight cycles. The direction that showed the largest dimensional change (Y-direction) was the direction of the longest tool path (the direction of printing within a single layer). The X-direction in Figure 4 is the direction of layer deposition, also known as the build orientation or the Z-axis in the printer.

Bushings		**Sample Thickness**	**No curing**		**After 8 cycles (121 °C ±5.5)**		**Differences**	
Sample	Diameter (mm)	(mm)	X Dev	Y Dev	X Dev	Y Dev	X Dev	Y Dev
1	8	5	-0.44	0.53	-0.45	0.37	0.00	0.17
2	8	10	-0.35	0.01	-0.35	-0.16	0.00	0.17
3	8	15	0.15	-0.60	0.17	-0.78	-0.02	0.18
4	6	5	-0.28	-0.14	-0.30	-0.32	0.02	0.18
5	6	10	-0.04	-0.25	-0.07	-0.42	0.03	0.17
6	6	15	0.12	0.41	0.12	0.24	0.00	0.17

Table 2. Accuracy Measurements for bushing locations.

The 0.18 mm of deviation was considered acceptable and manageable for Dassault Falcon Jet. Based on the dimensional data, a thickness of 10 mm for the face sheet was determined to be optimal as this provided complete support of the desired bushings and any additional part thickness did not display a significant effect on dimensional stability. There are multiple strategies for adding thickness at bushing locations in FDM tooling and parts. Although those strategies are outside the scope of this paper, they are covered in detail in the FDM for Composite Tooling Design Guide.

Part Selection

After testing the ULTEM 1010 resin material capability and bushing tolerance, the Falcon Jet team selected three parts to move forward with tool design. As previously indicated, two parts are categorized as "small" and one "large." Both small parts were selected for their ability to be built as a single structure in the Fortus 900mc™ or the Stratasys F900™, the largest Stratasys commercial FDM platform. The build volume of the Fortus 900mc is 914 x 609 x 914 mm. The large tools will require printing as multiple pieces and assembly to create the final tool structure.

Small Tool #1 – Medicine Cabinet Panel

The first part selected for evaluation was a sandwich panel for a medicine cabinet. The panel required a 121 °C cure temperature under vacuum pressure. The sandwich panel consisted of a fiberglass/epoxy prepreg and Nomex® honeycomb core. The panel dimensions were 890 x 190 x 6.35 mm. The medicine cabinet panel was selected for both its size and the ability to do a direct comparison against a current FRP tool.

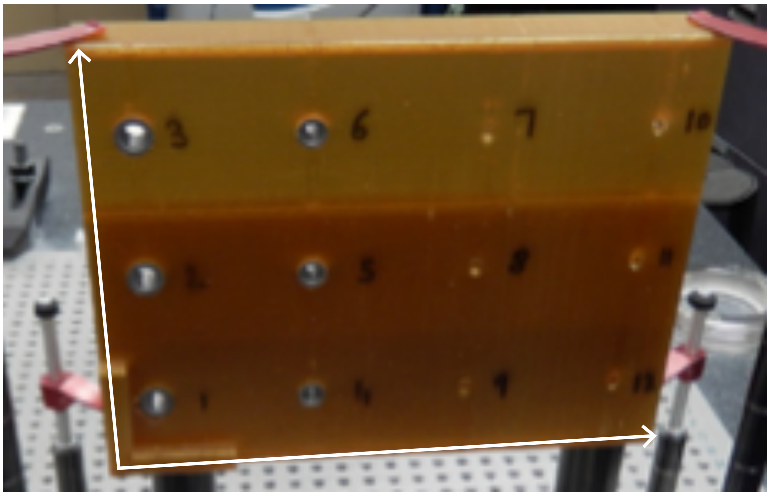


Figure 4. View of the printed geometry with inserted bushings. Solid arrows indicate measurement direction.

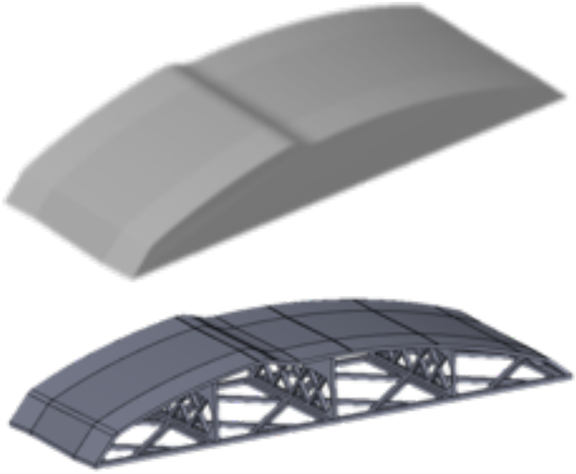


Figure 5. Medicine cabinet panel mold designs. Sparse style (top) and shell style (bottom).

With Falcon Jet's use case in mind, the Stratasys Composite Solutions team proposed two designs, shown in Figure 5. The designs can be categorized as sparse and shell style. Although a bit counterintuitive, the sparse style design actually required less material because of a mostly hollow internal structure, which is shown in Figure 6 next to the traditional FRP tool. The shell style tool shows some of the complexity that is achievable with additive manufacturing. However, the shell style tool is anticipated to require more material and be less resilient to the manufacturing environment. Both designs utilize the same optimization mentality of reducing excess bagging area and minimizing material use, while also optimizing lay-up surface quality. Ultimately, the sparse style design was selected for its reduced cost and higher anticipated robustness and usability.

The FDM medicine cabinet lay-up mold was built with ULTEM 1010 resin and sealed with a high temperature epoxy (BJB Industries TC-1614). The epoxy sealer helps ensure vacuum integrity and enables polishing to achieve a surface roughness below 0.8 µm Ra. As previously mentioned, ULTEM 1010 resin was selected as the FDM mold material for its superior temperature resistance (Tg 215 ˚C) and reduced CTE (47 µm/m·°C) relative to other FDM materials. The internal structure of the lay-up mold was left exposed (i.e., open on the ends/ sides of the tool) to enable better airflow in the oven and achieve quicker and more uniform heating and cooling at the tool surface.

Table 3 shows a basic comparison of the FDM lay-up tool to the traditional FRP tool. The FDM mold shows a dramatic reduction (>80%) in lead time, cost and mass over traditional FRP tooling. It should be noted that the life of an FDM mold is not projected to match that of an FRP mold. However, at the writing of this paper, Falcon Jet has successfully built 15 composite panels and the mold is predicted to last 100 cycles at the 121 °C cure temperature.

In addition to the lay-up mold, the machining fixture for the medicine cabinet panel was also designed and produced with FDM. Figure 7 shows the traditional FRP machining fixture next to the FDM fixture. The machining fixture will only be exposed to minimal loading from machining and no foreseeable elevated temperatures. Therefore, it was produced in ASA (Acrylic-Styrene-Acrylonitrile). ASA is a robust general-purpose material used in additive manufacturing

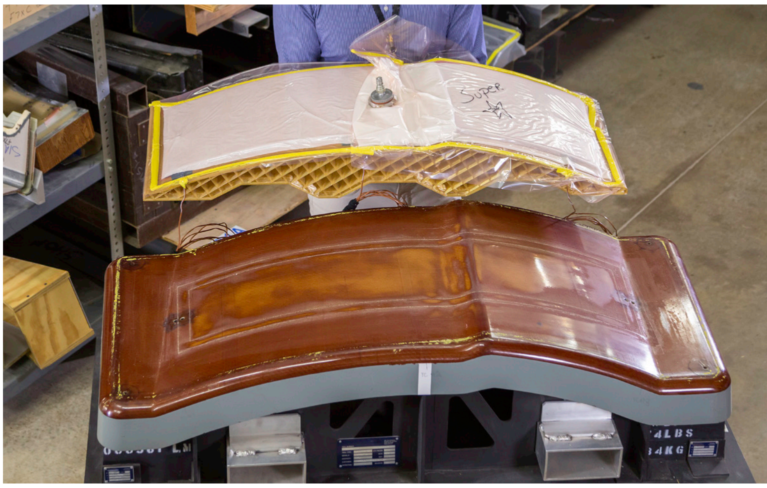


Figure 6. Medicine cabinet lay-up molds. FDM tool (top). Traditional FRP tool (bottom).

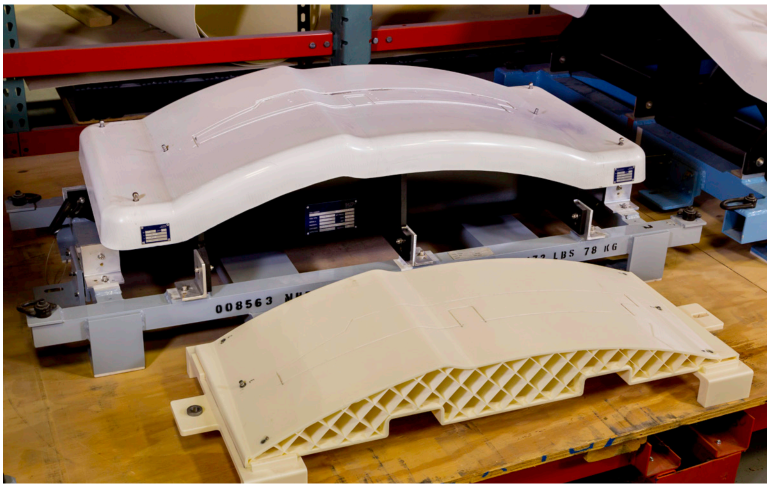


Figure 7. View of the FRP machining fixture (top) next to the FDM machining fixture (bottom).

Tool	Material	Build/ Lead Time	Cost	Weight (kg)	Footprint (mm)
MC – Lay-up – FDM	ULTEM 1010	38 hrs	$5,600	7	1,100 x 400
MC – Lay-up – FRP	Fiberglass/Epoxy	8-10 weeks	$20,200	48	1,200 x 200
MC – Machining – FDM	ASA	49 hrs	$4,300	9.5	1,200 x 600
MC – Machining – FRP	Fiberglass/Alu	10-12 weeks	$18,000	78	1,500 x 700

Table 3. Comparison of the medicine cabinet (MC) FDM tooling to the traditional FRP tooling.
Note: Build time for FDM refers to only the time to print the tool; no finishing time is included. Lead time indicates time from a purchase order to delivery.

for a variety of applications. It is offered in an array of colors to enable visual labeling or tool family coordination and it is a more economical material than the high-performance ULTEM 1010 material. Table 3 shows a comparison of the FDM machining fixture to the FRP fixture. Similar to the lay-up mold, the FDM machining fixture displays a dramatic reduction in lead time, cost and mass.

The design of the machining fixture mimicked that of the lay-up mold, utilizing a sparse style construction to minimize material use and maximize utility. The machining fixture required the incorporation of lift points to allow positioning on a multi-axis CNC table, as well as specialized brackets for mounting to the CNC table. The brackets were printed as separate parts and bonded to the main structure using a two-part epoxy paste adhesive. The composite panel is held in place during machining by part locator tabs and double-sided tape.

Small Tool #2 – Speaker Box

The second small part that was selected for evaluation was a speaker box panel. The traditional FRP tool for the panel is shown in Figure 8. It had the same material construction (fiberglass/epoxy with a Nomex honeycomb core) and cure requirements (121 °C under vacuum pressure) as the medicine cabinet panel. The panel's approximate dimensions were 500 x 431 x 6.35 mm.

The design concepts for the speaker box panel are displayed in Figure 9. Just like the medicine cabinet, the Stratasys team presented shell and sparse style design approaches. If desired, the shell style design could have been paired with a low-cost cradle to enable ergonomic lay-up and simplified use. Contrary to the medicine cabinet panel, the shell style design for the speaker box mold was predicted to require less material and cost roughly $1,400 less than the sparse style design. However, the Dassault Falcon Jet team selected the sparse style design for its greater robustness, usability and as a closer comparison to their current FRP mold.

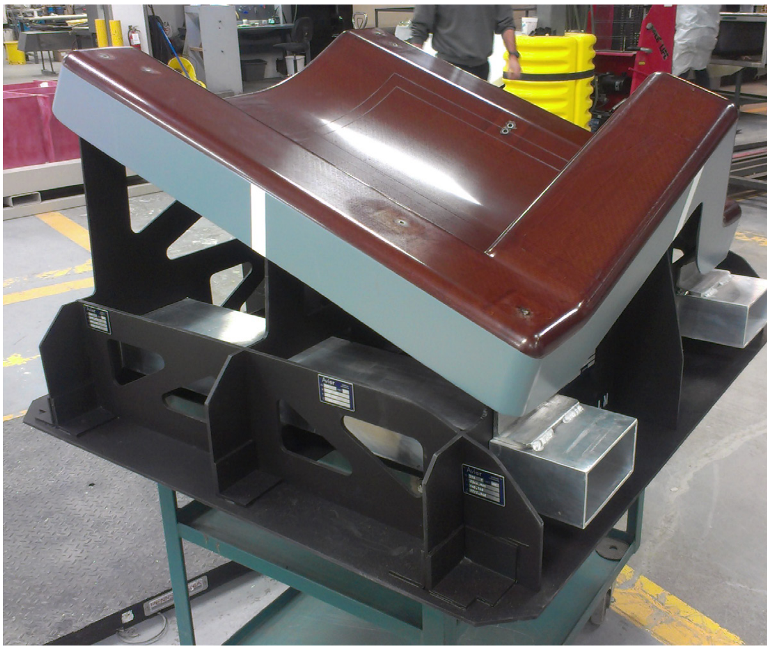


Figure 8. Speaker box FRP mold.

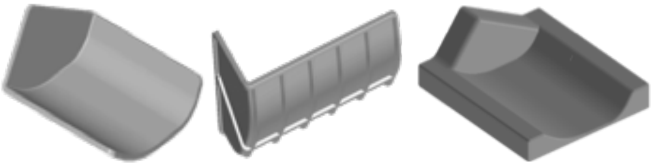


Figure 9. Proposed speaker box lay-up mold designs. Shell style (left and middle). Sparse style (right).

After initial printing of the speaker box lay-up mold, it was discovered that the incorporation of handles would greatly improve the handling of the mold. Therefore, the design was updated to that shown in Figure 10. This ability to cost-effectively alter tool designs to incorporate ergonomic features, increase design complexity and improve workflow with virtually no increase in manufacturing cost is a significant benefit of additive manufacturing.

In addition to the lay-up mold, the machining fixture for the speaker box panel was also designed and produced with FDM. Figures 11 and 12 show the FRP and FDM machining fixtures, respectively. The machining fixture for the speaker box panel shows a significant increase in design complexity from the medicine cabinet mold. The FDM machining fixture incorporates handles for usability, leveling points to enable greater freedom on the CNC table, and a shell-style design to minimize material use and print time. Table 4 shows a comparison of the FDM tool to the traditional FRP tool. The FDM lay-up mold and FDM machining fixture display a >80% reduction in lead time, cost and mass.

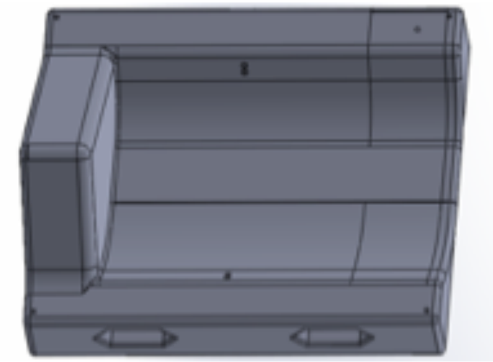


Figure 10. Updated mold design for the speaker box panel for improved handling.

Figure 11. FRP machining fixture for the speaker box panel.

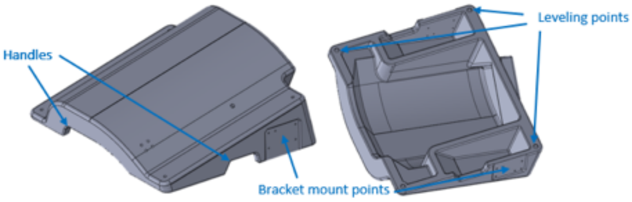


Figure 12. Views of the FDM speaker box machining fixture design.

Tool	Material	Build/ Lead Time	Cost	Weight (kg)	Footprint (mm)
SB – Lay-up – FDM	ULTEM 1010	70 hrs	$4,600	7	800 x 600
SB – Lay-up – FRP	Fiberglass/Epoxy	8-10 weeks	$22,000	48	1,000 x 1,000
SB – Machining – FDM	ASA	50 hrs	$1,720	9.5	700 x 600
SB – Machining – FRP	Fiberglass/Alu	10-12 weeks	$20,500	83	1,000 x 1,000

Table 4. Comparison of the speaker box (SB) FDM tooling to the traditional FRP tooling.
Note: Build time for FDM refers to only the time to print the tool, no finishing time is included. Lead time indicates time from a purchase order to delivery

Large Tool – Cabinet Headliner

The large part that was included in this evaluation was a cabinet headliner panel, shown in Figure 13. As with the other interior panels in this evaluation, the cabinet headliner panel was a fiberglass/epoxy sandwich structure with a Nomex honeycomb core. It required a cure temperature of 121 °C under vacuum pressure. Unlike the other panels in this evaluation, the cabinet headliner did not have an existing FRP mold for comparison. The approximate dimensions of the panel were 1,560 x 1,185 x 6.9 mm.

The design concept for the cabinet headliner mold is displayed in Figure 14. The mold was designed to be printed in four sections as it cannot be printed as a single structure on current FDM platforms. The mold was designed as a near-net geometry with 3 mm of excess thickness at the mold surface to allow for skim-coat machining to the final dimensions. The mold also incorporated lift points for handling, mount points for the skim coat machining operations, as well as localized reinforcement for bushings to allow CMM operations and for panel locating tabs. The sections of the cabinet headliner mold were designed to be bonded and assembled with mortise and tenon-style joints. Figure 15 shows the cabinet headliner mold after bonding and assembly.

Skim-coat machining of the large cabinet mold was anticipated to improve dimensional tolerance of the headliner mold as well as the surface roughness of the as-printed structure. However, surface roughness was not predicted to be reduced below 0.8 µm Ra or result in a vacuum-integral surface. Therefore, the large cabinet headliner mold was sealed with a high-temperature epoxy and polished to the desired surface roughness.

Table 5 displays basic cost, lead time and mass data in comparison to an equivalent FRP mold. The scale of the headliner mold and the added time and labor for finishing processes do impact the value proposition compared to the previously discussed molds. However, additive manufacturing with FDM still shows a reduction in lead time of > 65%, approximately 24% reduction in cost and a reduction in mass of 24%.

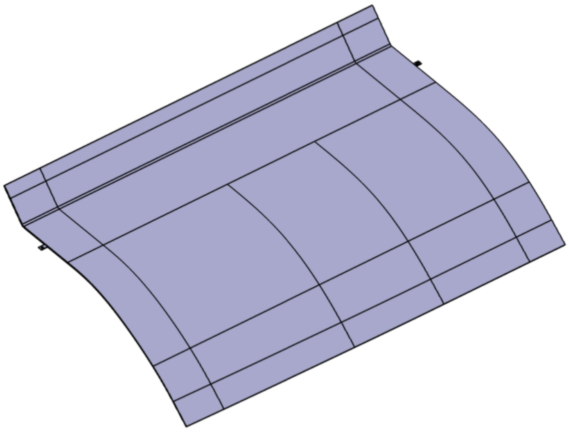


Figure 13. CAD rendering of the cabinet headliner panel.

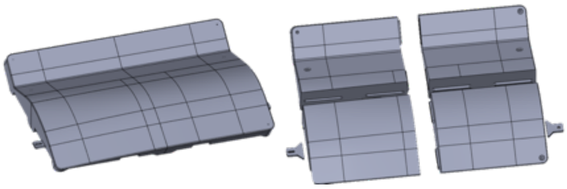


Figure 14. CAD rendering of the cabinet headliner panel.

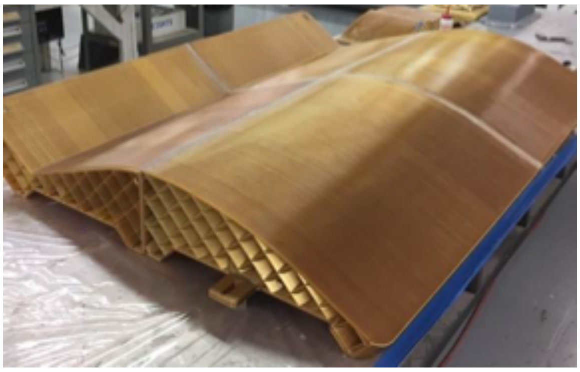


Figure 15. Assembled 4-piece FDM cabinet headliner lay-up mold.

Tool	Material	Build/ Lead Time	Cost	Weight (kg)	Footprint (mm)
CH – Lay-up – FDM	ULTEM 1010	6 weeks	~$34,000	76	1,800 x 1,400
CH – Lay-up – FRP	Fiberglass/Epoxy	12 weeks	~$45,000	100	2,000 x 1,500

Table 5. Comparison of the FDM headliner mold (CH) compared to the projected FRP mold.
Note: Build time for FDM in this case includes finishing operations. Lead time indicates time from a purchase order to delivery.

RESULTS AND CONCLUSIONS

The Manufacturing Tooling team at Dassault Falcon Jet has evaluated multiple geometries and applications of FDM technology for use in their manufacturing environment. The results for each of the aforementioned molds will be discussed in the sections below. Additionally, Dassault Falcon Jet has assigned a manufacturing readiness level (MRL) to FDM or additively manufactured tooling based on application. Table 6 offers a brief explanation of the various manufacturing readiness levels. Machining fixtures and templates have achieved MRL9 while lay-up tooling is still undergoing additional evaluation and is currently considered to be at MRL7

	Manufacturing Readiness Level
MRL10	Full-rate production demonstrated and lean production practices in place
MRL9	Low-rate production demonstrated; capability in place to begin full-rate productions
MRL8	Pilot line capability demonstrated; ready to begin low-rate production
MRL7	Capability to produce components in a production-representative environment
MRL6	Capability to produce a prototype system in a production-relevant environment
MRL5	Capability to produce prototype components in a production-relevant environment
MRL4	Capability to produce the technology in a laboratory environment
MRL3	Manufacturing POC completed
MRL2	Manufacturing concepts identified
MRL1	Basic manufacturing implications

Table 6. Manufacturing readiness level descriptions

Small Lay-up Tools

The Stratasys team provided the medicine cabinet lay-up mold to the Dassault Falcon Jet team sealed and polished to a surface roughness below 0.8 µm Ra. CMM inspection of the cabinet lay-up mold revealed a profiled tolerance of ± 1.5 mm. The speaker box lay-up mold has not yet been evaluated but will likely be investigated in future work. To date, Falcon Jet has produced 15 parts from the medicine cabinet lay-up mold, 10 of which were for production and the other five were prototypes for evaluation and testing.

The design and construction of the medicine cabinet lay-up mold resulted in an easy-to-use, efficient composite mold. Incorporating open ends to increase airflow resulted in reduced cure cycle times from their traditional FRP tool. This further reduced manufacturing costs for the laminate and increased capacity.

In addition to the medicine cabinet lay-up mold, machining fixtures for both the medicine cabinet and speaker box were provided to the Falcon Jet team. To date 10 parts have been trimmed utilizing FDM machining fixtures. The FDM tooling has proven to be easy to use, handle and repair.

Falcon Jet's use of the machining fixtures did reveal areas where minor design changes could further improve usability and effectiveness. Specifically, using more localized reinforcement at mounting points and lift points could improve durability in the shop environment. Additionally, increasing the weight of the fixtures could help reduce vibrations from the machining process.

Large Lay-up Tool

Dassault Falcon Jet assembled and machined the large lay-up mold at their Little Rock, Arkansas facility. However, due to scheduling and facility constraints, the mold was finished (sealed and polished) by an external vendor.

Dimensional inspection of the finished mold surface revealed a profile tolerance within the desired ± 1.5mm. At the writing of this paper one part had been produced on the mold and the Falcon Jet team described that part as good and acceptable. However, during their use of the large FDM tool, Falcon Jet had a few difficulties. The skim-coat machining and finishing operations were less than ideal process steps.

One of the primary reasons to produce composite tooling via additive manufacturing is to eliminate and/or minimize the need for CNC machining. Although machining FDM is possible, Dassault Falcon Jet does not anticipate utilizing the near-net shape approach in future projects.

Alternatively, they intend to pursue net shape or directly printed FDM tooling to maximize its lead time and cost advantages.

Additional work is needed to further characterize large FDM tooling and understand expected tool life, tolerances and assembly techniques. The results of such investigations will be addressed in future papers.

Conclusions

The Dassault Falcon Jet and Stratasys teams have demonstrated FDM is a capable and economically efficient technology for composite fabrication for both production mold tooling and machining fixtures. Although additional characterization is underway to further understand the limitations and longevity of various FDM materials for such applications, Dassault Falcon Jet has now qualified/approved utilizing FDM for small complex lay-up tooling, machining fixtures and templates to enable them to offer cost effective customization to their product portfolio. The Stratasys and Dassault Falcon Jet teams will continue to investigate and further characterize the applications discussed in this paper as well as new applications of additive manufacturing in their manufacturing environment.

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