3D Printing: The Next Industrial Revolution?
A look into the impacts on the aerospace industry

By Alan Kendrick, J.D., Nerac Analyst

Additive manufacturing (AM), also referred to as 3D Printing, is a term used to describe the fabrication of three dimensional objects from raw materials using an additive process wherein successive layers of materials are built up to create the product. Additive manufacturing technologies may be applied throughout the product life cycle. They are used for rapid prototyping of components in R&D and pre-production fabrication processes, tooling development and in full scale production operations using rapid manufacturing.

The use of AM technologies to produce plastic and metal components is expanding rapidly. There are an estimated 30,000 plastic and 500 metal AM machines currently in service, and sales of AM metal machines are expected to see double digit growth over the next five years. The potential for significant cost savings in manufacturing and tooling and reduction in time to market will continue to fuel the interest in AM.

AM processes are increasingly used in both the consumer and industrial markets. On the consumer side, AM is being used to produce home electronics and entertainment components, computer and mobile device parts, shoes and fashion accessories, and customizable consumer products and replacement parts. The use of AM technologies in the production of consumer goods allows for greater design flexibility and reduced time to market. One of the most interesting applications of AM technology to consumer products has been in the design of custom jewelry. Highly detailed and intricate wax models, some with complicated visible internal structures and details that would be difficult if not impossible to carve by hand, are being 3D printed for use in lost-wax casting processes to make a wide array of jewelry.

3D-printed wax jewelry designs by Wired Design.

Sterling silver bangle built up layer by layer in wax using 3D printing and cast in sterling silver using lost wax casting. Nervous Systems

However, by far the largest application of AM technologies has occurred in the industrial markets, particularly in the automotive, aerospace, medical and dental device markets, and it is estimated that these three industries will account for 84% of all AM activities by 2025 (Wohlers Associates, Wohlers Report 2012).

AM in the Aerospace Industry

Additive manufacturing using 3D printing technologies has become the preferred method for designers and manufacturers to create rapid prototypes for product designs and components, customized parts and production tooling. But the technology is making steady advances in terms of speed, size, materials and complexity, enabling the ability to produce complex full scale, multi-material, multi-component models as well as products.

The use of advance materials such as grapheme and carbon fiber in aerospace AM processes will allow major structural components to be 3D printed providing significant savings in terms of fabrication cost and time. Advances in multi-material printing capabilities are providing a means to integrate the printing of electronics into the AM process, as well as providing the ability create variable material properties throughout the component.

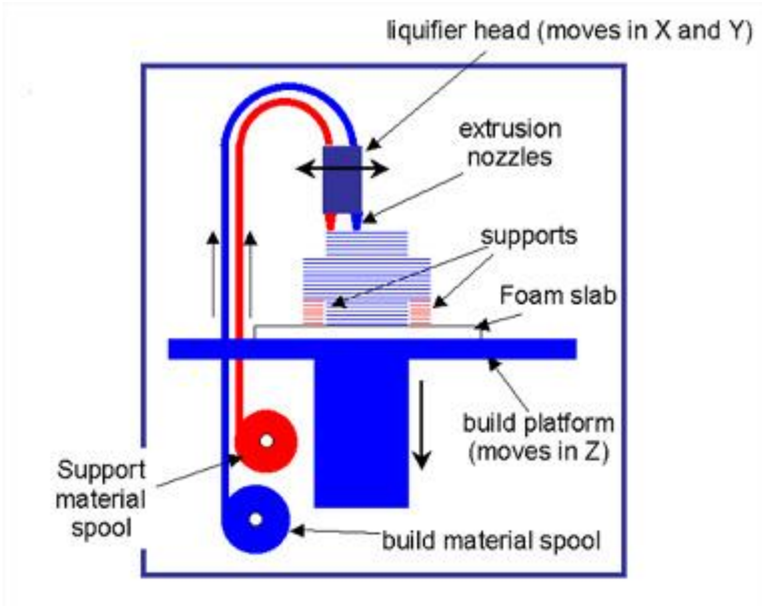
While the processes describe herein are equally applicable and important to the automotive and medical device industries, this article attempts to focus on the more interesting applications in the aerospace industry. Indeed, great strides have been made in the medical device and implant market, not only in the ability to create increasingly complex and customizable devices, but also in the development and incorporation of 3D printed biological material into those designs.

Additive Manufacturing Processes

There are three main methods for producing aerospace application components using additive manufacturing technologies; extrusion deposition or **Fused Deposited Modeling (FDM)**, granular material binding through **Selective Laser Sintering (SLS)**, and **Electron Beam Melting (EBM)**.

Fused Deposited Modeling (FDM) was developed in the late 1980's by Stratasys Ltd. (a major manufacturer of 3D printing equipment and materials) and is typically used in rapid prototyping operations. The process uses a plastic filament or metal wire which is fed to an extruding nozzle where it is heated to the material's glass transition temperature and deposited through the nozzle in a layer-by-layer fashion to build up the part.

FDM typically uses polylactic acid (PLA) or acrylonitrile butadiene styrene (ABS) materials, but polycarbonates (PC) and high-density polyethelene (HDPE) have also been used successfully. The process produces highly accurate, low distortion, production grade engineered thermoplastic components that do not require any curing or post-production treatment and are comparable to plastic injection molding components. However, support structures are need for parts with overhanging entities (as shown below) and there may be strength limitations in certain build directions.

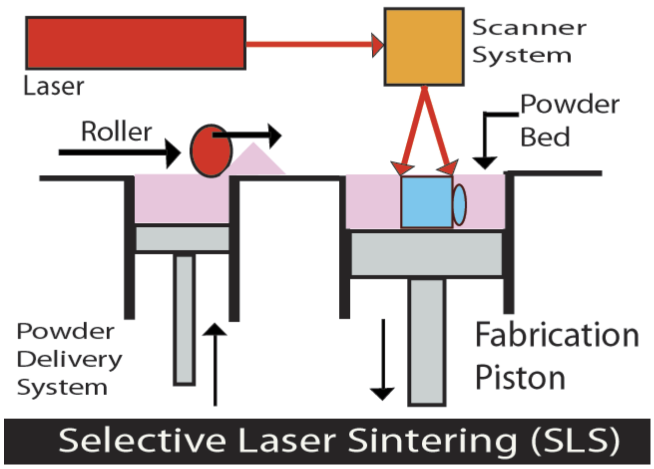


Fused Deposited Modeling (FDM) process schematic.
(XPRESS 3D Rapid Prototyping)

Rapid prototypes created using FDM. (PERIDOT, Inc. Rapid Prototyping)

Selective Laser Sintering (SLS) (also referred to a **Selective Laser Melting SLM**) was developed in the mid 1980's by Carl Deckard, a University of Texas at Austin graduate student. The process uses heat from a high power laser to fuse thermoplastic, metal or ceramic powders to form the three dimensional object. The raw materials are dispersed in a thin layer on top of a build platform where the laser fuses the material by tracing a cross section of the object onto the powder. Once a layer is completed, the platform drops exposing a new layer of powder for the laser to trace.

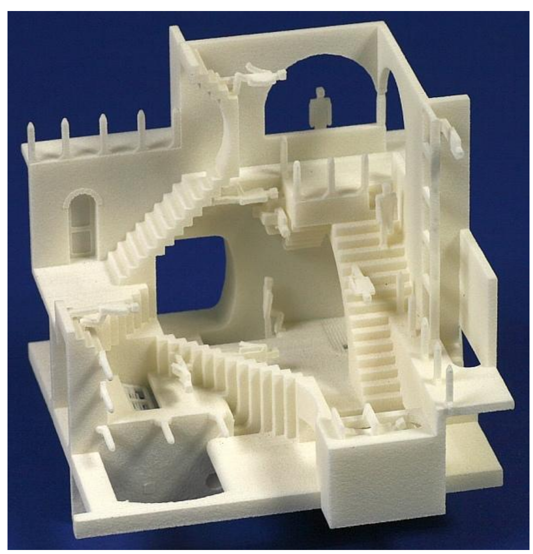
Unlike FDM processes, SLS builds a component within the un-sintered powder and therefore support structures are not required. With SLS, highly detailed and complex interior structures are possible including hinges or movable elements. While both processes produce parts that do not require any curing or post-production treatment, the SLS process is faster and produced parts with greater detail and accuracy. Materials used with SLS include aluminum, copper, gold, silver, tungsten and titanium with resulting part densities of 70-95%.



Selective Layer Sintering process schematic.
(Castle Island's Worldwide Guide to Rapid Prototyping; Laser Sintering)

Objects created using Selective Laser Sintering

(Solid Concepts rapid prototyping services gallery)



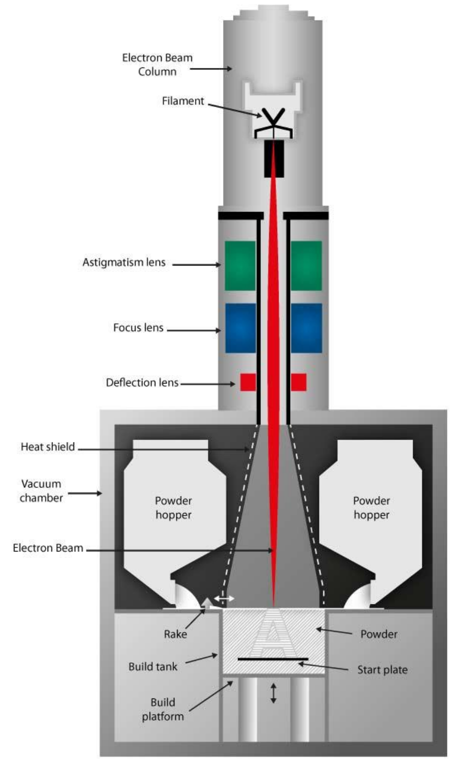
Escher's Relativity, made of nylon by selective laser sintering on a 3D printing machine. (Oded Fuhrmann and Gershon Elber, Technion – Israel Institute of Technology)

"Dodecahedron VI: Great Dodecahedron" Dodecahedron I: Small Dodecahedron
Steel & bronze composites using SLS (by Dr. Vladimir Bulatov, Independent Artist.)

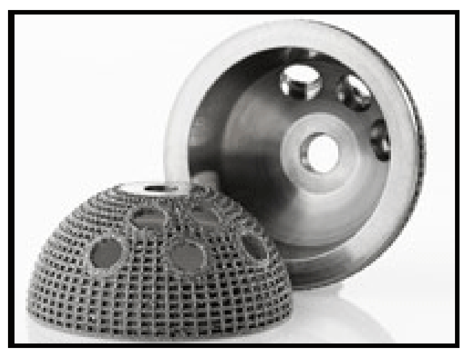
The **Electron Beam Melting (EBM)** process creates fully dense, void-free, stress relieved metal parts (typically titanium alloys) by melting layers of metal powder with an electron beam in a high vacuum chamber. EBM technologies have been employed in the manufacture and repair of gas turbine blades, and may be a promising technology for manufacturing higher production volumes due to processing speed advances in the electron beam and feedstock technologies.

Unlike SLS, the EBM process produces void free, homogeneously solid components by fully melting the metal particles under a vacuum. The process produces high strength high temperature components that are lightweight and ideal for aerospace applications. The efficiency of the electron beam is much greater than the laser in an SLS process resulting in a process that is 5 times faster, and while the surface finish and accuracies are less than SLS fabricated components, EBM produces homogenous solid parts can be flight-certified.



Electron Beam Melting (EBM) process schematic (Arcam AB Additive Manufacturing)

Impeller made using EBM
(Arcam AB Additive Manufacturing)



Titanium Medical Implant made by EBM
(M.Svensson & S. Thundal , Arcam AB)

Aircraft Applications

Stratasys has partnered with Autodesk, makers of AutoCAD, to create the first full scale model of a turbo-prop aircraft engine. The model was printed using FDM, has an overall length and prop blade span of more than 10 feet, and contains 188 components. The components were produced and assembled in **less than 7 weeks resulting in a 97% cost reduction and 83% time reduction** vs. creating the same model using traditional machining and casting manufacturing processes.

Stratasys has also partnered with Optomec, an additive manufacturing company with expertise in electronics integration, to develop a thermoplastic wing for an unmanned aerial vehicle (UAV) that contains electronics printed with and embedded in the wing. Aurora Flight Sciences, makers of the Orion Unmanned Aircraft System (UAS), has developed and tested a 5 foot wingspan UAV fabricated using a Stratasys FDM printed wing. Multi-material additive manufacturing techniques allow the ability to create complete wing structures with the required directional strength and stability.

The University of Virginia and The MITRE Corporation have also designed and built a prototype, 3D printed UAV for use as an aerial sensor platform. In addition, additive manufacturing techniques are increasingly used to create wind tunnel models for primary testing as these methods are significantly less expensive and time consuming as compared to traditional machining methods.

GE Aviation has invested $27 million in its Additive Lean Lab facilities specifically for the development of 3D printed aircraft engines and components. One such component is a 3D printed fuel nozzle which GE hopes to incorporate into its aircraft engine production line by 2016. The single piece 3D printed nozzle significantly reduces the number of manufacturing steps and thereby production time and cost.

Engineers at GE Global Research built this miniature model of a GEnx jet engine using an advanced 3-D printing technique called direct metal laser melting, a process similar to Electron Beam Melting. (GE Reports, 6/2013)

3-D Printing in Space

NASA has partnered with the California company Made in Space to design an additive manufacturing production system for use on the International Space Station (ISS). The printer is designed to operate in a Zero-G environment using an EDM process and will be used to produce ISS components and tools.

Extensive low gravity parabolic flight testing has been performed to validate that the components printed in microgravity are equivalent to those printed on Earth, and to provide ongoing data used in the development of the printer. The team has successfully produced and used a wrench created by the 3D printer on a microgravity test flight. The company estimates that more than 30 percent of the ISS spare parts can be manufactured by this printer.

By reducing our dependency on Earth based supply chains, we increase our reach and permanent presence in space. As NASA Administrator Charles Bolden said during a recent tour of Ames Research Center in Northern California; "As NASA ventures further into space, whether redirecting an asteroid or sending humans to Mars, we'll need transformative technology to reduce cargo weight and volume," "In the future, perhaps astronauts will be able to print the tools or components they need while in space." The Made in Space printer is expected to be put into service on the ISS in August 2014.

NASA low gravity parabolic flight testing of Made in Space 3-D printer.
(NASA Johnson Space Center photo, 5/06)

One of the most interesting and ambitious ideas is utilizing 3D printers to construct lunar habitats. The European Space Agency (ESA) in consortium with the architectural firm Foster & Partners, Italian space engineering firm Alta SpA and the university Scuola Superiore Sant'Anna at Pisa, are investigating the possibility of constructing lunar habitats using additive manufacturing technologies to create protective domes from a mixture of lunar soil (known as regolith) and a chemical binder. The concrete type domes would be constructed around an inflatable tubular structure using a robot printer to lay down successive 5-10 mm layers of the regolith composite. Foster and Alta have already created similar structures (up to 20' x 20') on Earth using simulated moon dust.

Future Prospects for AM Technologies

While AM technologies are currently largely confined to prototype activities, advances in material properties, printer output, repeatability and size will increasingly enable volume manufacturing of finished products. A recent Wohler Associates industry report estimates that small-volume manufacturing, led by aerospace and automotive components, will increase from just $1 million in 2012 to more than 1$ billion by 2025. According to Wohlers Report 2013, revenues from all additive manufacturing products and services worldwide were $2.204 billion in 2012 with nearly 30% of those revenues tied to final production parts, and that number is expected to reach $3.7 billion by 2015. A Landmark study from Lux Research estimates that these three industries, automotive, aerospace and medical devices, will account for 84% of an estimated $8.4 billion market by 2025.

With advancements in material strength and printer throughput speed and resolution, AM technologies will find increasing application in the production of aerospace components. The potential for significant cost savings in manufacturing and tooling and reduction in time to market alone will continue to fuel the growth of AM technologies in aerospace. But the potential to produce increasingly complex, lighter and stronger multi-material components and assemblies using AM technologies is of particular interest to the aerospace industry. Advancements in additive manufacturing technologies that allow for greater integration of materials, electronics and aircraft subsystems, and the printing of large assemblies will truly revolutionize the aerospace industry.

About the Analyst

Alan Kendrick, J.D.

Alan Kendrick specializes in mechanical and aerospace systems and provides clients with technical and intellectual property support. He worked for the systems engineering division of NASA's Ames Research Center in Northern California for twelve years as a mechanical/aerospace design engineer. While at NASA, Alan worked on a variety of design projects including wind tunnel design, modification and modernization, design and structural analysis of aircraft modification projects, biomedical and human habitat research equipment, electro-mechanical hardware modernization, design, selection and integration with mechanical systems, space flight hardware, and large facility piping and piping structure analysis and design. He has worked at Boeing/Hughes Satellite Systems as a mechanical/aerospace satellite systems design engineer where he designed component equipment for the Anik F2 communications satellite. Recently, Alan has worked in the solar industry in the design of large scale photovoltaic systems (200kW+) for industrial commercial applications. He has experience in the installation and operation of various mechanical, electro-mechanical, aerospace, hydraulic and R&D facility designs, hardware, equipment and models.

Mr. Kendrick also holds a Juris Doctor degree from the University of San Francisco and has been a California licensed attorney since 1998. His practice focused on intellectual property matters including patent, trademark, copyright, trade secret and unfair competition.

Credentials
J.D. University of San Francisco
B.S. *Magna Cum Laude*, Aerospace Engineering, San Jose State University
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Bar Member, U.S. District Court - Southern District of California
Bar Member, Supreme Court of California

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