Introduction to Additive Manufacturing for Composites

ENABLING A NEW ERA OF DESIGN OPTIMIZATION, COMPLEXITY, AND FUNCTIONALITY FOR COMPOSITE STRUCTURES

stratasys

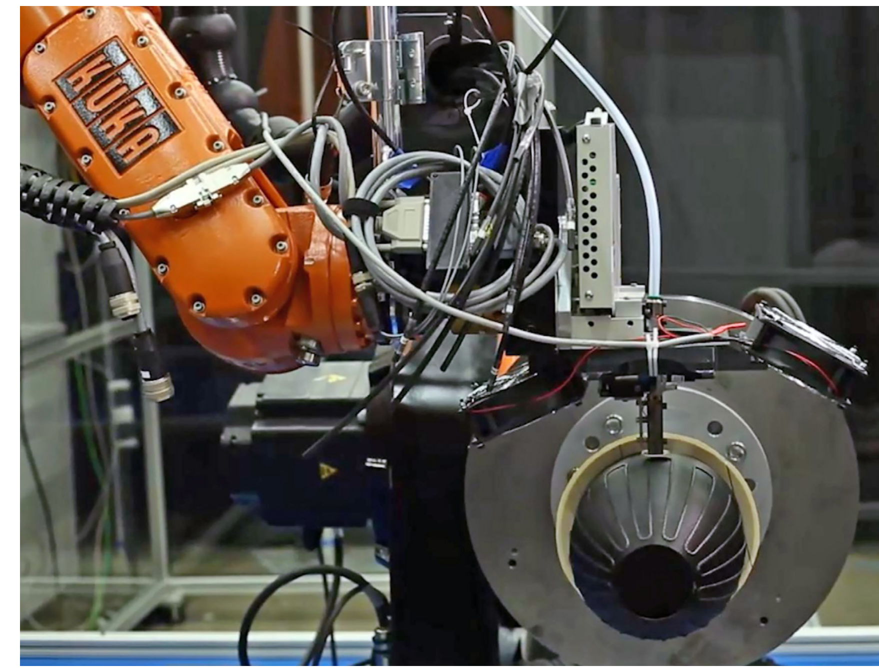
THE **3D PRINTING SOLUTIONS** COMPANY™

INTRODUCTION TO ADDITIVE MANUFACTURING FOR COMPOSITES

INTRODUCTION

Additive manufacturing (AM) encompasses methods of fabrication that build objects through the successive addition of material, as opposed to subtractive methods such as CNC machining, that remove material until a final shape is achieved. Composite fabrication is one of the most original forms of additive manufacturing. Whether the process involves wet lay-up, hand lay-up of prepreg materials, or automated fiber placement (AFP), methods of composite manufacture are distinctly additive in nature, building up to final part forms typically one layer at a time. However, the nature of additive manufacturing has been revolutionized with the advent of the 3D printing industry.

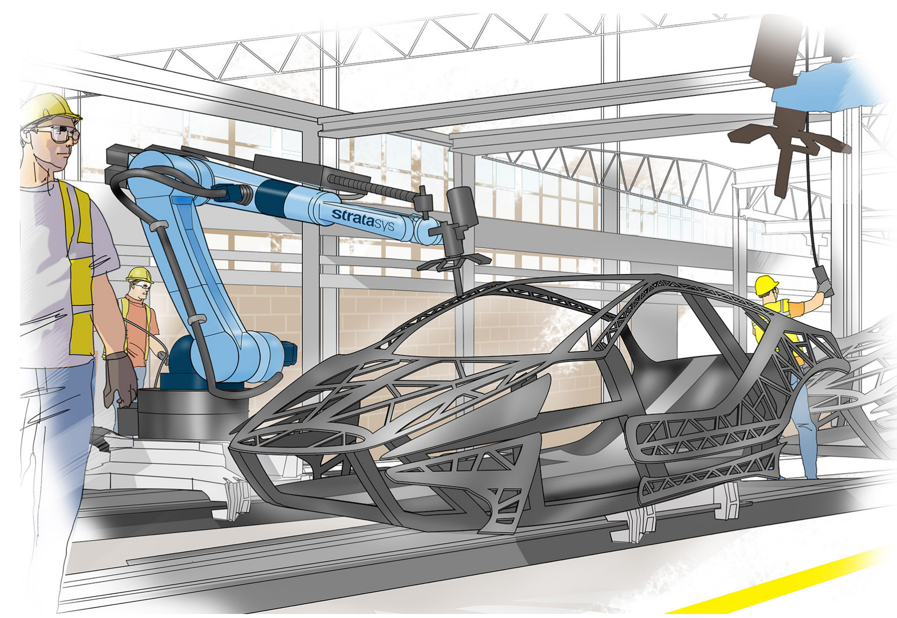
For the past several decades, 3D printing technologies have advanced rapidly and recently reached a state of mainstream adoption, particularly for rapid prototyping. Such technologies are only beginning to penetrate and influence the advanced composites industry, although the AM industry is clearly approaching a tipping point where the impact on the composites industry is expected to become as broad and significant as that in prototyping.



EXTRUSION-BASED ADDITIVE MANUFACTURING TECHNOLOGIES

While there are a variety of AM technologies and many have some potential relevance for producing composite parts, the focus here is on extrusion-based technologies, as they have both the most current relevance and a clear path to significant future impact as well. Fused Deposition Modeling (FDM®) is a patented AM technology, invented by Stratasys, which provided the basis for extrusion-based AM approaches. FDM technology builds parts layer-by-layer by heating and extruding thermoplastic materials in a highly controlled and automated manner.

FDM uses a wide range of materials from standard to engineering-grade, also encompassing the most high-performance thermoplastic materials. Such materials provide the foundation for high-performance composite systems, as the process is conducive to a similarly broad array of reinforcement or specialty filler materials, from particulates to short fibers to continuous-fiber reinforcements. This capacity to incorporate long and continuous fiber reinforcements sets extrusion-based approaches apart from other AM technologies. It is also a highly scalable technology, with commercial systems available using build platforms ranging from tens of centimeters to tens of meters in the largest dimension.



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THE FUTURE OF ADDITIVE MANUFACTURING FOR COMPOSITE STRUCTURES

Bringing together the design freedom enabled by FDM, the performance of composite material systems, and the multi-axis motion control of industrial robotics, industry leaders such as Stratasys have shown the future of AM for the composites industry. 3D printing technologies are well recognized for their ability to provide unparalleled design freedom relative to conventional methods of manufacturing. The addition of fiber reinforcement to printed parts pushed performance to a higher level, but resulting performance is still limited by the planar layer-by-layer nature of the build approach.

With the addition of multi-axis motion platforms, fiber alignment can be manipulated and controlled to a degree not previously possible. The complex structures enabled by this approach cannot be produced by hand lay-up, transfer molding, filament winding, or even other automated technologies, at least not without highly complex tooling approaches that are unlikely to be feasible or at least practical. The result is a new generation of potential lightweight structures with unprecedented degrees of geometric complexity, part consolidation, and design optimization.

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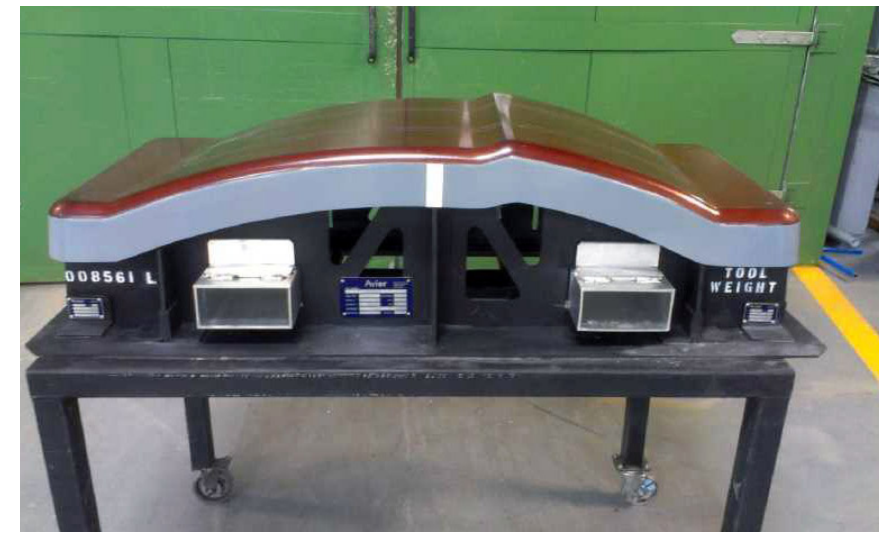
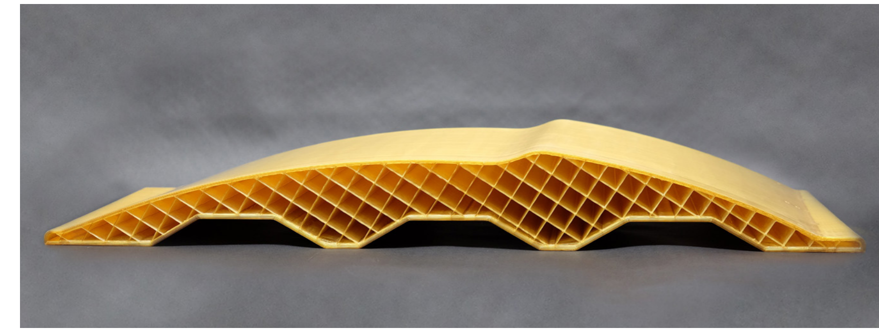
CURRENT APPLICATIONS FOR COMPOSITE FABRICATION

MOLD TOOLING

AM for composites is not only about a future of prominence and transformation. There are a number of key applications where 3D printing technologies are presently relevant and used to directly impact the manufacture of composite structures. One application is 3D printed mold tooling. The composites industry is continually pushing for innovative tooling solutions to enable new use cases and product improvements, as well as reductions in lead time and costs. FDM allows rapid production of effective composite mold tooling across a broad range of tool sizes and complexities, and are capable of performing at cure temperatures in excess of 180 °C in typical autoclave cycles (consolidation pressures exceeding 0.7 MPa).

Conventional manufacturing methods for composite structures typically use mold tooling made of metallic materials (aluminum, steel, or Invar alloys), although non-metallic materials are also frequently used, including specialized fiber-reinforced polymer (FRP) materials, high-temperature tooling board, and others. Regardless of material, tool fabrication typically requires significant labor and machining, leading to high costs, significant material waste, and long lead times. The use of AM technologies such as FDM for composite mold tooling has demonstrated considerable cost and lead time reductions while providing numerous other advantages such as immense design freedom and rapid iteration, nearly regardless of part complexity. It also provides the ability to produce lightweight tooling, directly simplifying transportation and storage operations within manufacturing facilities by eliminating heavy lift procedures that require cranes and forklifts.





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SACRIFICIAL TOOLING

Beyond conventional mold tools, AM technologies such as FDM are also directly altering the approach for creating complex, hollow composite parts. The challenges associated with tooling to produce such structures with “trapped tool” geometries are well established. The use of metal or other hard tooling drives the need for highly complex, collapsible designs. Inflatable bladders require investment in additional tooling, adding cost and time, and are limited in the geometries that can be addressed. And typical wash-out options, such as eutectic salts, ceramics, and similar materials, not only require machining from block forms or tooling to cast to the proper shape, they also have their own technical challenges with handling, phase changes, and dimensional stability. 3D printed wash-out tooling addresses many of these issues.

FDM sacrificial tooling uses proprietary, dissolvable (or break-away) thermoplastic materials to simplify the production process for many complicated composite part applications. AM sacrificial tooling eliminates both machining from a bulk form and the need for additional tooling to prepare the mold (e.g., a cavity mold to cast a conventional wash-out material) and permits direct printing of the final shape. Unlike many particulate-based, wash-out materials, FDM tools are resistant to handling-induced damage, dimensionally stable, and are effective, efficient, and relatively straight-forward to use.

ANCILLARY TOOLING

The final application where AM is presently impacting composite fabrication is the manufacture of the many ancillary tools that play a role in part production. For the most part, every composite part fabricated with conventional lay-up and infusion methods is a “near-net shape” part, meaning that additional processing is required to produce the final product. 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. AM technologies, and particularly FDM, are well-suited to produce the entire tooling string, in many cases, and typically provide significant design, cost, time, and weight savings.

PRINTED MOLD TOOLING

MATERIALS, CHARACTERISTICS, AND CONSIDERATIONS

From a functional perspective, the use of additive manufacturing for composite mold tooling is not that dissimilar from conventional approaches. Just as design and construction aspects of conventional lay-up tooling varies depending on the material used (tooling board, aluminum alloys, Invar, graphite/epoxy, etc.), there are a number of considerations to keep in mind for effective design and use of additively manufactured composite mold tooling. The primary considerations for FDM tooling in particular are as follows:

- **Cure Temperature:** The cure temperature of the composite material will directly influence material selection. There is a range of high-temperature FDM materials available, several with a glass transition temperature in excess of 200 °C that can be used effectively at common high-performance composite cure temperatures (typically 180 °C). Polyetherimide (PEI) and polyethersulfone (PES) are two such high-temperature thermoplastics that are well-suited to the application due to their high heat resistance and stability.

- **Coefficient of Thermal Expansion (CTE):** CTE is an important consideration for nearly all mold tooling applications since it impacts the final physical shape (and often the performance) of the composite structure. FDM is capable using materials with and without reinforcement (such as fibers) and fillers (such as glass beads, silica, carbon nanotubes, and many others). The presence or absence of such constituents has a significant impact on the resulting CTE of the tool. Unfilled/unreinforced thermoplastics tend to have a relatively high CTE, but even modest loading levels of reinforcing fibers can drastically reduce thermal expansion. Tool designs can and typically should be modified to compensate for the dimensional changes related to thermal expansion at elevated temperatures. In addition to geometric compensation, CTE differences between the tool and part materials are also factors that impact tool type (male versus female tools) and potential complexity.

- **Process Parameters (consolidation pressure and vacuum bagging approach):** Fabrication process (e.g., hand lay-up, AFP, RTM, compression molding) and cure cycle parameters, particularly cure pressure and vacuum bagging method (i.e., envelope vs. edge/surface bagging), impact the design approach of mold tools built with FDM technology. With proper design, printed molds are able to withstand the high pressure (0.7 MPa) autoclave cycles common to high-performance composite materials or even the much higher pressure levels used for RTM and compression molding.

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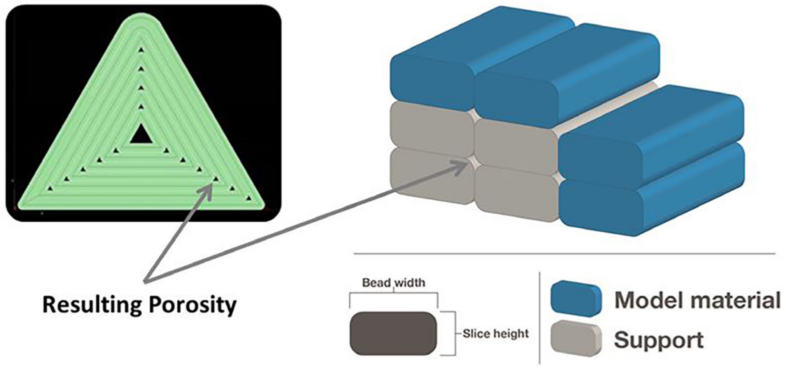
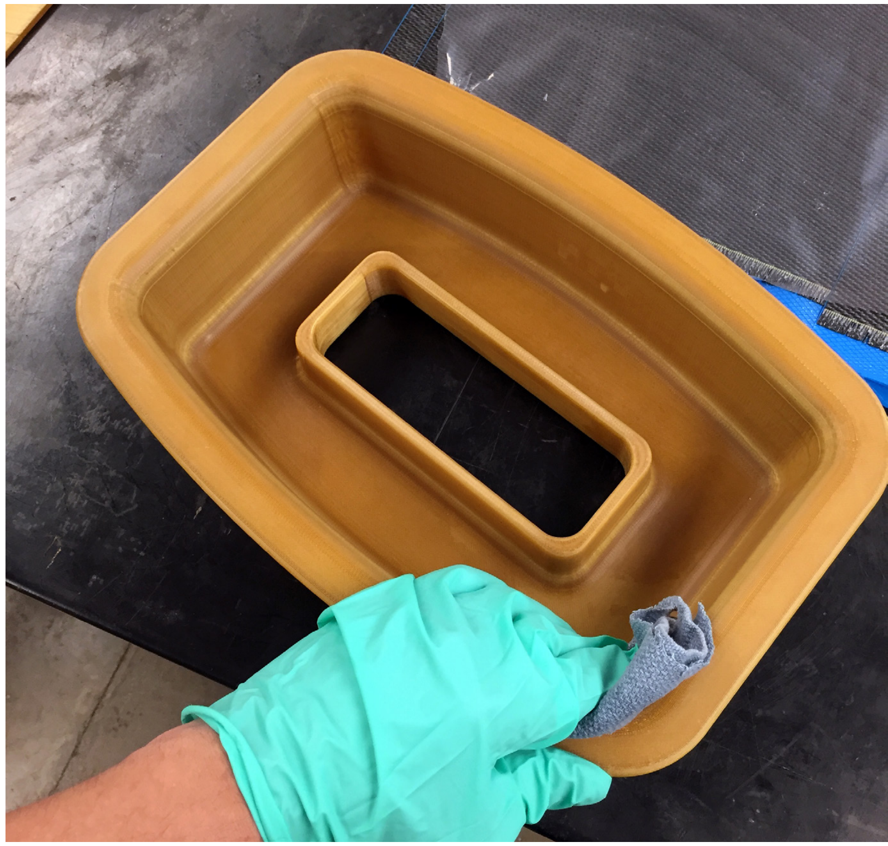
- **Tool Preparation (sealing)**: Extrusion-based AM processes such as FDM inherently produce some level of internal porosity due to physical limitations of extruded material profiles. This is depicted in the figure at right, which shows the cross-section of toolpaths for an example build layer and the cross-section of extruded bead profiles. The 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 mold tools is typically required. The method used can vary from simple hand sanding and sealing with a high-temperature resin (such as epoxy) to merely the application of an adhesive-backed release film, depending on the application. In many cases and particularly for larger tooling, the most effective approach is to incorporate CNC machining. Tools can be printed in a "near-net" shape, just slightly oversized, and then efficiently machined to the final geometry.

- **Anticipated Use Case (tool life):** A final consideration for successful design and use of FDM composite tooling is a thorough understanding of the intended use case, or specific application, of the tool. The use case tends to drive material selection (e.g., cure temperature requirements) and the overall design, and factors into the tool construction and sealing approach (i.e., will the tool be envelope- or surface-bagged and what is the consolidation pressure?).

  And as with conventional tooling materials, it is also important to consider the required tool life. Tools intended for a few prototype composite parts can be constructed to minimize cost. Tools intended for an impending, schedule-critical composite repair can be optimized for rapid build time. And tools intended for longer-term production use and higher part volumes require greater scrutiny regarding nearly all aspects. Like any polymer-based tool, process parameters such as temperature and pressure will directly influence the tool life and non-metallic tools will always have a shorter tool life than metal molds. That said, printed tools can be used effectively to produce hundreds of composite parts.





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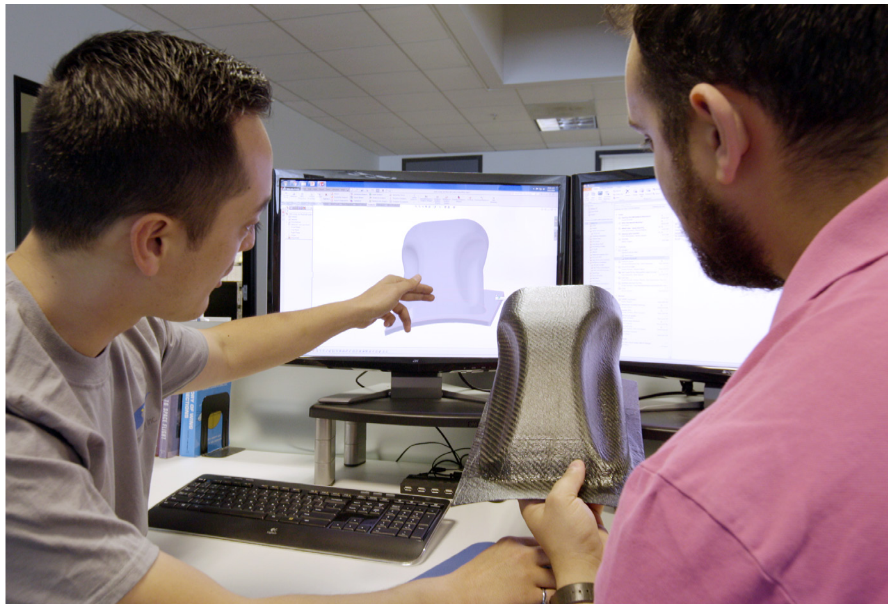
TOOL DESIGN

One major benefit of AM for composite mold tooling is the ability and freedom to tailor the tool design specifically to the application. For instance, a schedule-critical repair tool intended to produce one to two parts can be optimized for rapid build time whereas a mold intended for longer-term production use requires greater scrutiny in nearly all aspects and can be designed and built accordingly. The design process for an FDM tool is primarily driven by the process parameters for the final composite parts (cure cycle, pressure, bagging approach, etc.), as previously discussed.



FDM composite tooling designs can be as complex, simple, or functionally oriented as the application requires. And in general, there is virtually no additional cost for complexity when using AM technologies. With AM, no longer is a designer or engineer required to solely “design for manufacturability.” Rather, there is a need, or freedom, to take a completely different perspective, referred to as “design for additive manufacturing” (DFAM). DFAM enables enormous flexibility and can be thought of more as a mindset than a strict set of rules. AM technologies can generally build any shape or design that is rendered (within limits that vary based on the technology of course), but there are still methods to most efficiently use material, minimize waste and build time, enhance functionality or performance, and numerous other aspects. These concepts can be applied to both parts and tooling to produce highly optimized results with many performance benefits.

PRINTED TOOLING VS. CONVENTIONAL TOOLING

The benefits of technologies such as FDM for mold tooling and other ancillary tools has been touched on throughout. AM provides unparalleled design freedom, which permits tailoring designs specifically to the relevant use case or application. For mold tooling, this typically results in significant reductions in lead times, levels of touch labor, and cost. Such benefits are also important in that they subsequently enable additional design iteration, optimization, and the ability to incorporate changes much later in the product development cycle.

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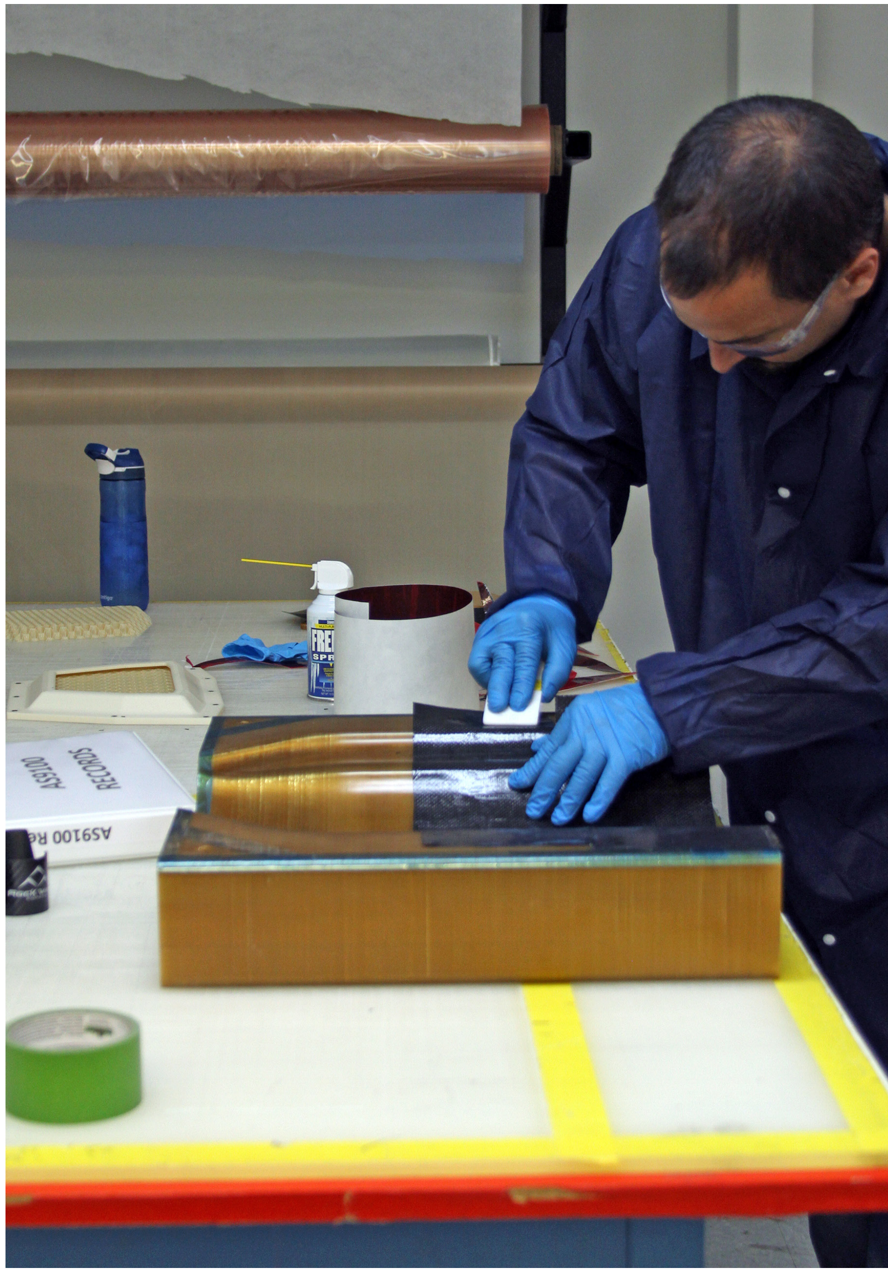
In addition to the business benefits, FDM enables high-temperature composite tooling that can significantly simplify manufacturing operations. A primary example of this is in resulting tool mass. Typical metal tooling can easily weigh hundreds or even thousands of kilograms. Such tools require heavy-lift procedures using forklifts and cranes to move throughout facilities. These procedures are time-consuming and present safety concerns. And the large thermal mass of the tools dictate longer cure cycle times and greater utilities consumption. Use of FDM typically results in equivalent composite tools at a fraction of the physical and thermal mass. Instead of forklifts and cranes, FDM tools can typically be moved easily by people, simplifying both transport and storage.



FDM offers a broad range of capable, high-performance materials that are well suited to handle the demanding processing requirements of high performance composite materials. However, there are trade-offs and limitations with all materials and methods. For instance, as with any polymer-based tooling, the ultimate tool life of a printed tool will be considerably more limited in comparison to tools made out of aluminum, steel, and invar alloys. Thermal expansion is another significant performance characteristic. Unfilled FDM materials have relatively high levels of expansion, particularly in comparison to materials such as Invar or conventional FRP composite tooling, although these materials typically have much higher cost, mass, and lead times. Reinforced or filled FDM materials provide comparably low thermal expansion while still addressing many of the disadvantages of conventional tooling, although the thermal expansion behavior tends to be anisotropic (similar to FRP materials), which can present challenges as well. It is important to consider the requirements of the application as there is no one solution that is ideal for all.

A FINAL NOTE ON ADDITIVE MANUFACTURING FOR COMPOSITES

AM technologies have many great benefits and the potential to enable a new era of lightweight structures with degrees of geometric complexity, part consolidation, and design optimization not previously possible. That said, whether for structures or tooling applications, AM will not necessarily replace conventional manufacturing methods for composites, nor is that the intent. In most cases, the greatest results can be achieved by implementing AM in a manner that complements conventional technologies, combining methods to capitalize on the strengths of each while avoiding many of the limitations.

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