3D Printing Composites for Aerospace

INTRODUCTION

Aerospace industry leaders are improving responsiveness to rapidly shifting supply chains and labor availability with additive manufacturing, from on-demand MRO and spare parts in commercial aviation to innovation in Urban Air Mobility.

AM gives modern manufacturers the simplest way to build with materials they already know, expanding the range of what's possible with new technological developments. Fabricate end-use carbon fiber composites unattended, overnight. Skip multi-week lead times and expedite fees for composite prototypes, tools, and fixtures. Print parts in high-performance thermoplastics with excellent flame, smoke and toxicity (FST) properties, with the strength and weight benefits of continuous carbon fiber reinforcement (CFR).

How has composite 3D printing been used in the aerospace industry up until now, and how can it be used in the future? This e-book provides an overview of:

+ How additive manufacturing fits into the aerospace industry
+ How aerospace companies overcome compliance and regulatory hurdles when using additive manufacturing
+ What overlooked applications in tooling and prototyping can reduce lead times and cut costs?
+ What advanced composite materials are available for in-flight aerospace applications
+ How automated in-process inspection technologies work to create strong parts ready for use as soon as the print completes.

INDUSTRY NEEDS

To compete in a tightly-regulated industry, OEMs, MRO service providers, commercial airlines and other industry players must prioritize safety and performance, while adhering to stringent regulatory guidelines and finding ways to drive business efficiency.

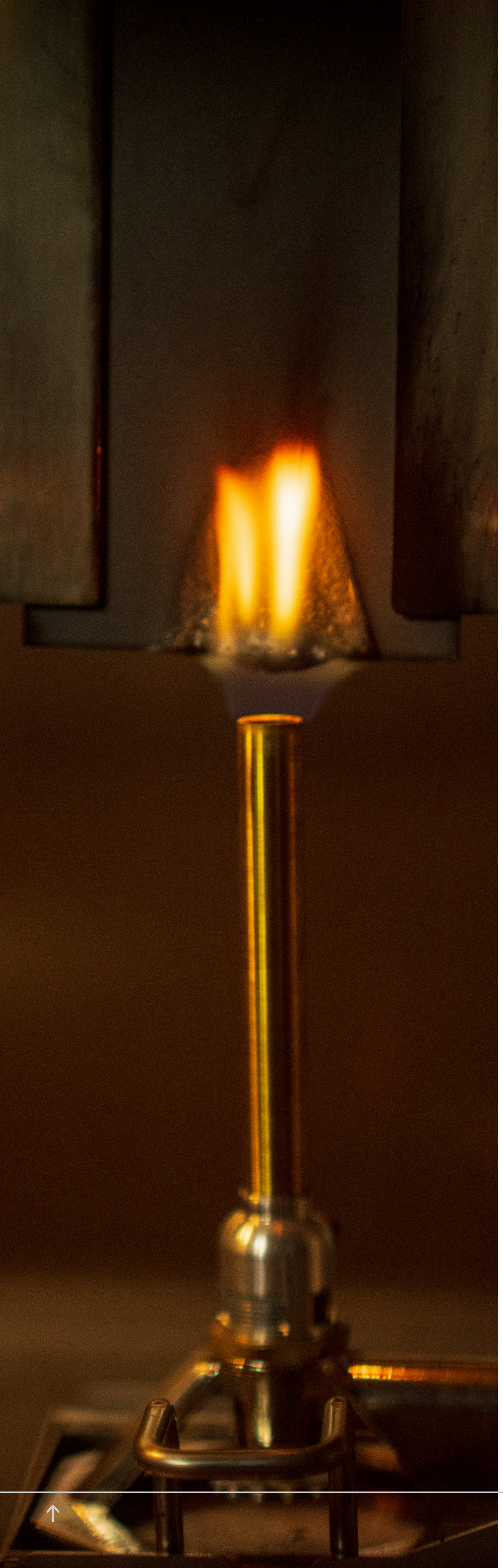
High Strength, Low Weight

Over time, plane parts traditionally made from aluminum alloys have been replaced increasingly with composites, such as carbon fiber — now, a Boeing 787 is 50% composite by weight, and 80% by volume.

Why are aerospace manufacturers continuing to find new applications for composites? With 3D-printed parts taking flight as aircraft components, it's imperative to minimize the weight of parts — this can lead to improvements in fuel efficiency, while minimizing Co2 emissions.

For example, replacing aluminum in aircraft and helicopters with lighter, equal-strength composites can easily reduce overall weight on the order of magnitude of pounds for each part swapped.

However, low weight cannot come at the cost of part strength or material properties — each manufactured part must meet stringent safety and reliability requirements. Printing carbon fiber-reinforced parts with aerospace-grade materials on the Digital Forge can yield parts as strong as 6061-T6 Aluminum, while offering a significant weight reduction compared to metal parts with comparable strength.



Material Properties

On top of high strength and low weight, materials for aerospace applications must be corrosion-resistant and able to sustainably withstand a wide range of operating temperatures. Aerospace-ready materials like Onyx FR-A, Carbon Fiber FR-A, and ULTEM™ 9085* Filament (printable on the FX20) can withstand operating temperatures seen in most aerospace applications.

Regulatory Compliance

The aerospace industry is tightly regulated. To qualify for flight, all aircraft parts and materials must receive approval from the relevant regulatory authority — such as the Federal Aviation Administration (FAA) or the European Aviation Safety Agency (EASA).

Aerospace manufacturers must prove that their parts and materials meet FAA requirements for a comprehensive range of testing criteria, such as strength, durability, UV exposure, fluid sensitivity, vibration, traceability, and flame, smoke, and toxicity (FST).

By choosing materials that will meet compliance testing requirements, aerospace manufacturers can make this process much faster and less complicated. Otherwise, the manufacturer will have to repeat the long qualification process from the beginning: sourcing a different material, fabricating the parts with potential re-designs, and repeating all of the necessary tests.

FR-A materials on the Digital Forge establish lot-level material traceability and pass the test suite necessary for qualification under 14 CFR 25.853 for most 3D-printable parts.

Material Traceability

When a batch of material is designated as traceable, it comes with documentation of where the material came from, testing history, and the specific processes used for its manufacture. This is to ensure end product quality, by guaranteeing the end products are being built with consistent material every time.

In order to qualify as traceable, material samples must receive proper documentation with both a formal Certificate of Conformance (CoC) and Certificate of Analysis (CoA). Once a manufacturer provides the Certificate of Analysis, NCAMP (National Center for Advanced Materials Performance) works with them to qualify the material.

Onyx FR-A and Carbon Fiber FR-A as printed on the Markforged X7 are currently undergoing NCAMP qualification.

Part Consolidation

Larger print volumes enable aerospace manufacturers to consolidate multi-part assemblies into a single part. This decreases assembly times, part count, and controls error that comes from tolerance stacking. Using the FX20, which has a build volume of 525 x 400 x 400 mm, manufacturers can print large, strong parts or print multiple smaller parts in one build session

* ULTEM™ and 9085 trademarks are used under license from SABIC, its affiliates or subsidiaries.

WHY IS AEROSPACE USING AM?

Compared to traditional manufacturing techniques, additive manufacturing offers tangible technical and business benefits for companies in the aerospace sector — speed and short lead times, optimized designs, cost-efficiency, printing directly at the point of need with distributed manufacturing, and reducing the need for tooling.

Small-Batch Production

Additive manufacturing is well suited to meet the aerospace industry's demand for small production runs of customized parts.

With suitable additive manufacturing technologies, these parts can be produced much quicker, at the point of need, and with superior cost efficiency without the need for fixtures and tooling.

Reduced Lead Times forRapid Prototyping and Production

With distributed manufacturing, parts can be printed directly at the point of need in a matter of days — as opposed to having a part manufactured and then shipped from across the globe with a multi-week lead time. If a key production component is still pending arrival, a placeholder part that maintains form and fit can be quickly printed, so that manufacturing is not unnecessarily held up when aircraft must be built around end-use parts with long lead times.

Reduced Supply Chain Bottlenecks and Complexity

For OEMs, using AM technologies can help them take control over their supply chains, while reducing risk and complexity. With on-site 3D printers, manufacturers can reduce the number of vendors their deliveries are dependent on, while circumventing logistical inefficiencies and interdependencies on suppliers that can affect delivery times and R&D speed.

When a supply chain disruption causes a shortage of tools and parts needed for manufacturing, production can stall for weeks. A single missing part can cause manufacturing operations to completely halt for however long it takes to procure the new part. AM drastically reduces lead times, while minimizing potential for logistical complications, for any given part needed — increasing agility, adaptability, and resilience to disruption in manufacturing operations.

Design Complexity

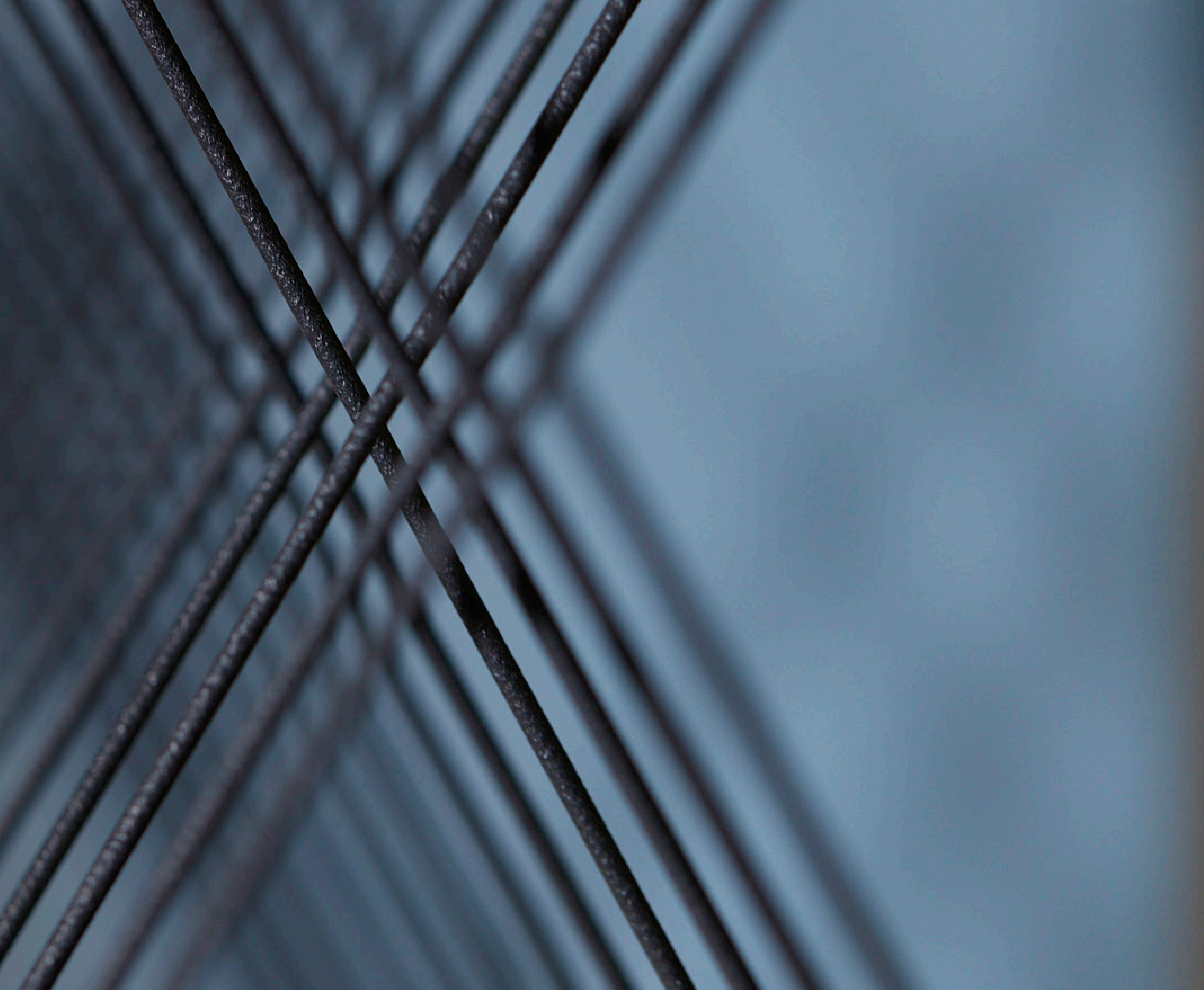
Using AM technologies, structurally complex designs can be manufactured, to easily optimize the strength of end-use parts while reducing weight and minimizing material costs. For many part designs, this is not practical or cost-effective through traditional manufacturing processes. AM can programmatically implement features that can reduce weight and minimize material consumption, while retaining strength and mechanical properties. AM software can automatically generate lightweighting features from user parameters: such as geometric infill and shell reinforcement with continuous fiber reinforcement (CFR).

Rapid Tooling

For many aging aircraft, original tooling has been misplaced, mishandled, or has deteriorated in usability over time. With additive technologies, new tooling can be made quickly and cheaply at the point of need while allowing for late-stage customization.

Cost Efficiency

Compared to traditional manufacturing methods, AM can save money in a few ways. By reducing weight, aircraft will use considerably less fuel, while also lowering weight-based maintenance fees. By displacing the need for tooling and being able to print on-site at the direct point of need, money can be saved without investing in tooling and shipping, which also makes low-batch printing considerably more economical. Furthermore, AM typically has a considerably lower material consumption than traditional subtractive manufacturing. As the aerospace industry generally relies on high performance materials, these costs can make a substantial difference.



AEROSPACE COMPOSITE MATERIALS

What is Continuous Fiber Reinforcement (CFR)?

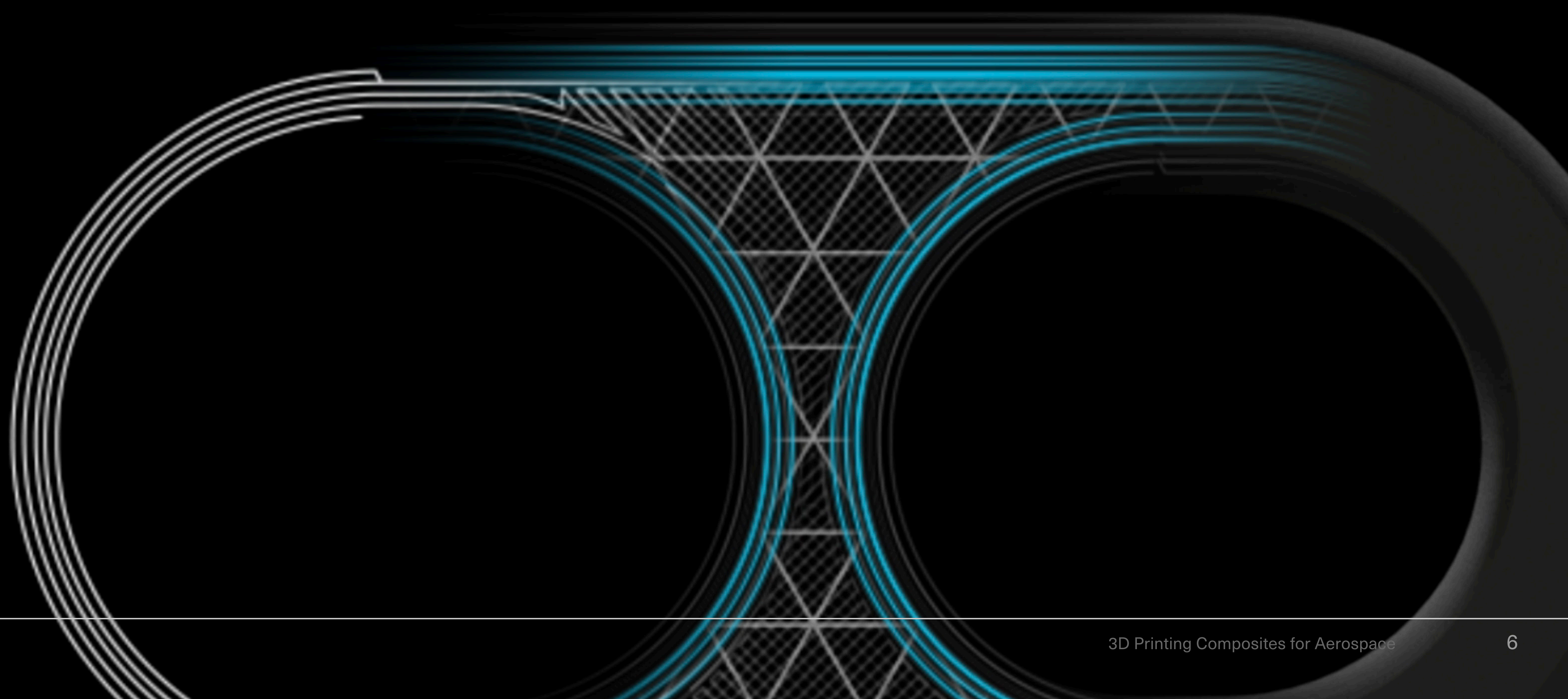
CFR is a proprietary Markforged process that enables 3D printers to reinforce Fused Filament Fabrication (FFF) parts with continuous fibers. A CFR capable machine uses two extrusion systems: one for conventional FFF filament, and a second for long strand continuous fibers.

Continuous fibers are laid down in-layer, replacing FFF infill. Resulting parts are significantly stronger (up to 10 times stronger than any FFF material), and can replace aluminum parts in-application.

Continuous fiber-reinforced parts boast high stiffness and tensile strength at a far lower relative density than steel and aluminum. Due to the very high strength to weight ratio, CFR is often used for aerospace, automotive, and other demanding applications.

Benefits of including parts with continuous fiber reinforcement (CFR) include:

+ **Stronger Parts** — CFR enables you to dynamically alter the strength of parts from plastic strength to aluminum strength. This enables users to design and 3D print parts as strong as needed.
+ **Durability** — CFR parts last longer than any other FFF 3D printed parts in application due to the strength, stiffness, and durability of the continuous fibers. In addition, filled plastics boast high wear resistance and toughness.
+ **Resistance to heat and chemicals** — CFR parts can resist ambient heat in most manufacturing environments, and the short fiber filled filaments they reinforce are extremely chemically resistant.



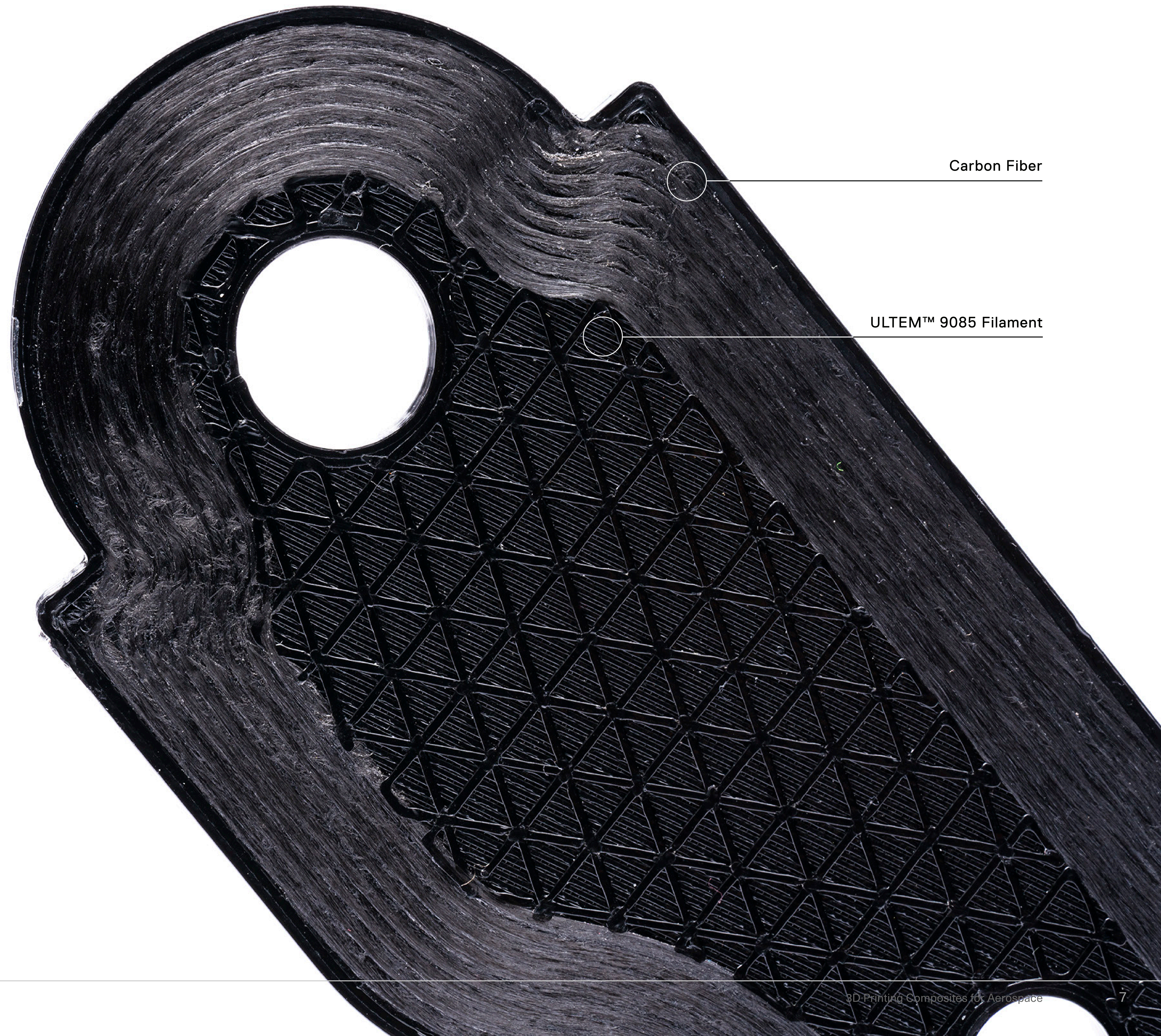
ULTEM™ 9085 Filament

ULTEM™ 9085 Filament is an ultra high-performance PEI thermoplastic. On the Digital Forge platform, it is compatible with continuous fiber reinforcement (CFR) technology for added strength.

A well-known material in the aerospace industry, it is the first high-temperature printing polymer available on the Digital Forge. It's an extremely durable thermoplastic that exhibits excellent flame, smoke, and toxicity (FST) characteristics.

Available on the FX20, the Digital Forge's ULTEM™ 9085 Filament makes it possible to print massive parts with these advanced material properties.

Usable in production aerospace applications, ULTEM™ Filament combined with Markforged's CFR technology brings strength to a new realm of parts — including interior paneling, brackets, handles, and knobs in aircraft. ULTEM™ Filament is available in Markforged's new 3200cc XL spool.



FR-A Materials

Onyx FR-A and Carbon Fiber FR-A are purpose-built for the requirements of the aerospace, transportation and automotive industries.

FR-A materials establish lot-level material traceability and can pass the test suite necessary for qualification under 14 CFR 25.853 for most 3D-printable parts. Onyx FR-A and Carbon Fiber FR-A as printed on the Markforged X7 are undergoing qualification through the NCAMP process.

Material Properties

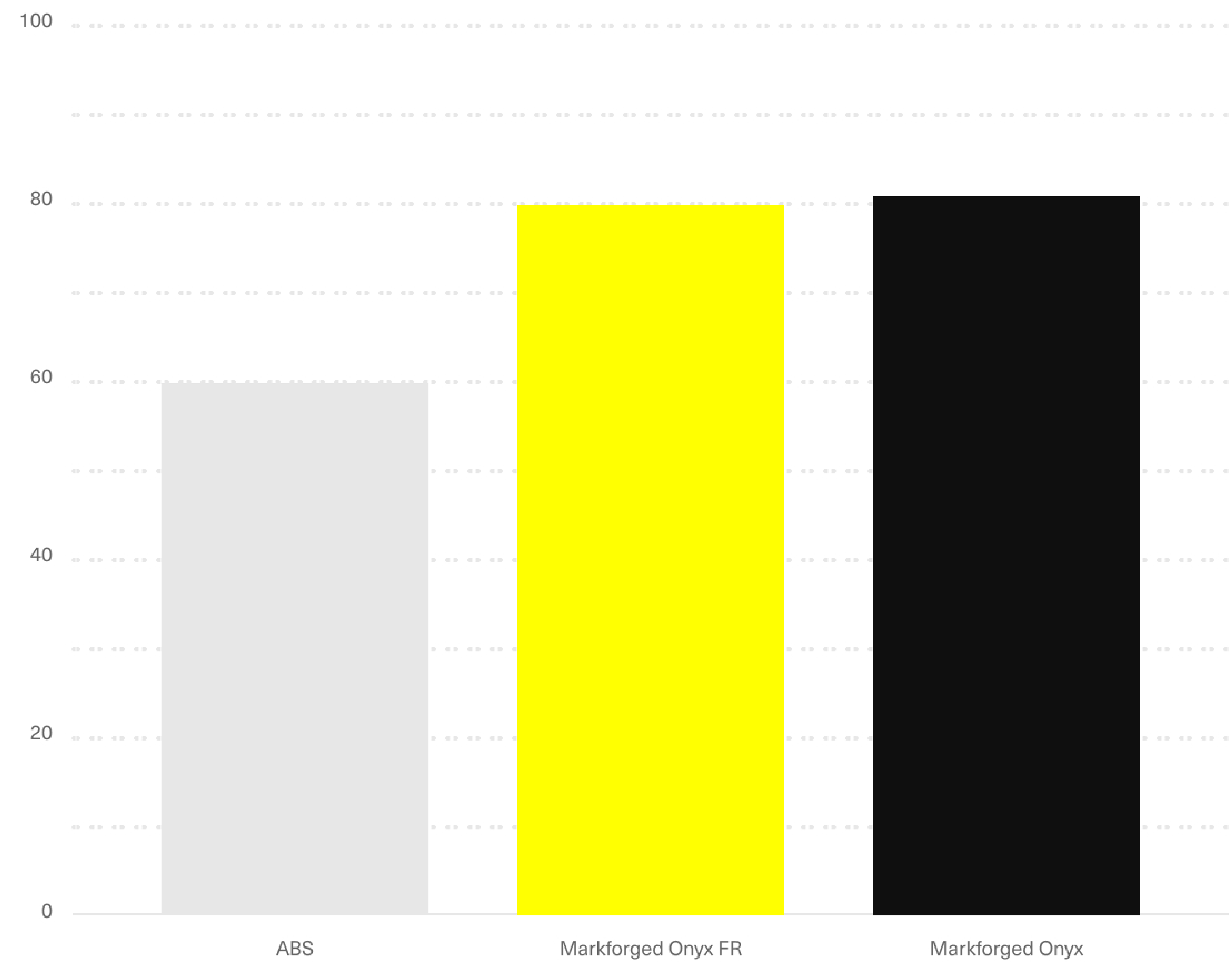
Property	Unit	Test (ASTM)	ONYX FR-A	Test (ASTM)	CF FR-A
Tensile strength	MPa (ksi)	D638	40 (5.8)	D3039	760 (110)
Tensile modulos	GPa (ksi)	D638	3 (440)	D3039	57 (8280)
Tensile strain at break	%	D638	18	D3039	1.6
Flexural strength	MPa (ksi)	D790	71 (10.3)	D790	540 (78.32)
Flexural modulus	GPa (ksi)	D790	3.6 (520)	D790	50 (7250)
Flexural strain at break	%	—	—	D790	1.6
Izod Impact - notche	J/m (ft•lb/in)	D256-10 A	—	D256-10A	810 (15.2)
Density	g/cm^3	—	1.2	—	1.2
Heat Deflection Temp	deg C (deg F)	D648 B	145 (293)	D648 B	105 (221)
Mean XY CTE, 25-145 °C	µm/(m•°C)	—	30	—	—

Material Performance —The FR-A variants of Onyx and Carbon Fiber are used in a similar manner to their standard counterpart. Carbon Fiber FR-A can enhance the mechanical properties od Onyx FR-A parts. The rule of mixtures can be used to approximate bulk mechanical properties of printed composites. Your reults may vary based on a number of factors including environmental, print orientation, and loading conditions.

Flexural Strength

71MPa

Markforged Onyx FR



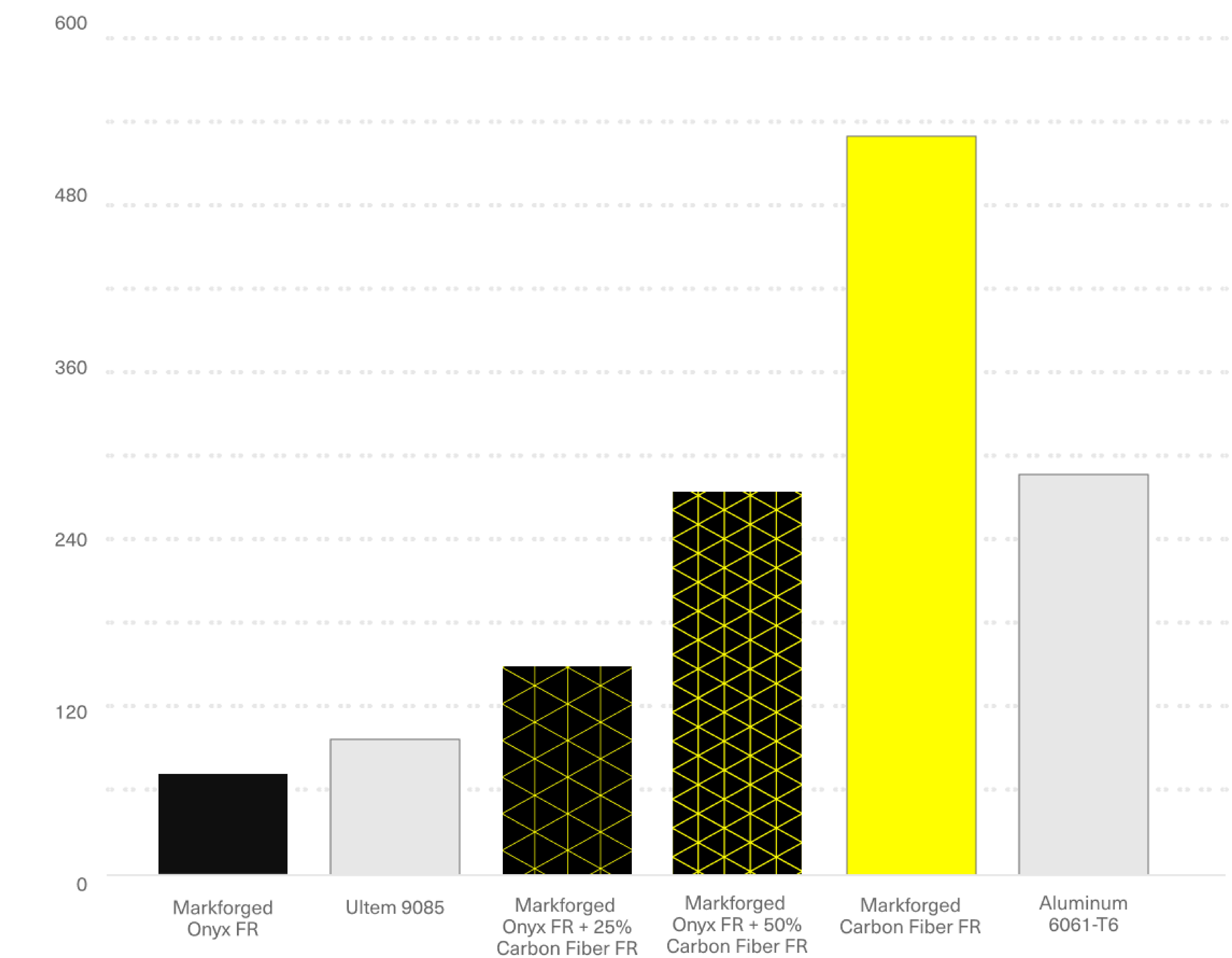
Onyx FR-A is a traceable, aerospace-ready, flame-retardant variant of Onyx designed for use in applications where parts must be non-flammable. The material is considered V-0 (self extinguishing) at thicknesses greater than or equal to 3mm. It can be reinforced with any Continuous Fiber and is compatible with industrial composite 3D printers. Onyx FR-A is undergoing qualification through the NCAMP process.

Flexural Strength

540MPa

Carbon Fiber Reinforced

Carbon Fiber FR-A is a traceable, aerospace-ready, flame-retardant variant of Markforged's unique, ultra-high-strength Continuous Carbon Fiber — when used to reinforce a Composite Base material like Onyx FR, it can yield parts as strong as 6061-T6 Aluminum. It's extremely stiff and strong, and can be precisely laid down in a wide variety of geometries. Programmatically trace curved features, reinforce holes, and mimic unidirectional fiber layups — all within a few clicks.

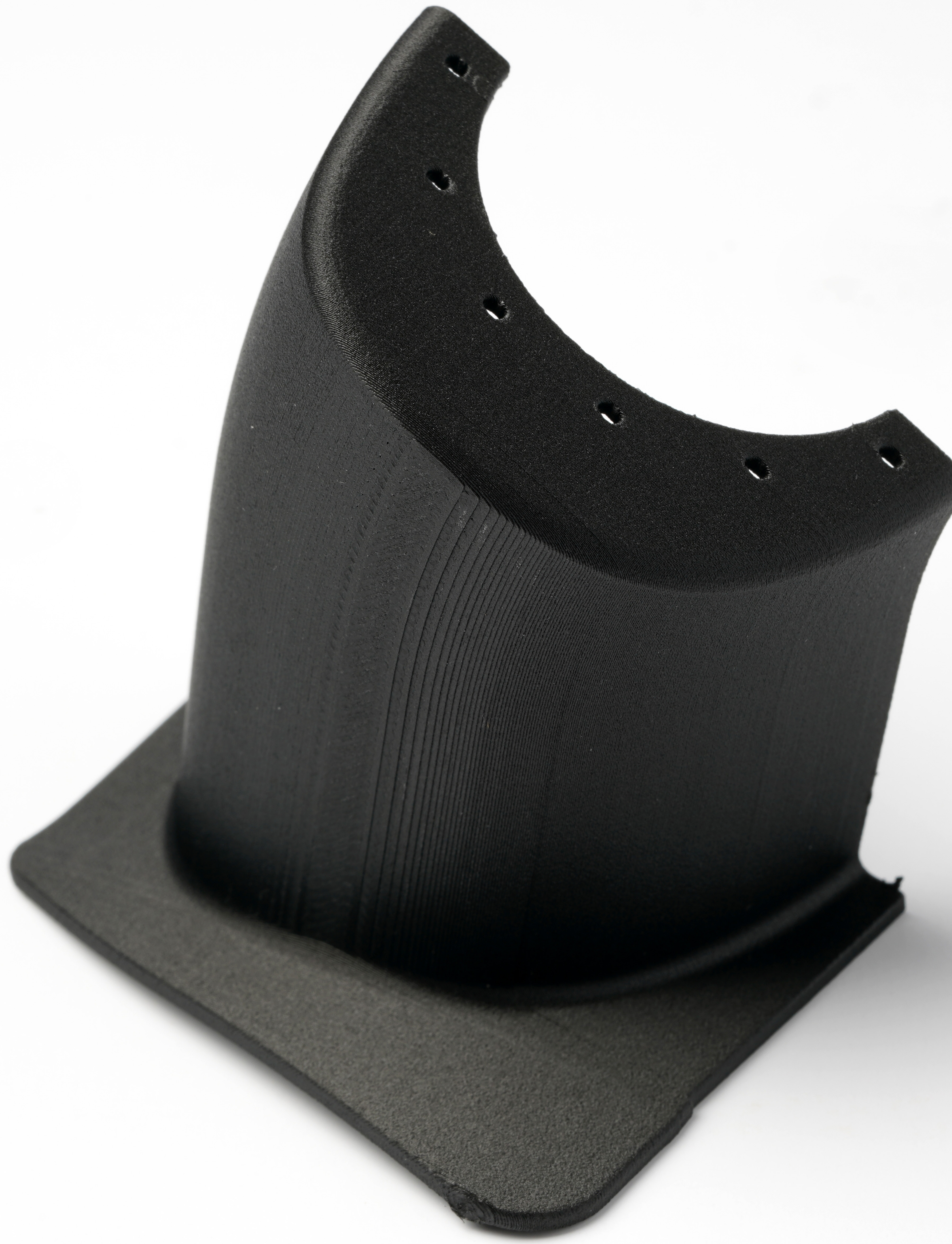


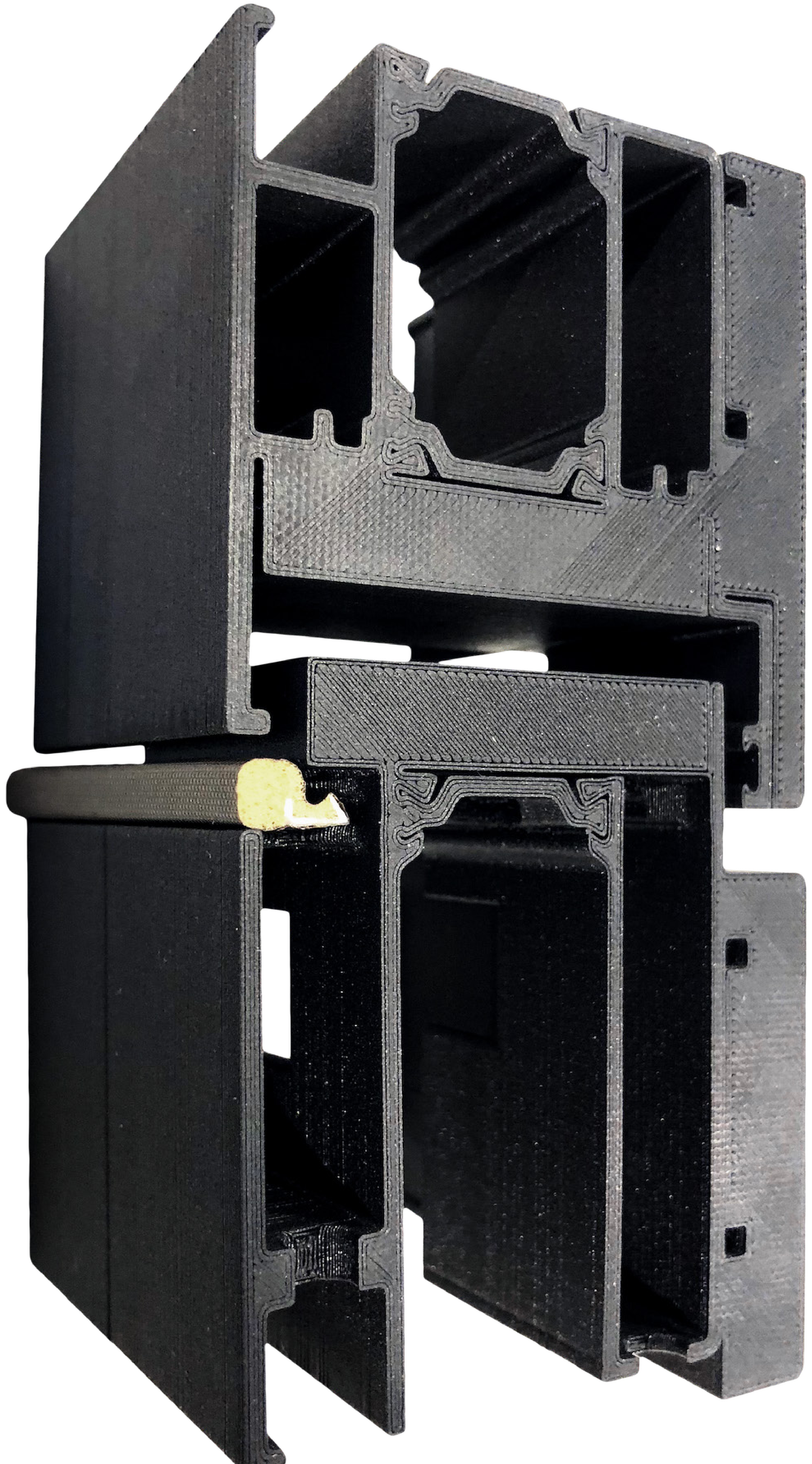
The aerospace and defense (A&D) industry was an early adopter for 3D printing technologies, with AM technologies being used experimentally as early as the 1980's. In the coming years, industry adoption of AM has steadily increased — to use in prototyping, aerospace tooling, cabin interior components, and other flight-ready end use parts.

Prototyping

Temporary fairing (Onyx FR). This temporary fairing served as a surrogate manufacturing part for a permanent airplane fairing that needed to be made out of machined metal.

A machined metal fairing typically carries long lead times of about 4 months. As the manufacturer had to build much of the flight deck around the fairing, quick printing of this temporary part — which acted as an effective placeholder — prevented project progress from halting. When the machined metal fairing arrived, it was easy to replace. Use of temporary prototyping parts can help aircraft manufacturers effectively meet project timelines, without lead times causing unnecessary delays.





Functional door hardware prototype (Onyx). Initial prototypes for this part were machined out of metal — which required high costs, long lead times, and allocation of specialized labor from a trained machinist. Furthermore, this came at an opportunity cost: the machinist had less available time to make monetizable production parts.

3D printing this prototype freed the machinist to focuson production parts, while this part could be passively manufactured with short lead times, lower costs, and without the need for skilled labor.

With other 3D printing systems, having the necessary print accuracy for these complex parts to consistently fit together every time was a tricky proposition.

With the Digital Forge, this set of complex parts was able to be printed within the tight tolerances needed to fit together every time reliably. The ability to accurately print these parts in a repeatable manner — which have a low margin for error — increases efficiency and accelerates design cycles while avoiding assembly issues.

Tooling

Rotor check gauge (Onyx). Check gauges are used to verify the quality of parts manufactured. Check gauges are expensive, take skilled machine time to make, and are often very small. This can lead to concerns about losing or damaging them — on top of high manufacturing costs, long lead times can lead to costly factory downtime by stalling part quality verification.

3D printing check gauges in-house can alleviate these concerns, as fabrication costs, lead times, and labor to manufacture are minimal. Complex check gauges with more geometries can measure multiple different dimensions without significant extra cost.

This rotor check gauge can check three different dimensions with one gauge — as opposed to three separate tools — which can greatly simplify the verification process.With the Digital Forge's print quality and Blacksmith part inspection software, this check gauge — as well as other parts that require high degrees of precision — can be printed accurately with repeatable results, as opposed to sending parts out for expensive, time-consuming post-print production.

Drill Template (Onyx, Continuous Carbon Fiber). This specific drill template is for drilling holes into a round object; however, conformal drill templates for curved edges are expensive to machine as they require more machining time and a larger block of material.

3D printing allows in-house fabrication of a round, conformal drill template — with very short lead times and no extra costs for complexity.

Stiffness and rigidity are imperative for drill templates, which must ensure the hole is reliably guiding the drill into the right place. Using continuous carbon fiber reinforcement, the drill template has the strength and rigidity to withstand any vibrational force it may be subjected to from the drill.

Weld fixtures (Onyx). Initially, this weld fixture was made by welding plates of metal together. For large, welded metal racks, such weld fixtures are required.

However, the initial welded fixtures limited design freedom — oftentimes, the geometries of the weld had to be designed around the geometries of the fixtures, creating unnecessary limitations.

This 3D printing weld fixture offers far more flexible design freedom — welds can be designed as needed, then customized weld fixtures can be printed quickly and cheaply.

Soft jaws (Onyx, Continuous Carbon Fiber).
This pair of soft jaws is used for workholding on milling machines. Typically, workholding fixtures are machined from metal — this is because the part must be able to reliably withstand the high forces of the milling machine.

3D printing workholding fixtures, such as pictured, offer the opportunity to print in custom shapes and orientations for increased design freedom. With continuous carbon fiber in the print, the part is rigid, strong, and durable enough to hold in place firmly for the duration of the milling operation. As Onyx is highly tolerant to industrial coolants used in milling, traditional milling concerns for similar parts — such as exposure to liquid and degradation — will not lead to issues.

As Onyx is non-marring on parts, users do not have to worry about scratching the surface of metal parts and leaving surface damage, a concern when deploying metal workholding fixtures. This opens up decorative applications.

End Use Parts

Replacement nut plates (Onyx FR-A, Continuous Carbon Fiber FR-A). Manufacturing replacement nut plates additively is simple, fast, and cheap — with simple CAD software and hole spacing measurements, this part can be printed in as little as ten minutes and for just one dollar.

Nut plates are ubiquitous in the building of experimental aircraft. When taking apart aircraft components, damage to or loss of nut plates can lead to procurement difficulties.

Gold-plated Bezels (Onyx FR, Continuous Carbon Fiber). These bezels are a part of in-flight entertainment retrofit kits, alongside screen-mounting brackets and housings for control units. The high-quality surface finish of Markforged 3D printers allows for easy printing of these decorative parts, which have specific aesthetic needs. These bezels were made quickly, in-house for cheap, with a quick turnaround time and an aesthetic surface finish.

By 3D printing this part, the manufacturer was not tied to typical constraints — such as what metals were in stock at a given time, quantity of raw material available to work with, or having to keep a range of material types and sizes in stock.

Onyx is a particularly suitable and versatile material to fabricate this part due to its surface finish aesthetics: parts printed can be made to resemble wood grain, painted, or be plated to look like any type of metal.

Water bottle holder (Onyx FR, Continuous Carbon Fiber). This customized water bottle holder is made for special mission helicopter finishing, for pilots on long-duration flights using 1L water bottles. Reinforced carbon fiber gives this part the strength and stiffness to secure the water bottle in place while subjected to repeated high loads of force — so that pilots do not have to worry about the water bottle coming loose mid-flight.

Before this part was 3D printed, attaching the cupholder to different types of airframes posed a challenge — there was no standardized structure in every airframe that could serve as a consistent point of attachment. Expensive adapters often had to be machined with long lead times, or the entire cup holder had to be redesigned to fit specific airframes. When 3D printing this part, design customizations and adaptors can be implemented easily and cheaply to fit unique airframes.

CASE STUDY: TOP FLIGHT AEROSTRUCTURES

3D Printed Aircraft Bracket Forming Tool

Top Flight Aerostructures is an aerospace engineering and manufacturing business that supports the US Military aviation by providing engineering support, manufacturing, repair, and overhaul for composite and adhesively bonded metal components. “Our challenge is that we typically receive orders for a small quantity of parts, where pricing must be very competitive,” says Greg Kress, VP at Top Flight Aerostructures. On many of their orders, tooling represents a large portion of their manufacturing costs — skilled labor is expensive, and the CNC bandwidth required for tooling takes away from time they could be using to make revenue generating parts. In an effort to find a low-cost tooling solution, the company discovered Markforged continuous fiber 3D printers and decided to invest in a Mark Two.

One of the first applications Top Flight Aerostructures found value in was forming tools. This tool — printed in Onyx reinforced with continuous fiberglass — was used in a 100 ton hydraulic press to form an edge support bracket for a C-5M Galaxy, the largest cargo plane in the American military. Top Flight was able to quickly model the tool in SolidWorks 2019 and quickly and easily print it on their Mark Two, completely bypassing the need to program and set up their CNC. Eiger, Markforged’s 3D printing software, allowed them to reinforce the tool with continuous fiberglass fiber at high-stress points. The resultant tool performed just as well as a CNC tool would have for a fraction of the cost, labor, and machine bandwidth.

CASE STUDY: CABIN MANAGEMENT SOLUTIONS

CMS works with aircraft maintenance, repair, and overhaul (MRO) companies and private owners to design and develop cabin control and entertainment systems for luxury private and business jets. The company was founded to provide a cost-effective, quick-turn alternative to the long lead times and high costs associated with cabin management maintenance, upgrades, and replacements.

Download the customer success story now →

See how Markforged helped CMS compete with the big companies.

CASE STUDY: JJ CHURCHILL

In order for aircraft to fly true, JJ Churchill (JJC) meticulously inspects every blade of its jet engine turbines. Markforged's Onyx with continuous carbon fiber reinforcement is the only material that met their requirements of strength and stiffness at an affordable price. These printed parts exceeded all expectations held by JJC regarding part life on the shop floor.


Markforged

APPLICATION SPOTLIGHT

CMM Fixtures

	Time	Cost
Traditional	10 days	$1590
Markforged	3 days	$330
Savings	**70%**	**80%**

JJ Churchill Ltd
PRECISION ENGINEERING

JJ Churchill (JJC) is a long-standing leader in precision aerospace engineering and manufacturing.

Challenge

Inspection fixtures require enormous time and cost to machine because they must be highly accurate, repeatable, and strong.

Solution

Markforged 3D printers produce complex custom geometries for efficient, secure workholding of valuable low-volume parts.

Results

JJC can design and test fixtures within the same week, with lower material waste and exceptional quality and precision.

Precision Quality Inspection

In order for aircraft to fly true, **JJ Churchill (JJC)** meticulously inspects every blade of its jet engine turbines. Their coordinate measurement machine (CMM) fixtures must maintain tight tolerances and deflect minimally in order to ensure a high level of accuracy. Markforged's Onyx with continuous carbon fiber reinforcement is the only material that met their requirements of strength and stiffness at an affordable price. These printed parts exceeded all expectations held by JJC regarding part life on the shop floor. Manufacturing Engineer Karan Singh said, "once we realized the directional strength properties available with the Markforged products, we haven't used anything else".

Traditional manufacturing of CMM fixtures involves multiple roughing and refining operations, which underlie slow iteration and machining wait times. JJC engineers constantly seek innovative solutions to such bottlenecks. They turned to Markforged to achieve major advancements in processes and materials. Combining custom additive manufacturing with off-the-shelf parts enables streamlined production and improved functionality.

\+ Non-Marring Material

With Onyx, turbine blades and other components do not get scratched and deemed defective as a result of inspection itself.

\+ Hardware Integration

Threaded inserts allow screws to apply higher force with lower deformation, and locating dowel pins can press fit into the printed part to aid positioning.

\+ Minimal Deflection

Continuous carbon fiber reinforcement along fixture jaws greatly reduces any workpiece deflection, thus ensuring accurate measurements.

Precision Quality Inspection

Download the Application Spotlight →

See how Markforged printers can produce complex custom geometries for you.

CASE STUDY: HANGAR ONE AVIONICS

Hangar One Avionics is a San Diego-based avionics and maintenance company. The team specializes in completions of law enforcement and special mission aircraft for a number of global customers including global customers, on Airbus Helicopters, Bell, Cessna, and MD airframes.

Oftentimes, specific customer needs will require unique and custom parts — such as a pilot-seat console. Until a few years ago, Hangar One Avionics built all of these custom and low-volume parts for customers through CNC machining, a traditional subtractive method of manufacturing.

Cockpit Console and Cupholders

Many of Hangar One Avionics' customers require low production or one-off custom parts to increase cockpit safety and convenience. To create these parts, the team would often rely on conventional machining methods using raw materials — a time consuming, impractical process resulting in up to a 65% scrap rate.

The Hangar One Avionics team needed to make a center console — a part that sits between the pilot and copilot seats — for a fixed-wing Cessna. Instead of going with the slower and expensive machining process, the team used their Markforged X7 printer. As a result, they not only printed the console in record time, they also added further customizations including two cupholders, a niche for the pilot's keyboard, and disconnects for hand controllers and USB chargers. The console and its additional features were printed using Onyx FR — a certified UL 94 V-0 rated flame-retardant nylon filled with chopped carbon fiber. The team's decision to use 3D printing rather than conventional methods significantly freed up the machinist's time to focus on other important tasks.

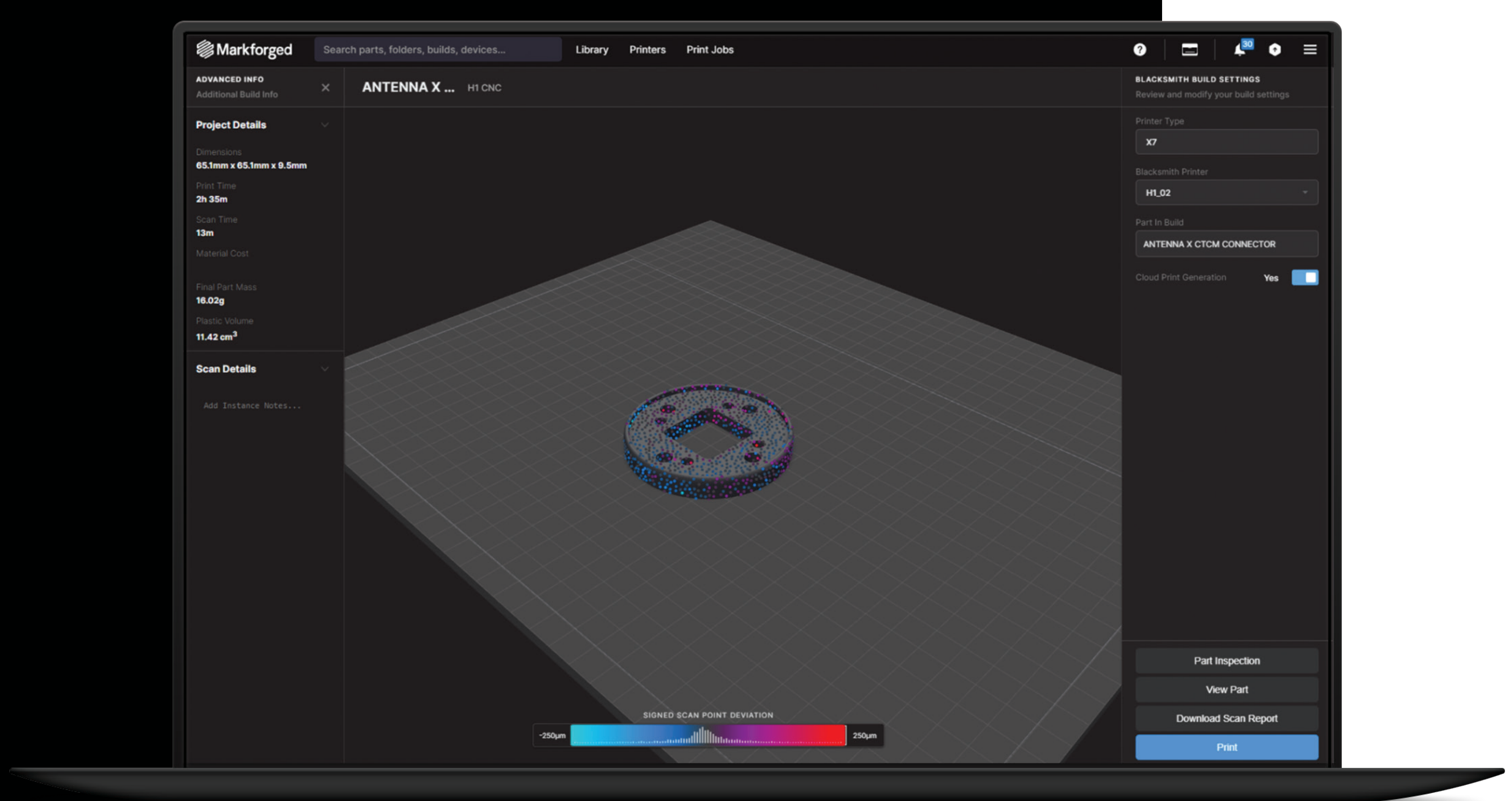
Matthew Roth, Head of Machining at Hangar One, has kept a close watch on Markforged ever since the company began to focus on increasing aerospace industry support. Matthew Roth is very interested in the company's latest releases, such as a traceable version of Onyx FR and Carbon Fiber FR, as well as Markforged's current effort to receive National Center for Advanced Materials Performance (NCAMP) qualification for its additive manufacturing process and aerospace targeted materials.

"Adding traceability and helping speed testing and approvals with NCAMP qualification gives us more ways to add value to our customers."

MATTHEW ROTH
HEAD OF MACHINING,
HANGAR ONE

"Explaining why we use Blacksmith is simple. Blacksmith does the same thing that the old manual inspection process did. The difference is that Blacksmith digitizes the process which makes it faster, easier and more reliable."

MATTHEW ROTH
HEAD OF MACHINING,
HANGAR ONE



Blacksmith Software

Saving Time with Blacksmith. With AM, one time consuming aspect of the traditional manufacturing process still remained for 3D printed parts. Before parts could be used or installed in aircraft, they had to pass through a rigorous full inspection. This manual process was time consuming — it required setting up appropriate test procedures, retrieving inspection equipment, and conducting the testing. On average, this took 30-45 minutes to complete for each part.

Hangar One estimates that using Markforged's Blacksmith part inspection software saves 30 minutes per part on average. With Blacksmith, inspection is an automated process that works while the parts are printing. After each part is printed, reviewing the analysis and report only takes a few minutes.

In addition to making the inspection process both easier and faster, Blacksmith ensures that inspection data is available reliably for future reference because its data is stored in the cloud, rather than on paper. This is critical, due to traceability and FAA requirements for keeping aircraft part records over a long period of time.

Testing Blacksmith. Before Hangar One could introduce a formal change to the way it inspected parts, the company knew that it had to rigorously test the value of this new process to satisfy its own internal staff as well as its customers. This required verifying that Blacksmith had the level of accuracy and consistency that the company needed for aircraft parts.

After printing several parts with Blacksmith, the parts were also inspected with conventional measuring tools. When the two sets of data were compared, Blacksmith was found to be more accurate. Since then, Blacksmith inspected parts have consistently been accurate within 3-4 thousandths of an inch.

THE FUTURE OF ADDITIVE IN AEROSPACE

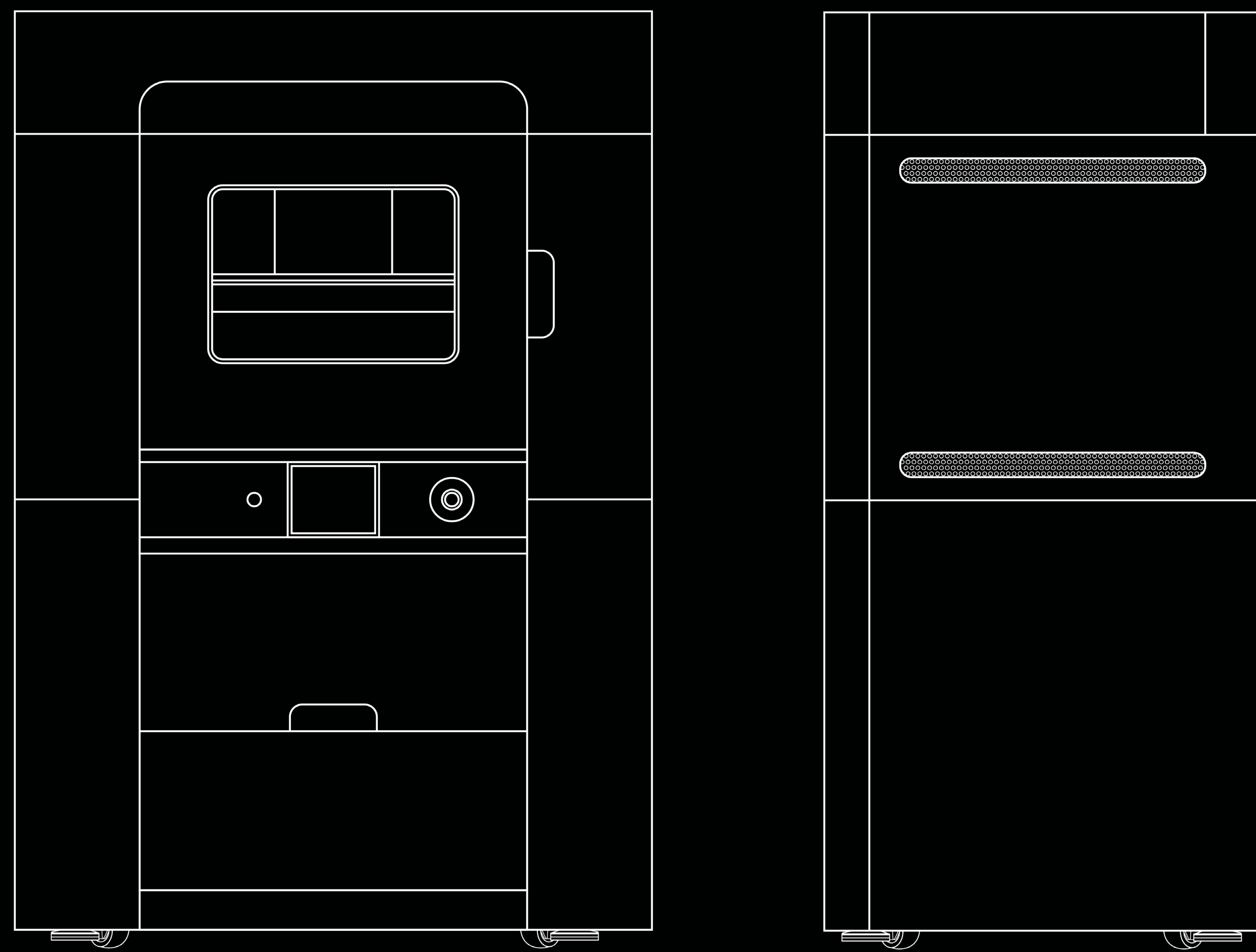
As adoption of composite 3D printing in aerospace continues, technological advances in the field continue to develop — such as larger build sizes, increased precision, improved surface finish qualities, easier to use interfaces, and incorporation of high-performance thermoplastics — opening up new business cases and applications.

The FX20

The FX20 brings the transformational benefits of The Digital Forge and Continuous Fiber Reinforcement to a previously unseen scale — pairing size and throughput to make larger builds at incredible speeds, opening up a new realm of parts and applications in the aerospace industry.

The FX20 is the largest and most precise machine Markforged has ever produced, featuring an 84L heated build chamber and massive, verified-flat vacuum bed with print sheets. The motion control system offers closed loop control through precision linear encoders. FX20's turbo mode builds parts at unprecedented speeds, while new XL material spools minimize the need for spool changeover.

The FX20 is easy to use, featuring a large touchscreen from which users can simply control the printer. Automated calibration and leveling reduces operator input, while a wide variety of sensors give live feedback on machine performance. A built-in advanced material cabinet contains two active XL spools and can store two more with precise moisture control.



Hardware

Internal Part Geometry	Closed Cell Infill with Continous Fiber Reinforcement	
Build Volume	525 x 400 x 400 mm (20.7 x 15.7 x 15.7 in)	
Z Resolution Range	50 - 250 µm	
Print Bed	Heated up to 200° C	
Build Chamber	Precision Machined Aluminum	
Materials (Compatible)	Plastics:	ULTEM™ 9085 Filament, Onyx™, Onyx FR™, Onyx ESD™, Nylon
	Continuous Fibers:	Carbon Fiber, Carbon Fiber FR, Fiberglass, Aramid Fiber (Kevlar®),* HSHT Fiberglass
Power	200-240VAC 3P+E, 24A or 347-416VAC 3P+N+E, 14A; 8 kW	
Weight	453 kg (1000 lb)	
Footprint	1325 x 900 x 1925 mm (52 x 36 x 76 in)	

* Dupont™ and Kevlar® are trademarks and registered trademarks of E. I. du Pont de Nemours and Company. Support for Markforged plastic and fiber materials will be added over time, although not every combination.

Massive Builds, Fast

Prints on average 8x faster than other Markforged printers, includes an 84L build chamber, and can print sizes up to 525 x 400 x 400 mm.

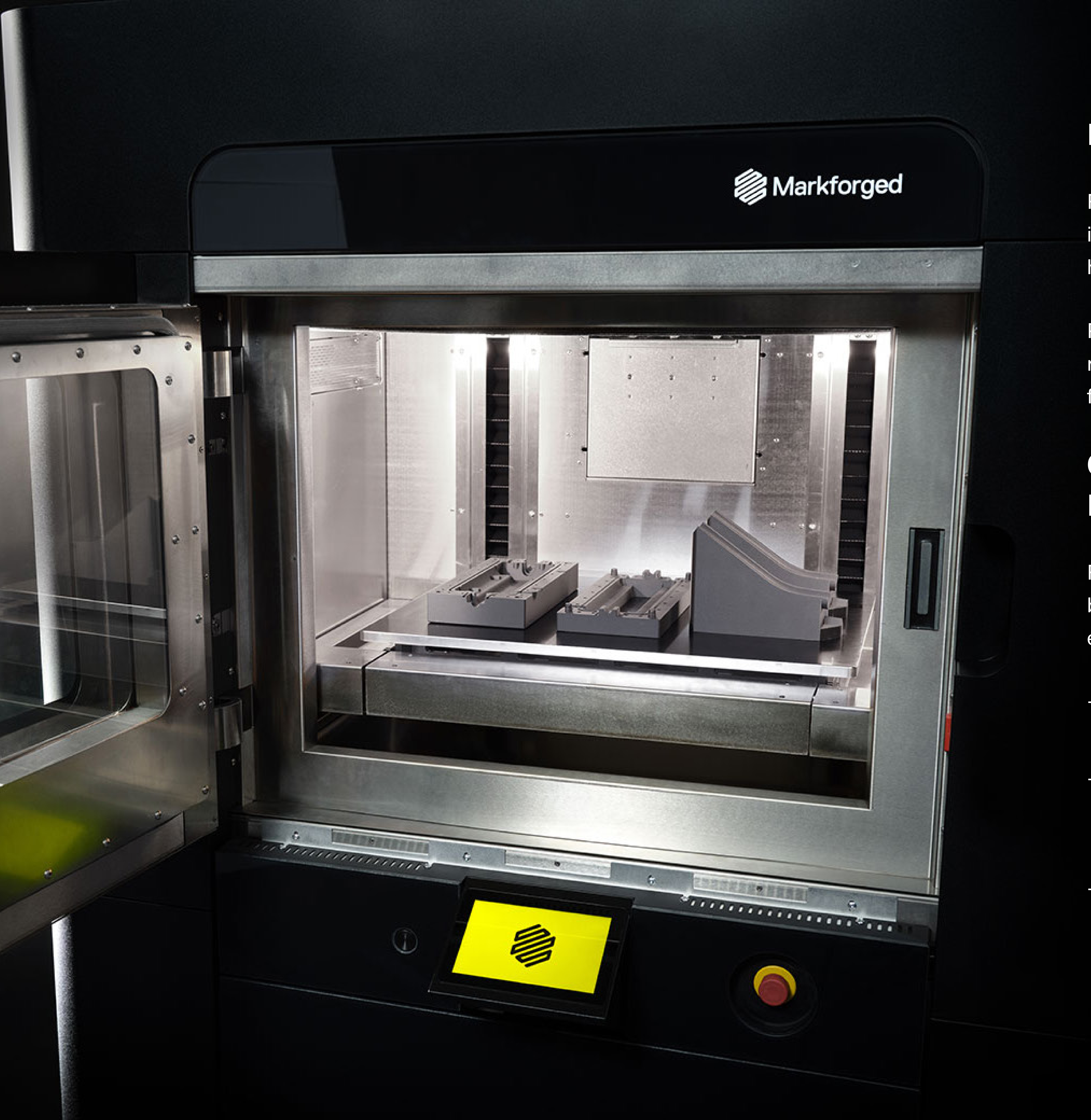
With the capacity to print larger parts, an assembly of multiple individual components can be combined into a single, unified body.

Production-Ready Performance Made Simple

Precision-designed and sensor-driven to deliver breakthrough accuracy, quality, and reliability; all with the most simple user experience in class.

The FX20's aesthetic surface quality makes it possible for parts to go directly from print to application, without extensive post-processing.

+ Micron-precision linear encoders on each axis that measure gantry and stage position directly, with closed-loop feedback control that maintains accuracy under continuous industrial use.
+ Material cabinet moisture sensing capable of measuring down to 10 ppm to prevent out-of-spec filament from ruining your print.
+ Dozens of sensors working in harmony to maintain thermal and spatial control for maximum part performance and consistency.
+ Cloud-based platform enables centralized design and distributed production.
+ Full-stack ecosystem enables "just click print" usability with confidence in repeatable results across the flee



Functional Parts from Factory to Flight

From industrial tooling and fixtures to flight-ready production parts, FX20 is capable of printing metal-replacement composites using a range of high-performance, aerospace-ready materials.

Printing parts in ULTEM™ 9085 Filament with continuous carbon fiber reinforcement (CFR) is an industry-leading capability for extremely strong flight-ready parts.

Continuous Fiber Reinforced ULTEM™ 9085 Filament for even stronger parts

FX20 reinforces aerospace-ready polymers with continuous carbon fiber, bringing stronger high temperature thermoplastic parts to engineers everywhere. Benefits of continuous fiber reinforcement include:

+ Similar strength to aluminum, a continuous carbon fiber reinforced part has the ability to replace machined components in application.
+ Enhanced stiffness, impact resistance, heat resistance, and durability are possible through a range of specialty continuous fiber reinforcement materials.
+ Continuous fibers complement filled filaments. As an example, Markforged uses short carbon fiber in Onyx to improve accuracy and surface finish of printed parts, and continuous carbon fiber for a tenfold boost in strength and stiffness.

FUTURE OUTLOOK

The outlook for 3D printed composites in the aerospace industry is strong. According to data published in February, 2022*, analysts expect the global market for aerospace-specific additive manufacturing to grow at a compound annual growth rate (CAGR) of 16.1% in the next four years, reaching US $1.9 Billion by 2026.

Additionally, the Biden administration introduced the Additive Manufacturing Forward program in May 2022. AM Forward was launched as a series of agreements between five large manufacturers (primes) and their small to medium-sized U.S.-based suppliers. In each of the agreements, the large manufacturers plan to help facilitate additive adoption for their smaller suppliers. As of launch, the program has five large manufacturers as its initial participants, including three major aerospace industry OEMs — GE Aviation, Lockheed Martin, and Raytheon. More primes are expected to join the program.

Through AM Forward, each of these manufacturers will support their smaller, U.S.-based suppliers by:

+ Purchasing high volumes of additively manufactured parts
+ Providing additive manufacturing training
+ Providing technical assistance to support AM adoption
+ Contributing to the development of common standards and certification for additive manufacturing technologies and products

Manufacturers pushing the boundary of additive today with Markforged:

* Global Industry Analysts

Markforged anticipates that this initiative will accelerate adoption of additive manufacturing in the aerospace industry in multiple ways. In the near term, we expect an increase in demand for additively manufactured aerospace parts, while in the long term, we expect the foundation of qualified AM applications to expand beyond prototyping and custom one-off components into low and medium volume production. Aerospace industry suppliers gain a competitive edge through the flexibility and reduced labor requirements of AM technologies, while opening up new manufacturing partnerships and lines of business. Larger manufacturers who invest in scaling AM through supplier partnership networks gain resilience in their supply chains, helping them navigate the rapidly changing landscape of global manufacturing.

AM Forward also programmatically tackles one of the biggest barriers to scaled AM adoption, by making technical knowledge and assistance more accessible than ever. Knowledge from experience helps companies get the most out of their 3D printers — reducing risk, laying the groundwork for repeatable and reliable processes, accelerating development of in-house expertise, and empowering engineers to design more game-changing parts for innovative applications.

Markforged stands by the AM Forward program to support American supply chains, domestic SME suppliers, and advances in the field of aerospace engineering. We have the largest connected fleet of industrial printers that build end-use parts at the point of need, as well as the most secure AM platform (first AM company to achieve ISO 27001). Our team has extensive experience with materials qualification for aerospace applications through NCAMP.

Markforged has led supply chain transformations within organizations from the U.S. Air Force and Army, to wind energy companies, automotive manufactures, and aircraft OEMs. Empowering SMEs with supply chain self-sufficiency at scale, we helped Michigan's state government deploy 300+ printers on a connected network.

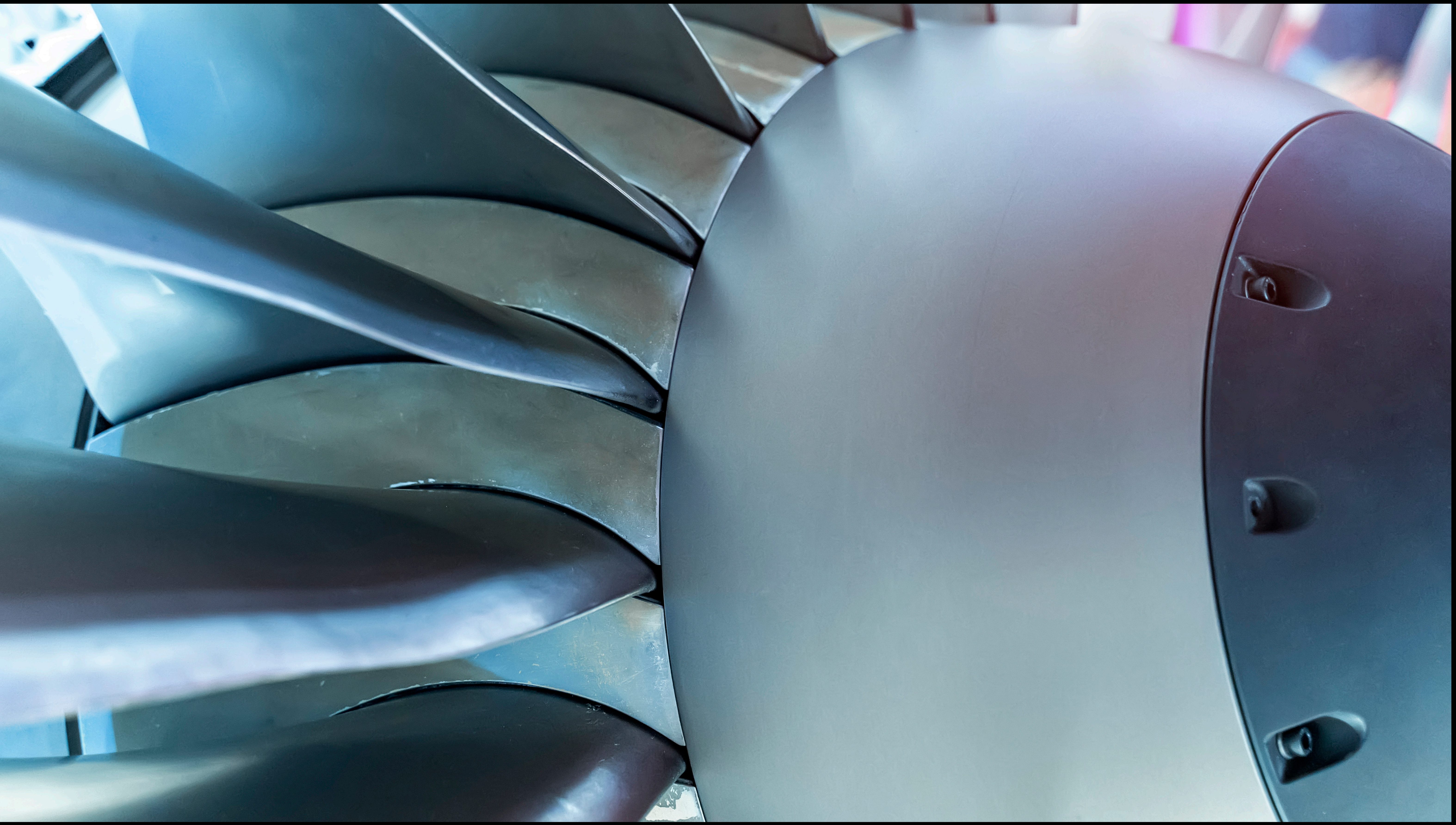
For more information on AM Forward, read our article.

CONCLUSION

Modern additive manufacturing platforms offer numerous advantages over traditional manufacturing processes: allowing companies to produce more parts in-house, increase design freedom, speed up design cycles, cut costs on tooling and low-volume high-mix parts, and regain control of their supply chains.

Advances in composite 3D printing have made these benefits easily accessible to aerospace manufacturers. New printers can fabricate CFR-reinforced parts with materials that meet the needs of demanding aerospace applications. Strong, lightweight AM materials engineered for flight aboard aircraft make FAA/EASA compliance easy with lot-level traceability.

Demand for additively manufactured composites is expected to increase in the coming years. As aerospace manufacturers grow their in-house AM knowledge and experience, expect to see companies qualify more AM parts for flight. AM Forward will likely contribute to further demand for additively manufactured parts, specifically in the aerospace industry.



Markforged (NYSE: MKFG) is reimagining how humans build everything by leading a technology-driven transformation of manufacturing with solutions for enterprises and societies throughout the world. The Markforged Digital Forge brings the power and speed of agile software development to industrial manufacturing, combining hardware, software, and materials to solve supply chain problems right at the point-of-need. Engineers, designers, and manufacturing professionals all over the world rely on Markforged metal and composite printers for tooling, fixtures, functional prototyping, and high-value end-use production. Markforged is headquartered in Watertown, Mass., where it designs its products with over 350 employees worldwide.

To learn more about Markforged, please visit: markforged.com

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