DEVELOPMENT AND APPLICATION OF CONTINUOUS FIBER 3D PRINTING PROCESS FOR AEROSPACE

Bob Koon
Lockheed Martin Aeronautics
86 South Cobb Drive
Marietta, GA 30063

Nathan Stranberg
Continuous Composites
215 E. Lakeside Avenue
Coeur d'Alene, ID 83814

ABSTRACT

Accomplishing dramatic reductions in the manufacturing cost of composite structures requires a combination of developments in automated processes, high speed material application and reduced dependence on hard tooling methods. To benefit high performance aerospace applications these developments are best accomplished on processes suitable to continuous fiber composites. The Continuous Fiber 3D Printing (CF3D$^{®}$) process, a newly developed technology for additive manufacturing of continuous fiber composites, offers the combination of necessary attributes to revolutionize the manufacture of low cost, high performance composites. This paper provides a description of the technology, ongoing development efforts, and plans for future improvements and applications. Initial aerospace application is focused on the USAF Low Cost Attritable Aircraft Technology (LCAAT) program, but opportunities for exquisite airframe applications, including cost effective fabrication of topology optimized structures and multifunctional material options is also discussed.

1. INTRODUCTION

The use of advanced composite materials on current aircraft is limited, in large part, to skins located over metallic substructure [1]. The efficiency and reproducibility of the Automated Fiber Placement (AFP) process has played a significant role in the transition from metallic to composite in much of these skin applications [2, 3]. The configuration of metallic substructure as used in bulkheads, frames, keel beams, ribs and spars has not transitioned to composite. This is because composites are poorly suited to these applications due to inherently poor interlaminar tensile and shear (ILT/ILS) performance as well as an inability to automate much of the manufacture of these somewhat smaller and more complex shaped articles [4]. Increasing the fraction of airframe structure composed of composite material will require increased stiffness in addition to advances that address the ILT/ILS drawbacks, and that the industry work to develop manufacturing concepts that drastically reduce the touch labor costs and span times characteristic in smaller, hand laid, complex components.

There have been, and continue to be, a number of innovative concepts addressing the inherently poor ILT and ILS performance of composite materials [5-7].

- Z-pinning
- Improved damage tolerant resins
- 3D weaving/braiding

In regards to addressing the cost of labor intensive layup of smaller, complex shaped articles, other industries, such as the automotive industry, have begun adopting discontinuous fiber composite materials and processes (M&P) for cost effective, lightweight, and corrosion resistant alternatives to metallics. Compression molding and injection molding of short glass and carbon reinforced materials are making inroads into these markets [8]. These materials, however, lack the in-plane mechanical performance required in the majority of aircraft substructure applications. In these aircraft applications it is important that the components be composed of composites that have continuous fiber reinforcement; principally carbon fiber. The challenge, therefore, to the aircraft materials and manufacturing community, is to develop automated processes for continuous carbon fiber composites, that can be used to manufacture the complex configurations expected in future composite substructure applications.

One such technology, under development by Continuous Composites of Coeur d'Alene, ID, is called Continuous Fiber 3D Printing (CF3D®). The founders of this small business understood the merits of the Additive Manufacturing process while recognizing the mechanical drawbacks associated with extrusions containing little or no fibrous reinforcement. In response, Continuous Composites was founded in 2015 based on foundational patents for the CF3D® process filed starting in 2012 [9]. Work began in 2015 on finding technical solutions to additive manufacturing using continuous fibers. More recent efforts at Continuous Composites, in cooperation with Lockheed Martin, and sponsored by the US Air Force Research Labs (AFRL), are looking to adapt their process for use with carbon fibers [10].

1.1 CF3D® Description

CF3D® is akin to AFP in that a robotically manipulated end-effector disperses impregnated tows of composite tape which are compacted onto previously placed material. Figure 1 shows the current generation CF3D® head attached to a Fanuc motion platform. As with AFP, the CF3D® head also feeds tow(s) at controlled rates and includes automated tow cutting at preprogrammed locations. CF3D® differs from AFP in that the tow is snap cured using an ultraviolet source. With glass fiber reinforcement this ultraviolet light source can instantaneously cure the liquid resin during the extrusion process. When using carbon fiber the light source is capable of only partial cure of the resin. The current state-of-the-art (SOTA) with carbon fiber requires an oven postcure to complete the resin's cure. Continuous Composites is working with material suppliers to formulate resin systems, suited to carbon fiber, that calls for little or no thermal postcure requirement. These developments will be discussed in section 2.

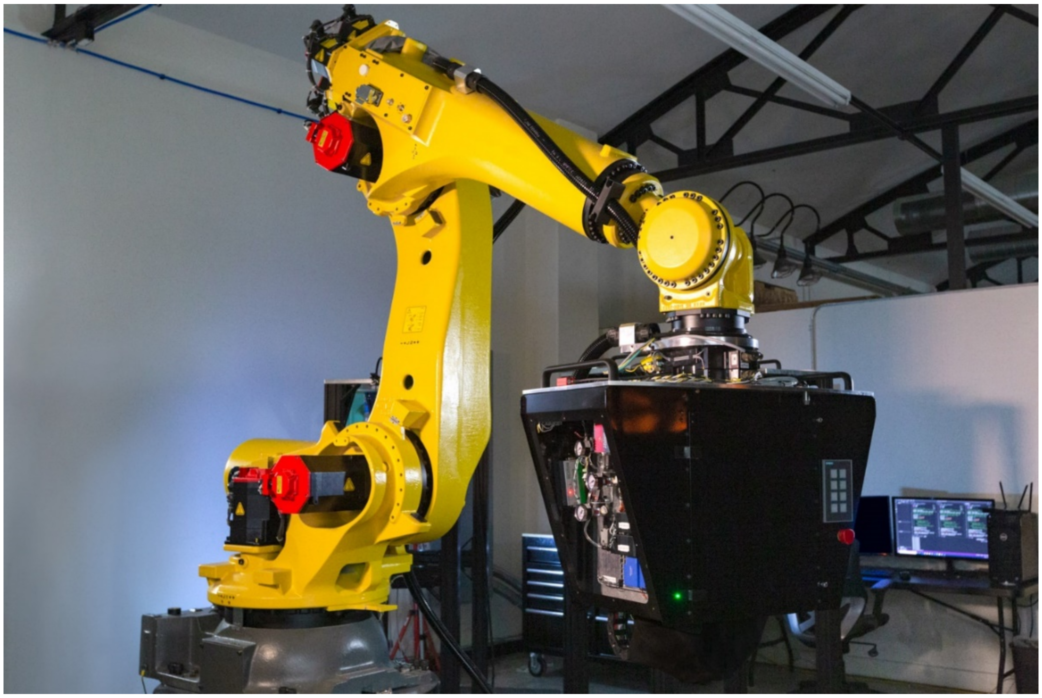

Figure 1. Current Version of the Continuous Composites CF3D® End Effector and Motion Platform (Version 0.7).

CF3D® is also unique from AFP in that resin is applied within the head just prior to extrusion. This feature replaces costly slit tape with dry fiber tows and liquid resin; permitting fiber volume adjustments to be made as the part is being processed. The current SOTA has extruded fiber volumes up to 56vol%.

Fully curing (with glass fiber) or solidifying (with carbon fiber) the composite on-the-fly offers the unique ability to manufacture parts without the need for tooling other than a flat project plate on which to start the additive process. The cost savings benefits of this feature are obvious and will be explored more extensively in sections 3 and 4.

Continuous Composites is not the only innovator targeting continuous fiber additive manufacturing. Markforged has also developed 3D printing systems for use with continuous carbon fibers where the resin systems are thermoplastic [11]. This capability is not addressed in this paper.

1.2 Material Options

The fundamental principles of CF3D® work with any continuous fiber and liquid polymer. The continuous fiber can be structural or functional utilizing carbon, aramids, ceramics, and glass. Additionally, resins can also be multimodal, relying on traditional thermosets or thermoplastics and be doped with additives for additional property changes or functionality.

In CF3D®, the matrix material starts in the print head as liquid resin and solidifies nearly instantaneously as it discharges from the print head. The snap cure property allows geometries and fiber orientations that are not possible with traditional techniques as well as the ability to be moldless and out of autoclave (OoA). Continuous Composites has chosen to focus on high-end applications such as aerospace, which require high mechanical performance. To meet these requirements, CF3D® development has been focused on UV curable thermoset matrices because of their superior mechanical and snap cure properties. Continuous Composites is partnering with prominent materials companies and customers to establish a library of resins that work with CF3D®. Through a Joint Development Agreement with Arkema®, custom polymer solutions are in development to meet customer application requirements for strength, modulus, glass transition temperature, among other properties [12]. In addition to traditional polymers and composites, new photoinitiated polymers are in development that convert to ceramic or carbon, allowing the creation of Ceramic Matrix Composites (CMCs) and Carbon Bonded Carbon (CBC) composites.

2. CF3D DEVELOPMENT

CF3D® relies on three technology components to achieve new functionality in composites manufacturing. Research and development have been conducted in hardware platforms, software, and materials to support true three-dimensional part generation that can leverage specific material combinations to maximum effect.

2.1 Hardware Development

The hardware system consists of various motion and active control packages, accommodating a range of systems and build volumes and various end effectors that conduct the entire print process. A simplified process diagram of the CF3D® end effector is shown in Figure 2. Several versions of end effectors and motion strategies have been iterated to arrive at the current SOTA package.

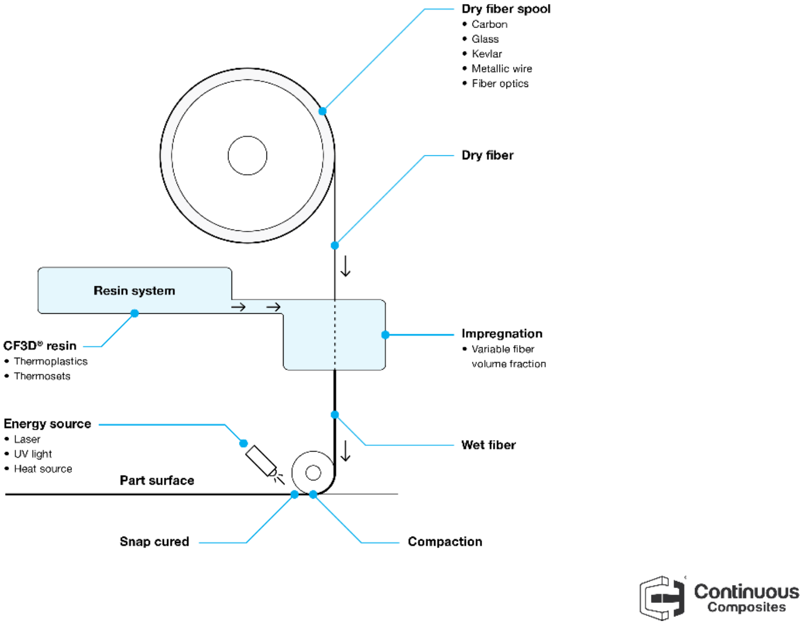

Figure 2. Simplified CF3D Process Diagram.

Previous iterations of the CF3D® end-effector were comprised of a combination of mostly passive control loops and proof of concept subsystems as shown in Figure 3. After rigorous lab testing and down-selection, the current version builds upon previous iterations of the technology and the current SOTA in automated additive composites manufacturing. Real-time active controls are present in each critical subsystem utilizing robust industrial controllers, electronics, and mechanical components.

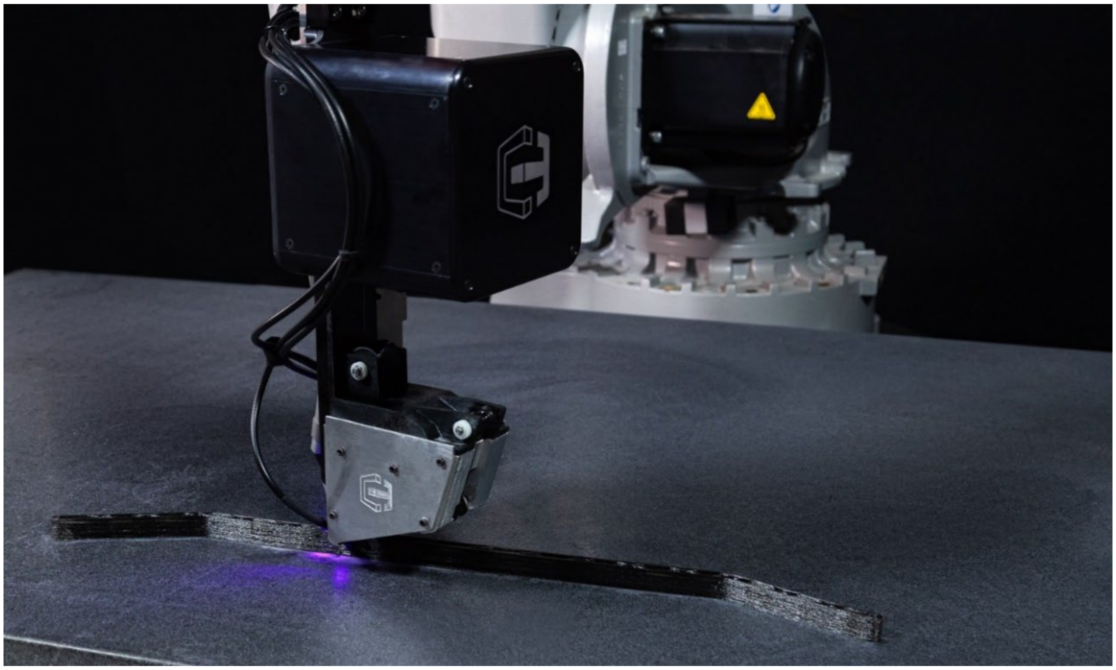

Figure 3. Previous Iteration of CF3D End-Effector (Version 0.6).

CF3D®'s initial consumable is dry fiber (as opposed to prepregs) or other continuous media that is impregnated in the tool head with an onboard resin system and compacted and cured at the tool center point (TCP). Due to this process, several new challenges were presented that are atypical to previous manufacturing techniques. Active control systems have been deployed to control fiber tension, creel torque, alignment, fiber cross-section geometry, impregnation, feed distances, cut positions, compaction, and cure source dose. Particularly unique to the process is a custom-designed accurate no-pulsation pump system and hydrostatic impregnation module that allows for accurate, consistent and user-specified fiber volume fractions. After impregnation, several fiber-handling subsystems direct, feed, clamp, cut and deliver a wetted tow to the TCP. At the point of contact with the work, the fiber is compacted with a user or process definable force where it is simultaneously snap cured by a linearly variable dose of UV light. Depending on the fiber and resin combination as well as the initiation package, the deposited material may be fully cured or B-staged for end application full conversion methods.

CF3D® end effectors have been deployed on both articulated robotic arms and gantry systems. The motion platform can impact several capabilities of the system, including build volume, speed, and accuracy. Continuous Composites has worked with robotic and numerical control manufactures as well as precision linear drive component manufacturers to increase the accuracy of integrated platforms. Using precision laser trackers, scanners as well as both static and dynamic compensation models, Continuous Composites is approaching industry-leading accuracy and repeatability in demonstration units. High accuracy Numeric Controllers are being utilized over traditional robotic controllers for increased accuracy and repeatability.

2.2 Material Development

CF3D® relies on several different off-the-shelf and custom material combinations to achieve target end part performance and properties. The ability to bring additive into a true 3D Euclidian coordinate space is enabled, among other factors, by snap curing photopolymer chemistry. Various matrix solutions can offer several property optimization combinations, including fillers and additives, to augment capabilities including surface properties, thermal attributes, and electromagnetic susceptibility. Engineered matrix solutions are being developed to support additional part types involving phenolic, ceramic, and other atypical matrix systems. These new material considerations are enabling CF3D® application in carbon-ceramic, carbon-carbon and ceramic-ceramic composites.

To date, CF3D® has been mostly deployed using off the shelf fiber solutions including various grades and sizes of carbon fiber, fiberglass, ceramic fibers, aramid fibers (Kevlar, Spectra, Xylon, Dyneema), as well as function fibers like conductive single core wire, fiber optic cable, and exotic R&D embedded electronic fibers. This expands the potential for a wide array of end-user applications. Carbon fiber and silicon carbide fiber, being black bodies, absorb wavelengths used to cross-link photopolymers. Polymers are in development that harden through the surface of the fiber enough to hold shape, but that require secondary full conversion methods such as a thermal postcure to complete polymerization. In addition to these polymers, new chemistries are in development that propagate the reaction to achieve full depth of cure at room temperature and do not require secondary full conversion methods.

Through custom resin solution development with Arkema® and Sartomer® combined with a wide availability of various commercial fibers, creating products with specific requirements and enhanced functionality beyond traditional composites is possible. As a result of the unique material combinations and fiber orientation introduced by CF3D®, standard ASTM tests may not fully characterize CF3D®.

2.3 Software Development

A new approach to software-driven analysis is needed to leverage the possibilities of CF3D®. Continuous Composites is developing the software tools that drive CF3D® - tools that consume material properties, part geometry and required physical characteristics to generate motion-platform specific steered fiber tool paths. Unlike traditional manufacturing techniques, CF3D® composites are composed of steered fibers that can be oriented to maximize load distribution in specific directions. This takes advantage of the principal strength axis of high-performance fiber, without having to rely solely on the strength of the underlying matrix. By using techniques grounded in traditional FEA and topology optimization, CF3D® software analysis incorporates physical, geometric, and material characteristics to create and validate motion plans for material deposition on a given part.

3. AEROSPACE APPLICATIONS

Transitioning a new process technology like CF3D® into aerospace applications can be challenging even when the technology offers clear cost and performance advantages. Mature production programs require considerable returns on investment before even considering replacing proven technologies. The ideal transition platform for a new, low cost, composite process like CF3D®, would currently be in its conceptual design phase and would benefit from CF3D® features including automation, tool-less processing, low cost raw materials, and high rate material deposition. A new vision for future military aircraft operations championed by AFRL is providing just such an opportunity.

3.1 Application to LCAA

In response to the increased proliferation of advanced capabilities by adversaries, the US Air Force has established a vision for a Low Cost Attritable Aircraft (LCAA) program that calls for the development of single-purpose unmanned platforms that can be designed, built and fielded over such short timeframes and at such low costs that they enable bringing "mass" and cost imposing effects to future engagements [13]. As part of a large, distributed strike package, these platforms will also compliment manned assets like F-22 and F-35. This vision calls for affordable and individually unique unmanned air vehicles (UAVs) to be assembled as required for the mission, permitting fielding of new capabilities in months rather than years.

Meeting Air Force requirements for the LCAA vehicle will require aggressive changes in both design and manufacturing paradigms. Average unit flyaway costs for the aircraft, which include the basic avionics and propulsion systems, are to be less than $3M. Production runs, which will vary from 10’s to 100’s, will necessitate design and manufacturing approaches that are largely independent of order quantity and production rate or span. To aid in this achievement the Air Force has recognized that several changes in cost dependent requirements will need to be realized. For example, LCAA vehicles are expected to achieve shorter service lives, reduced system airworthiness and mission reliability, and require no depot-level maintenance. The short list of performance requirements envisioned for the LCAA systems include:

- 3,000 nm range minimum
- 500lb payload
- Mach 0.9 dash capability

A Lockheed Martin preliminary design concept for the LCCA demonstration program is shown in Figure 4. This design features an austere air vehicle strategy which eliminates non-essential features, consolidates functions, simplifies components and uses low-cost manufacturing technologies. As an illustration of this strategy, the concept contains no wing trailing edge devices or rudder function. Overall, the body substructure has 30 to 50% fewer parts than alternative arrangements.

Figure 4. Lockheed Martin's initial (Vision Vehicle) LCAA configuration.

A fully automated composite design and build environment, in combination with snap curing and tool-less fabrication capability, positions CF3D® ideally for application to LCAA manufacturing. For that reason Lockheed Martin and Continuous Composites have teamed up to develop CF3D® for fabrication of wing spars within the AFRL sponsored "Wing Structural Design & Manufacturing Demonstration" (WiSDM) program [10]. For this program Lockheed Martin is demonstrating and documenting the cost and cycle time savings achieved for an LCAA wing box that employs innovative design and manufacturing techniques. The wing box spars provide an excellent demonstration case for CF3D® since the bending loads in these components require the use of continuous carbon fibers and its tool-less attributes help achieve AFRL goals for accelerated design-to-build cycles. This later feature highlights CF3D® over AFP processing.

3.2 Automation

As noted prior, AFRL desires LCAA manufacturing approaches that are largely independent of order quantity and production rate or span. Lockheed Martin reasons that cost independence from production volume and rate can only be achieved with processes that are highly automated. Automated processes provide a path for volume cost independence by permitting much of the learning, through digital simulation, to be conducted prior to the first article build. Processes, like CF3D®, that are performed using mobile robotic platforms, can be readily adapted to meet increased production rates by simply investing in more machines and factory floor space. Finding and/or training new skilled technicians to meet surge requirements in a manual production environment is not practical and would negatively impact production span times.

CF3D® is highly suited to helping achieve the vision of the Digital Factory of the Future (DFotF) in which autonomous automation capabilities; learning robots which extend beyond following pre-programmed instructions to perform manufacturing and assembly tasks as virtually illustrated in Figure 5. Autonomous automation enables the robots to adapt to human interactions on the factory floor and continuously lean out the manufacturing process without changes being made to the robot's programming [8]. Central to the DFotF is the use of digitally controlled manufacturing processes. Without such, the digital thread running from design, through manufacturing, to service life, is not continuous.

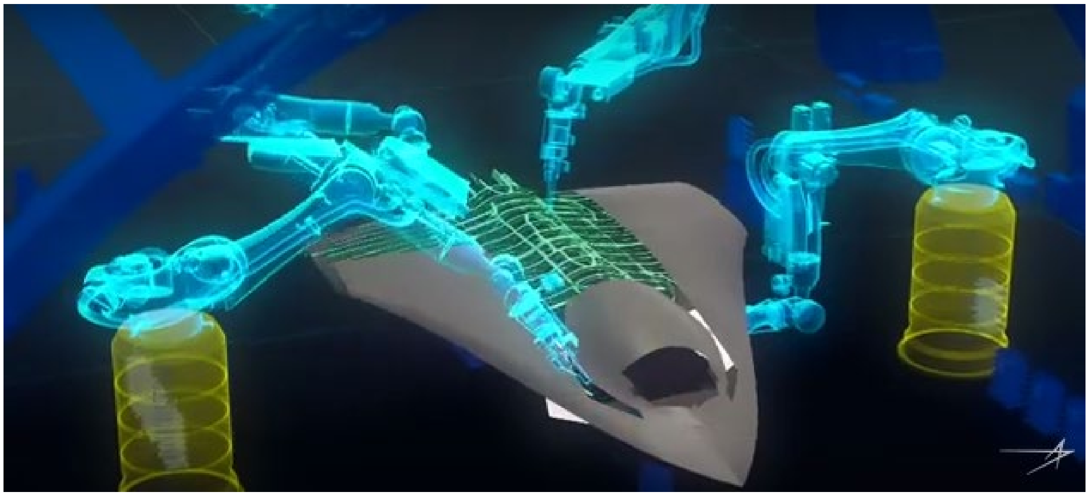

Figure 5. Robots, representing CF3D®, apply advanced materials to a UAV concept demonstrator in a virtual environment.

3.3 Tool-less Manufacturing

Meeting AFRL goals for designing, building and fielding LCAA platforms over such timeframes of months rather than years imposes significant schedule pressure on preproduction functions such as tool manufacturing. LCAA production will therefore be reliant on rapidly formed tooling or, better still, processes that do not require any non-recurring tool fabrication. Because the CF3D® process permits fully cured or solidified parts to be formed without support tooling, many LCAA parts can be built using nothing more than a flat project plate to support the part during lay-up.

4. FUTURE CF3D

The flexibility of the CF3D® process offers unique opportunities for future composite designs and capabilities. Cost effective fabrication of topology optimized designs as well as structurally integrated multifunctionality are two such future capabilities of interest to Lockheed Martin.

4.1 Topology Optimized Composites

Topology optimization is a mathematical method that optimizes material layout within a given design space, for a given set of loads, boundary conditions and constraints with the goal of maximizing the performance of the system. This design philosophy has been an interest of study within the aerospace community for several years. Within the aerospace currently, engineers mostly use topology optimization at the concept level of a design process. Due to the free forms that naturally occur, the result is often difficult to manufacture [14, 15].

This is particularly true for structural composites incorporating continuous fiber reinforcement because of the necessary complexity of the hard tooling required to consolidate and cure the composites by either autoclave or resin injection processing. Even relatively simple representations of topology optimized designs, like the stiffened leading edge component shown in Figure 6 cannot be built using traditional composite manufacturing in a cost effective way and require redesign for processability. Thanks to CF3D®'s ability to place, consolidate and snap cure without tooling support, we can now more cost effectively consider the manufacture of fully topology optimized design concepts.

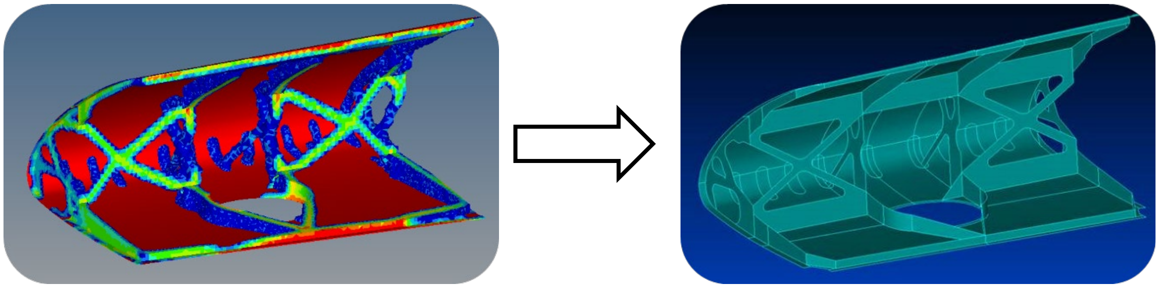

Figure 6. Current application of topology optimized designs requires CAD interpretation for realism.

4.2 Multifunctionality

CF3D® offers a unique ability to readily insert alternative fibers alongside the dry structural tows to provide multifunctional capability to the resulting composite structure. Continuous Composites has previously demonstrated CF3D®'s ability to embed fiber optic filaments and nichrome wires as manufacturing demonstrations (see Figure 7). Ongoing developments with embedded fiber optics have proven their ability to provide for in-situ cure monitoring and structural health monitoring capabilities. Light sensing and light emitting fibers can be used in conjunction to sense ice on the surface of composites, and nichrome or other embedded conductive wires can be used for lightweight and cost effective deicing of leading edges. Other fibers in development include temperature sensing and energy storing fibers. In addition to functional fibers, polymers are in development that can be doped with additives for additional functionality such as manipulation of waves across the electromagnetic spectrum and electrical properties [16].

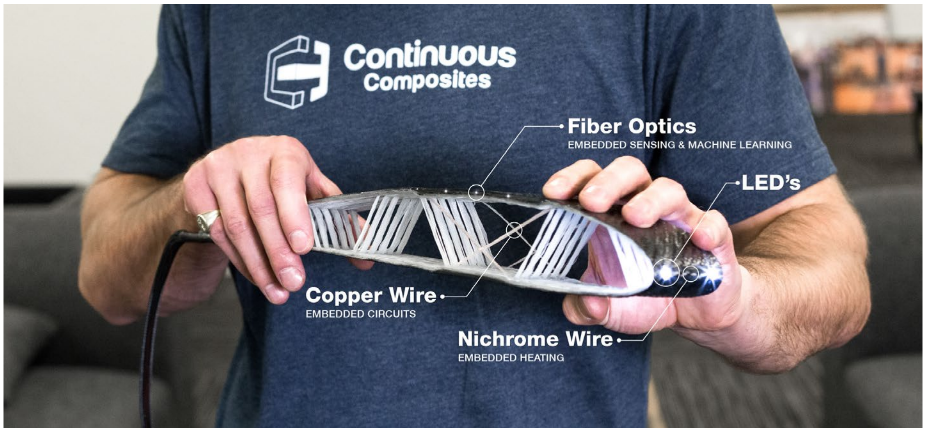

Figure 7. Continuous Composites has demonstrated the ease in which CF3D® can be used to embed specialty fibers to provide multifunctionality to structural composites.

5. SUMMARY

CF3D® technology personifies a new class of additive manufacturing which enables the low cost manufacture of high performance composite structures. Through the design of a unique robotic end-effector Continuous Composites has successfully developed the ability to place continuous fibers, impregnated on-the fly with UV snap cured resins. The use of snap curing allows for tool-less fabrication of complex composite configurations. This tool-less feature, in combination with its fully automated additive manufacturing concept will provide breakthroughs in cost effective composite structures and is ideally suited to application on a new family of Air Force UAV designs called Low Cost Attritable Aircraft. Future developments will include continued improvements to compatible resins, production design of the end-effector, and demonstrations on aircraft structures including consideration of advanced topology optimized designs and multifunctional capabilities beyond structural integrity.

6. REFERENCES

1. Trawinski, D., “F-22 Raptor: Material and Process Development and Applications”, *SAMPE Proceedings*, June 1998.
2. Sloan, J., “The first composite fuselage section for the first composite commercial jet”, *Composites World*, July 2018.
3. Gardiner, G., “A350 XWB Update: Smart Manufacturing”, *Composites World*, September 2011.
4. Rousseau, C.J., Engelstad, S.P., & Owens, S.D., “Industry Perspectives on Composite Structural Certification and Design”, presented at the AIAA/ASME/ASCE/AHS/AHS Structures, Structural Dynamics, and Materials Conference, Honolulu, Hawaii, April 2012.
5. Foster-Miller, Inc., “Method and System for Inserting Reinforcing Elements in a Composite Structure,” U.S. Patent 5589015, 1996.
6. Williams, J. & Rhodes, M., "Effect of Resin on Impact Damage Tolerance of Graphite/Epoxy Laminates," in Composite Materials: Testing and Design (6th Conference), ed. I. Daniel (West Conshohocken, PA: ASTM International, 1982), 450-480.

7. Potluri, P., Hogg, P., Arshad, M. Jetavat, D & Jamshidi, P., "Influence of Fibre Architecture on Impact Damage Tolerance in 3D Woven Composites", *Applied Composite Materials*, 19, 799-812, 2012.
8. Koon, R., Rademacher, M., & Getty, M., "Challenges and Opportunities to Transitioning Automotive Composites to Aerospace", *The Composites and Advanced Materials Expo (CAMX) Proceedings*, December 2017.
9. Continuous Composites Inc., "Method and Apparatus for Continuous Composite Three-Dimensional Printing," U.S. Patent 9511543, 2016.
10. Koon, R., "Wing Structural Design & Manufacturing Demonstration", Defense Manufacturing Conference, December 2018.
11. MarkForged.com
12. Mason, H., "Continuous Composites, Arkema Partner to Advance Continuous Fiber 3D Printing", *Composites World*, September 2019.
13. "Design, Manufacturing, Assembly and Testing for Future Low Cost UAS", Department of the Air Force, Air Force Research Laboratory (AFRL), Request for Information (RFI), October 2016.
14. Muzzupappa, M., Barbieri, L., Bruno, F., & Cugini, U., "Methodology and Tools to Support Knowledge Management in Topology Optimization". *Journal of Computing and Information Science in Engineering*. 10 (4): 044503, 2010.

15 Zhou, M., Fleury, R., Shyy, Y.K., Thomas, H., & Brennan, J.M., "Progress in Topology Optimization With Manufacturing Constraints", *9th AIAA/ISSMO Symposium on Multidisciplinary Analysis and Optimization*, September 2002.

16. Taylor A.C., "Adhesives with Nanoparticles", Öchsner A., Adams R.D. (eds) *Handbook of Adhesion Technology*. Springer, Berlin, Heidelberg, 2011.