The Dynamic Duo: 3D Printing and Optimization

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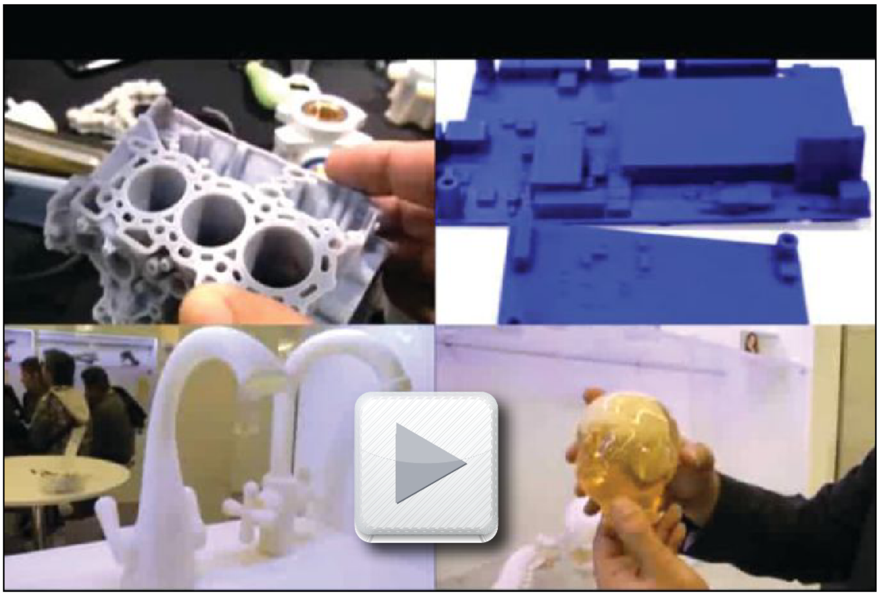

The fascinating potential of 3D printing is explained in this video.

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Cover: 3D printer image courtesy of Stratasys. Optimized part courtesy of solidThinking Inspire.

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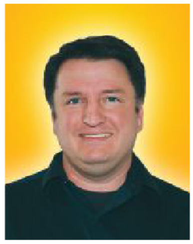
Lightweight Mandate



Advances in 3D printing, material science and optimization software have converged with government mandates to make lightweighting a top priority for design engineers. Thankfully, there are plenty of mature technologies and processes available to reduce product weight.

For example, Stratasys patented the Fused Deposition Modeling (FDM) method of 3D printing more than 25 years ago. When FDM is paired with topology optimization software, a lighter design can quickly move from an algorithm-generated concept to a physical part. 3D printers allow the often unusual optimized designs to be prototyped, tested and sometimes incorporated as end-use parts. In some cases, the optimized designs are too complicated to be manufactured via traditional methods.

Real-world examples can be seen in the pages that follow, such as how one company used FDM to save $150,000 and six months time to produce components for its unmanned aerial vehicle.

The steady march of 3D printer and material technology has advanced in tandem with HPC and optimization software to make lightweighting and 3D printing more of a requirement than an option. After all, if your competitors are reducing material costs and product development time, can you afford not to?

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Stratasys

The Dynamic Duo: 3D Printing and Optimization

Thanks to technology advances, there's a new dynamic duo powering many leading-edge companies' lightweighting efforts. The combination of modern optimization software with state-of-the-art 3D printing is allowing engineers to conceptualize and produce lightweight, but structurally sound organic shapes that may have never been considered or manufactured using traditional design and production methods.

Companies in industries like automotive, consumer devices and industrial equipment, among others, are under constant pressure to shave weight from their products. Some are embracing lightweighting initiatives to meet regulatory requirements and to reduce energy consumption while other sectors are chasing more lightweight designs to reduce material costs or to satisfy customers' increasing desire for sustainable, more energy efficient products. Whatever the driver, optimization software and 3D printing are proving to be a potent combination in helping companies meet their lightweighting goals.

Advance Beyond Barriers

The 3D printing/additive manufacturing (AM) market has changed dramatically over the years. Once a niche player in targeted segments like aerospace, 3D printing has taken off across a range of industries, including specialty automotive, medical devices and industrial machinery. With the influx of more affordable professional-grade 3D printers, the technology is now accessible to small- and mid-sized companies. Moreover, the increased performance and expanded materials palette now make it possible for organizations to produce structurally sound end-use components, not just working prototypes.

Likewise, there have been a slew of advances in optimization software, particularly in the area of topology optimization — a mathematical approach to making the most of material layout within a given design space. As opposed to the typical 3D CAD model, which treats a solid object as a homogeneous and discrete entity, components designed using topology optimization software operate under the assumption that a volume of virtual material can be continuously varied in stiffness and density much like structures in nature. As a result, the software comes up with organic structures that only call for material where it is needed to maintain structural integrity — a potentially huge asset for lightweighting initiatives.

Companies that have seen good results with topology optimization studies have been hampered by the constraints of traditional manufacturing processes like casting or machining. These tried and true manufacturing techniques too often aren't able to effectively output the complex organic shapes and latticed internal structures imagined by the software. Faced with a choice between an optimized design and ease of manufacturing, companies are forced to compromise, either including manufacturing constraints in the actual optimization or simplifying the unconstrained optimization. Either scenario limits the number of feasible designs and undermines the lightweighting effort.

The combination of easier-to-use optimization software and high-performance 3D printers eliminate many of these constraints. Engineering teams are empowered to create the shapes truly optimized for function and performance without any excess material baggage. They are unencumbered by the limitations imposed by traditional fabrication methods.

The Stratasys Dimension 1200es uses Fused Deposition Modeling to create lightweight ABSplus thermoplastic parts.

Optimization software like Altair's solidThinking Inspire can be used to 1 import or sketch a part, 2 defeature it, 3 assign materials and loads, and 4 then generate an ideal shape with the click of a button using mathematical optimization. Once a shape has been optimized, optimization software can help 5 confirm the part's performance so that the part can be 6 refined in a CAD program. More complex, lighweight designs can be 3D printed for a fast prototype or short-run production parts.

Images courtesy of solidThinking Inspire

Optimization and FDM's Magic Touch

"FDM (Fused Deposition Modeling) technology lends itself to lightweighting," notes John Dobstetter, business development manager for Stratasys' Manufacturing Solutions Group. "The engineered thermoplastics used in traditional manufacturing and production are now available through FDM technology, allowing organizations to take advantage of those materials plus the ability to create lightweight shapes that otherwise would have been too complex with traditional production technology."

Drawing inspiration from nature, topology optimization software takes a different approach than traditional computer-aided design (CAD) software to come up with these complex organic shapes. With CAD, engineers define a part's shape, add loads and constraints, and then run a simulation to prove out the design. In contrast, topology optimization requires engineers to identify a specific design space, add loads and constraints, and the software automatically generates optimal shapes that fit into that space while satisfying the specified weight and stiffness targets.

Case Studies in Complexity without Constraints

There are numerous applications of FDM-based 3D printers helping companies meet lightweighting targets. NASA's Jet Propulsion Laboratory (JPL) collaborated with Stratasys Direct Manufacturing (formerly RedEye), a 3D printing services division of Stratasys, to lower the cost and weight of satellite antenna array supports for the FORMOSAT-7/COSMIC-2 satellite. Using FDM technology and the ULTEM 9085 thermoplastic material, Stratasys Direct Manufacturing was able to create an array that met NASA JPL's weight and load bearing specifications while producing the structure as a single unit, which helped reduce both weight and costs.

FDM improves the performance of Joe Gibbs Racing's teams via custom 3D printed parts.

For its 3D printed parts, NASA uses ABS, PCABS and polycarbonate materials. FDM supports production-grade thermoplastics, which are lightweight but durable. Watch the video.

NASA is also employing FDM technology in its research efforts to create a human-supporting rover for future space exploration to Mars. FDM technology was employed to 3D print parts, including flame-retardant vents and housings, camera mounts, large pod doors, custom fixtures and a large part that acts as a front bumper. FDM's design flexibility and support for production-grade thermoplastics materials were instrumental for accommodating the tailored housings that would hold the complex electronic assemblies—in particular, one ear-shaped design that would have been cost prohibitive to machine with traditional manufacturing methods.

"You always want it to be as light as possible, but you also want it to be strong enough that it's got your safety factors, that nobody's going to get hurt," recounted NASA Test

While the outward dimensions of a structure appear more varied than a traditional solid model, the interior elements are where topology optimization really works its magic. As part of the optimization process, the software systematically analyzes the stresses on the shapes and removes any non-essential material from the volume. The result is a design that varies material properties like stiffness and density throughout the structure, creating a lattice or skeletal composition that can significantly reduce the weight of a part without impacting its structural integrity.

Engineer Chris Chapman in a case study published by Stratasys.

Likewise, FDM technology is really making a difference in lightweighting applications for the automotive sector along with industries that rely on custom parts. At Joe Gibbs Racing, for example, a Stratasys Fortus FDM system was tapped to create a custom part — in this case, a filter housing used with a vehicle's air conditioner to clean the air blown into a driver's helmet — without having to sacrifice performance to satisfy machining constraints, according to Brian Levy, a JGR design engineer.

The ability to produce fully functional parts using direct digital manufacturing methods is instrumental to Klock Werks' success.

At Klock Werks Kustom Cycles, which builds one-of-a-kind motorcycles, FDM 3D printers paved the way for building any kind of part with complex geometry far more quickly and at less expense than doing so with traditional injection molded plastic or machined aluminum, noted Jesse Hannssen, a Klock Werks mechanical engineer, in another Stratasys case study. "FDM put no limits on our imagination," Hannssen said. "We built all these parts in five days from polycarbonate. The cost of producing the parts with FDM was less than a quarter of the cost to injection mold or cast them."

To produce these optimized shapes, additive manufacturing methods employ high-performance materials to create functional prototypes and end-use parts requiring tight tolerances, toughness and environmental stability. For example, FDM-based 3D printers, patented by Stratasys, use engineering-grade thermoplastics that put them on par from a performance standpoint with traditional manufacturing methods.

3D printers based on FDM technology build parts layer-by-layer from the bottom up by heating and extruding thermoplastic filament. Anywhere support or buffering is needed, the 3D printer deposits a removable material that functions much like scaffolding. Once the part is complete, the support material can be broken off or dissolved — a process that can accommodate the complex geometries and cavities introduced via optimization studies.

Even other kinds of AM technologies don't have the same dexterity for outputting the complex shapes produced by lightweighting optimization studies, says Dobstetter. For example, liquid or powder-based AM systems have no easy way of removing the excess materials created by lattice structures or hollows. As a result, a part would have to be produced as two pieces and then bonded together, an extra step that also adds additional weight to the structure.

The broad range of materials available for FDM-based 3D printers also is well suited for tackling complex lightweighting applications, Dobstetter says. From ULTEM's strength and heat resistance to ABS-M30i, a biocompatible, sterilizable engineering plastic, FDM materials address specialized properties like electrostatic dissipation, translucence, biocompatibility, VO flammability and FST ratings. The diversity provides engineering groups with viable options for producing lightweight, complex structures that could be used in applications across aerospace, automotive, medical and other industries.

Limiting possibilities is not an option for companies under constant pressure to deliver products that are not just aesthetically pleasing, but also environmentally responsible and affordable. Optimization software paired with FDM-based 3D printers can pack a powerful punch for lightweighting initiatives, helping companies innovate far beyond what's possible with traditional manufacturing and design processes.

3D Printing Helps Launch Satellite Mission

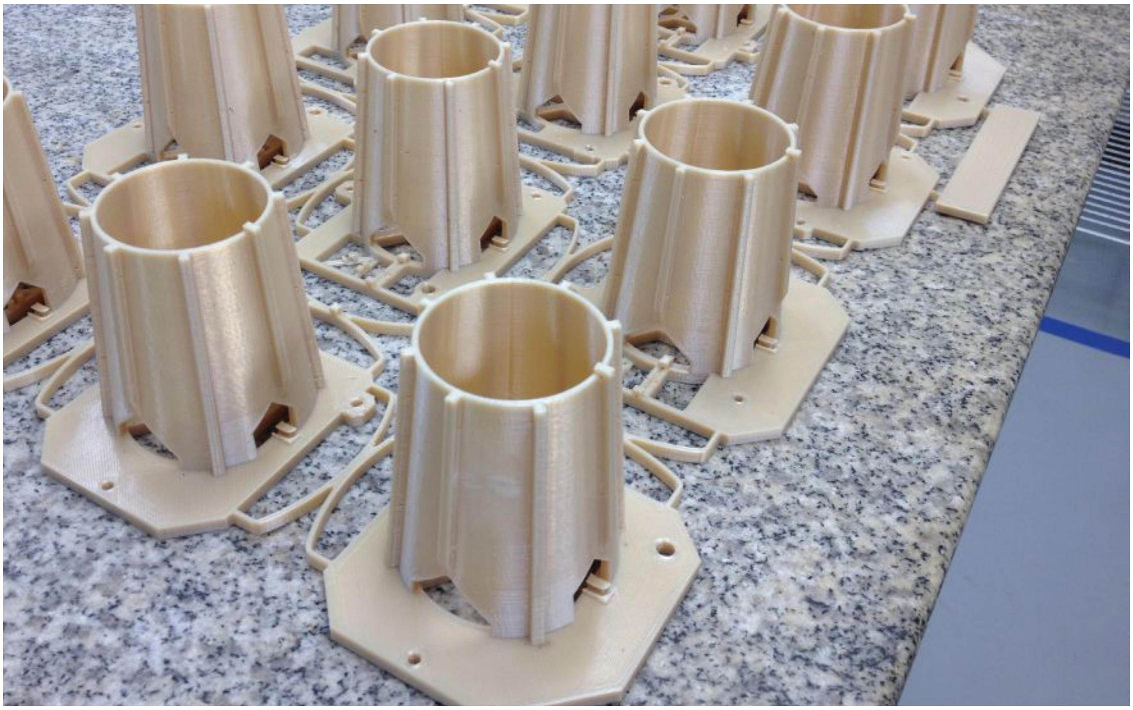
NASA's Joint Propulsion Lab turned to additive manufacturing to lower cost and weight of new satellite antenna array supports.

By Brian Albright

For the aerospace industry, additive manufacturing holds the promise of helping companies reduce cost, weight and complexity for a variety of applications. NASA's Jet Propulsion Laboratory (JPL) recently collaborated with 3D printing services company Stratasys Direct Manufacturing to do exactly that as part of the upcoming FORMOSAT-7/ COSMIC-2 satellite launch.

In 2006, a consortium of U.S. research universities and the Meteorological Society of the Republic of China (Taiwan) collaborated on the original Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) project, using satellites to collect temperature, moisture and pressure data. A follow up project, the FORMOSAT-7 COSMIC-2 satellite mission, will gather even more weather-related data. That mission will launch six satellites into low-inclination orbits in 2016, along with another six satellites in high-inclination orbits in 2018. The atmospheric data provided by the satellites will support research in hurricane analysis and prediction, climate processes and other areas.

The Global Navigation Satellite System (GNSS) radio-occultation (RO) payload is being developed by NASA JPL and will be capable of tracking up to 12,000 high-quality profiles per day once both constellations are fully deployed. NASA began its development work in 2011, and additive manufacturing quickly entered the mix.



Stratasys Direct Manufacturing used Fused Deposition Modeling and the ULTEM 9085 thermoplastic to create an array that matched NASA's specifications.

Image courtesy of Stratasys Direct Manufacturing

Control Cost, Increase Speed

Key components of the satellite are actively steered, multi-beam, high-gain phased antenna arrays. COSMIC-2 would use 30 of these traditionally expensive custom arrays, and NASA JPL wanted to find a way to minimize manufacturing costs and assembly time. NASA approached Minneapolis-based Stratasys Direct Manufacturing, a Stratasys subsidiary that provides rapid prototyping and additive manufacturing services, to work on the project.

NASA's JPL is developing the antenna arrays to place on FORMOSAT-7 COSMIC-2 satellites. The mission will collect atmospheric data.

Image courtesy of SpaceX

The antenna array supports are usually machined from a composite material called astroquartz, but the COSMIC-2 design would be expensive to produce that way. "Machining those parts was time consuming and costly, and that raised concerns about validating and testing the design," says Joel Smith, strategic account manager for Aerospace and Defense at Stratasys Direct Manufacturing.

"We're seeing a move in aerospace from traditional manufacturing to additive manufacturing, where it makes sense," Smith says. "Different companies are using FDM (Fused Deposition Modeling) to make brackets and retainers that are not load bearing. They can take out weight and reduce assembly steps by producing single-unit parts."

Using Stratasys FDM equipment, Stratasys Direct Manufacturing could produce the structures as a single unit out of ULTEM 9085 thermoplastic. By doing so, NASA's JPL could quickly create prototypes for testing at a lower cost, and reduce the overall cost and time required to manufacture and assemble the final products.

"The array originally would have been produced in separate parts, and then assembled," says Trevor Stolhanske, senior application engineer at Stratasys Direct Manufacturing. "They wanted to produce the arrays as one unit. They had a rough CAD model, and we worked with them to ensure the specifications would work well with the FDM process."

"We could also provide flexibility for design changes," Smith adds. "With additive manufacturing, you can reduce the cost of producing prototypes and end-use items."

Most 3D-printed parts in the space program have not been for external use on a spacecraft. To create the antenna array supports, NASA and Stratasys Direct Manufacturing would have to test and validate the material and the parts to ensure their performance in that environment.

Thermoplastics in Space

When NASA JPL approached Stratasys Direct Manufacturing, they had already identified ULTEM 9085 for the application. The thermoplas-

3D printing systems fit every stage of the design process from initial idea to high powered prototypes to full production parts. Watch the video.

tic is as strong as aluminum, but much lighter. More importantly, it had already been vetted and approved for aerospace applications.

"It's a flight-certified material, and one of the more robust materials for additive manufacturing," Smith says. "It was also a good fit for radio and antenna applications."

The material had never been used on the exterior of a spacecraft, so the parts had to be tested for antenna beam pattern, efficiency and impedance match, as well as for NASA class B/B1 flight hardware requirements. Those tests for susceptibility to UV radiation, atomic oxygen, outgassing, thermal properties (including compatibility with aluminum panels), vibration/acoustic loads and compatibility with the paint and primer used on the structure.

A high emissivity protective paint was used on the plastic structure to reflect solar radiation and optimize thermal control of the antenna operating conditions.

Collaborative Design Process

The JPL began with a CAD model based on the original machined antenna array design, which was then altered for the FDM process. NASA and Stratasys Direct Manufacturing worked primarily in SolidWorks, Magic and Stratasys' Insight software.

One critical change was the inclusion of 45°, self-support overhead angles in the design to avoid using breakaway support material. That reduced machine run time, increased printing speed, and minimized part breakage during support removal.

"By eliminating the support material, that creates less havoc when you are removing the support," Stolhanske says. "You don't have to remove material from complex areas, and the run time is drastically reduced. The head on the FDM machine does not have to toggle back and forth, layer over layer. You have a twofold savings of run time and support removal, along with minimizing potential damage."

Stratasys Direct Manufacturing and the NASA JPL conducted numerous conference calls and onsite meetings throughout the course of the project to collaborate on the final design. NASA conducted testing of each prototype throughout the process, and would come back to Stratasys Direct Manufacturing with any design adjustments.

"With every iteration, there was a design review and modifications made to the drawing and the printed version," Smith says. "Each part we delivered was a complete component, so they were able to do mock-up assemblies for form, fit and function tests, as well as more detailed changes. They had an end-use part throughout the prototyping phase."

Between March 2012 and April 2013,

Big 3D Printed Build Enables Lockheed Martin to Simulate Fuel Tank

The FORMOSAT-7 COSMIC-2 project was not Stratasys Direct Manufacturing's first time working on a space-related build. Last year, the 3D printing services provider partnered with Lockheed Martin's Space Systems Company (SSC) to 3D print two large fuel tank simulators for a satellite form, fit and function validation test and process development. With the biggest tank measuring nearly 7 ft. long, the project marked one of the largest 3D printed parts Stratasys Direct Manufacturing had ever built.

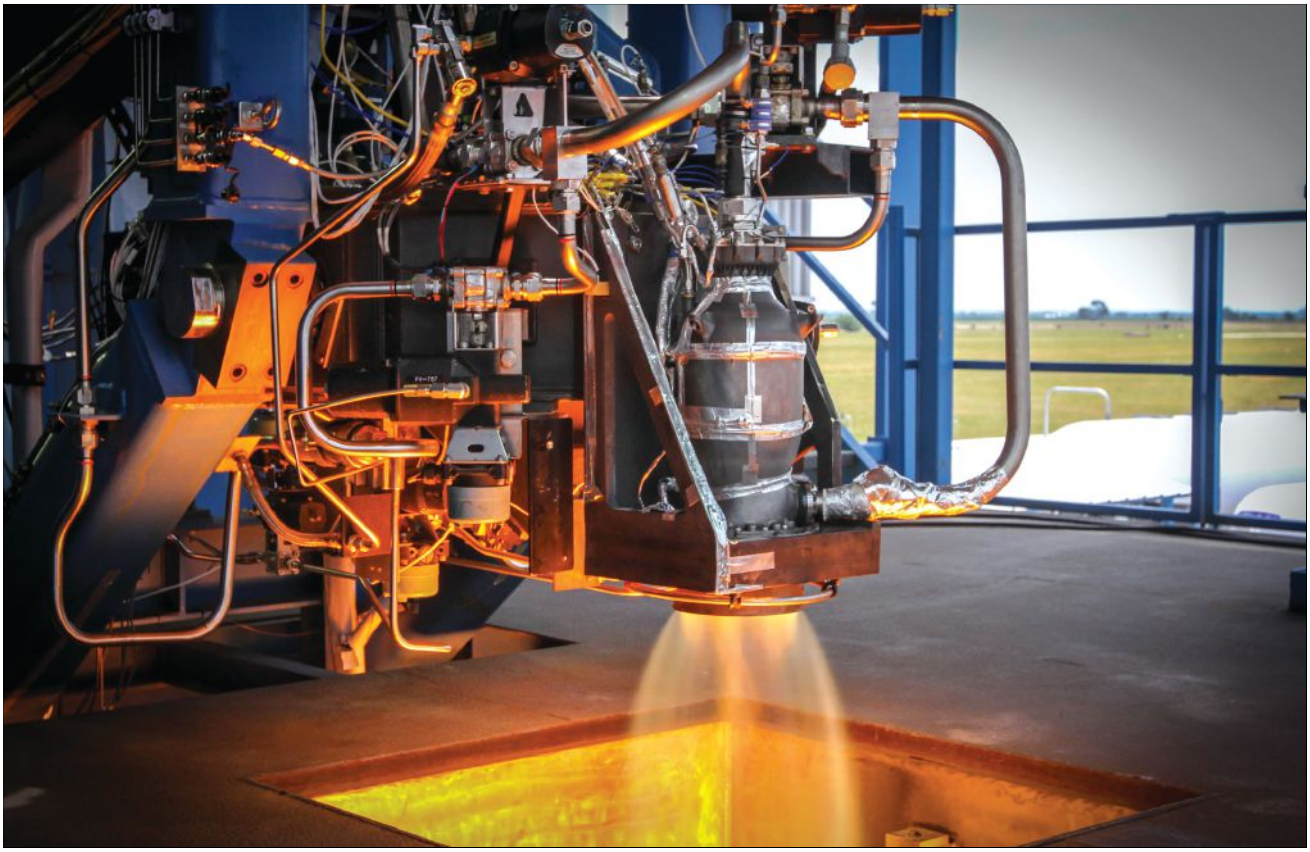
With Stratasys Fused Deposition Modeling (FDM) technology, the team says it developed the fuel tanks within a condensed time frame and at about half the cost of machining the parts.

"With Stratasys Direct Manufacturing's machine capacity and engineering support, we were able to successfully build these tank simulators in a fraction of the time and at a fraction of the cost," said Andrew Bushell, senior manufacturing engineer at Lockheed Martin Space Systems Company, via a press statement.

The larger tank was built in 10 different pieces and the smaller in six different pieces using polycarbonate (PC) material. Combined, the fuel tanks took nearly two weeks to print, taking roughly 150 hours per section. Based on the sheer size of the parts, customized fixtures were required to support the structures as they were bonded together and shipped to be machined to meet specifications. Once all of the pieces were machined, the final assembly required 240 hours.

"This project is unique in two ways — it marks the first aerospace fuel tank simulation produced through additive manufacturing and is one of the largest 3D printed parts ever built," stated Joel Smith, strategic account manager for aerospace and defense at Stratasys Direct Manufacturing, in a press statement.

Lockheed Martin first embraced the design benefits of additive manufacturing with Stratasys Direct Manufacturing in 2012 and has invested in purchasing in-house 3D printers from Stratasys. Stratasys Direct Manufacturing has worked with Lockheed Martin on various tooling and additive manufacturing projects that support its Space Systems Company.



Rocket engine parts made by 3D manufacturing in copper alloy undergo hot-fire testing at NASA Glenn with Aerojet Rocketdyne.

Image courtesy of NASA

Stratasys Direct Manufacturing produced 30 of the structures for testing. The JPL and Stratasys Direct Manufacturing engineering teams collaborated to process STL files and ensure the parts met exact tolerances. Stratasys Direct Manufacturing deburred parts, stamped each with an ID number, and provided a material test coupon, as well as reaming holes for fasteners that would attach to the aluminum panels and small channels in the cones for wiring.

According to Stolhanske, a key challenge was ensuring the wiring holes met the exact tolerances. "The holes had to be a specific dimension that was not too big or too small, and we had to ream precise holes for them," he says. "It was a challenge because they had to be within a certain spec on their drawings in order to work."

Each of the antenna arrays requires roughly 55 to 60 hours to manufacture using FDM. Stratasys Direct Manufacturing was able to deliver the completed antennas for final testing and integration, and has been added to the JPL Approved Supplier List.

In addition to reducing weight, saving time and reducing costs, NASA was also able to validate the FDM process and materials for use on future projects.

"The aerospace and defense markets are really entrenched in traditional manufacturing, so it takes some understanding and education to make the move to something like FDM," Smith says. "We were able to provide support for NASA so they could move from concept to finished part, and be able to make design changes without all the cost and time penalties of traditional manufacturing."

—Brian Albright is a contributing editor for Desktop Engineering *magazine. Contact him via DE-Editors@deskeng.com.*

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Perfect Partners

Designing for manufacturability has already taken a back seat to optimized design in many industries, thanks to additive manufacturing.

By Jamie J. Gooch

Additive manufacturing (AM) can optimize prototyping by allowing multiple physical iterations of a design to be quickly created and evaluated. However, the technology really shines when it's used to create optimized end-use parts that would not be economically feasible to manufacture via traditional means. It's a win-win situation when an optimal design can be realized with rapid manufacturing.

Jeff DeGrange, former vice president of Direct Digital Manufacturing for Stratasys, has first-hand knowledge of end-use 3D printed parts. He worked at Boeing for more than 20 years, including a tenure leading the company's advanced manufacturing efforts. He was the principal engineer involved in getting laser-sintered parts certified for use on F-18 fighter jets and later was the manager overseeing the use of AM on Boeing's 787 Dreamliner.

Leptron's RDASS 4 remotely powered helicopter.

"Even back in the late '80s and early '90s Boeing was using stereolithography," he recalls. "We had one machine. I remember its serial number was 007. I called it the James Bond machine. It was used to make models for low-speed wind tunnels."

Fast forward to today and end-use AM has spread well beyond aerospace. It's especially found its niche in medical, jewelry, and specialty automotive industries, and it continues to spread into all corners of aerospace–from NASA rovers to unmanned aerial vehicles (UAV) to corporate jet interiors.

"There are a number of different things causing the growth of the technology in end-use parts," says DeGrange. "Additive manufacturing now has a broader array of materials, the machines are getting bigger and faster, and the price points are coming down on those machines."

Design Optimization Meets Rapid Manufacturing

We may be able to add optimization strategies to that list of growth factors. The use of optimization software could help engineers realize AM is the perfect partner for building optimized design concepts for lighter weight products that meet strength requirements while using less materials.

"With additive manufacturing, imagine an I-beam that is not all solid–it could be made out of trusses. It doesn't necessarily need to be solid," DeGrange says. "It could be a lattice structure that bridges the beam to distribute the weight of the load. That would use less material and energy to manufacture, if it could be manufactured–and it can with direct digital manufacturing."

AM can enable manufacturability without compromise in many situations, what DeGrange calls "low-volume, high-product mix" environments.

One such environment is the racing industry, which creates many of its customized parts. For example, Joe Gibbs Racing (JGR) recently used Stratasys' Fortus system to manufacture a filter housing that is mounted in line with the driver's air conditioning to help clean the air blown into the driver's helmet.

"The complex design of the part makes it ideal for an FDM (Fused Deposition Modeling) application," said Brian Levy, a JGR design engineer, in a case study published by Stratasys.

"If we tried to machine the part, we would be forced to sacrifice some of its performance to satisfy machining constraints."

Faster Time to Market

In addition to greater flexibility when it comes to manufacturability, designs intended for AM can also help optimize the manufacturing process by saving time and money. We can see one example of this in Leptron's use of AM to develop components for its 5-lb. remotely powered helicopter, the RDASS 4. Design variations are needed for the specialized applications of the company's different customers.

According to the company, injection molding would have cost $250,000 and taken six months to build tooling for the RDASS 4's fuselage components. Design changes would have required more time and expense to modify the tooling. Using a Stratasys Dimension 3D Printer, the RDASS core components can be printed in 48 hours, and smaller components are printed in 6 hours. According to the company, it cost $100,000 to 3D print the parts needed for prototypes and eight production UAVs.

"We made approximately 200 design changes during the course of the project," said John Oakley, chief executive officer of Leptron, in a case study published by Stratasys. "It would not have been possible for a company of our size to design and build this product using conventional manufacturing methods."

Material Challenges

While many AM materials–from Stratasys FDM and PolyJet materials, to sintering materials from EOS, Arcam, and others–are used in manufacturing, it's only the tip of the iceberg. DeGrange says one factor is still holding back more mainstream adoption: a lack of understanding of AM material properties.

"We need to teach this, and not just at select universities, to explain that additive manufacturing is not just for prototyping," he says. "It really needs to start in the education system."

Beyond academia, Stratasys is compiling material test reports that come from accredited third-party sources to show how the company's materials stand up vs. heat, cold, gasoline, flames, etc.

Both Arcam and Stratasys are also working with Oak Ridge National Laboratory to advance AM materials' acceptance by manufacturers, and to develop new materials.

"One goal is a thermal plastic that has the same strength as aluminum," DeGrange says. "You could do complex shapes and parts for automobiles to minimize weight for improved fuel efficiency. You could optimize parts with complex geometries to enhance crash worthiness by putting materials where they're needed to channel forces away from drivers and passengers."

To meet mainstream adoption goals, the industry needs a broader array of materials and material pricing needs to drop, DeGrange says. But with the industry and government working to meet those challenges, realizing the full promise of optimized design using AM doesn't seem out of reach.

F1 Roll Hoop Design

An F1 racecar's rear roll hoop is a structure that protects the driver's head in the cockpit, serves as air intake for the car, plus includes camera mounts and pick-up points. The heavy component at such a high point on the car is not ideal. 3T RPD's goal was to use titanium additive manufacturing get the weight of this component down to 1 kilo (2.2 lbs.), which would drop 1 to 2 kilos. Because of the weight constraints of F1 cars, ballast is commonly used to balance the car and meet minimum weight. By reducing the weight of the roll hoop, engineers can put the saved weight lower down in the car design, thereby improving the overall performance of the vehicle.3T RPD teamed up with Within Technologies to create a new design for the roll hoop. Using Within Enhance software, which has an optimization process linked to an internal finite element analysis (FEA) process, the team 3D printed a lightweight design, which incorporated thin walls and internal features. They were also able to minimize the number of support structures that usually accompany metal AM processes.

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