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Technical Paper Presented at the PowderMet 2021 & AMPM 2021 Conference
Organized by the Metal Powders Industries Federation (MPIF)
Orlando, Florida, USA; June 20-23, 2021

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ABSTRACT

The Aerospace and Space Exploration (Aerospace) industries have been early adopters of Metal Additive Manufacturing (AM) or Metal 3D Printing technology, for both commercial and military applications.

Metal Additive Manufacturing technology has some great attributes that make it a great fit for aerospace applications, such as: designing of complex components; allowing incorporation of multiple components into a single additive manufacturing part; shortening product development cycles via rapid prototyping with scalability to low-volume production; extending product life by providing a route to produce obsolete spare parts; and creating a robust supply chain with ability to produce new components and spare parts on-demand.

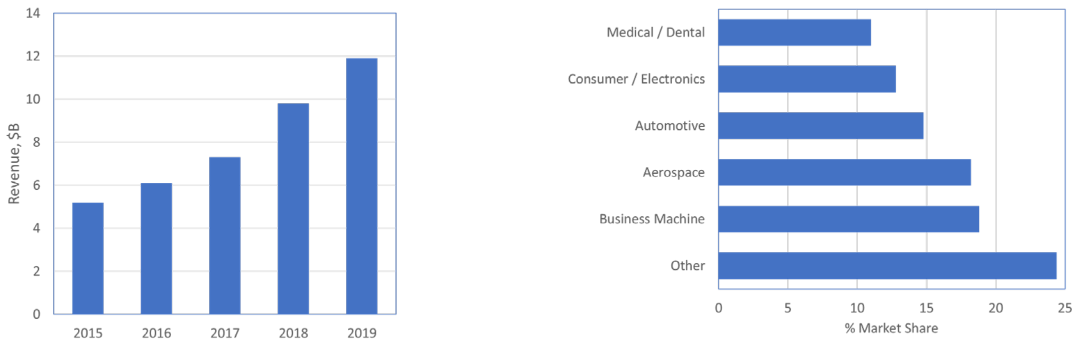
The aerospace industry is utilizing or evaluating a range of AM-grade metal powders and additive manufacturing technologies. Additive manufacturing materials of interest include: stainless steel, nickel alloys, cobalt alloys, titanium alloys, superalloys, and aluminum alloys. Additive manufacturing technologies adopted or being explored by these industries include: laser powder bed fusion, direct energy deposition, binder jetting, fused deposition, and friction-stir technology.

With recent advances in Metal Additive Manufacturing technology, improved build quality, robust supply of metal powders, material reuse, ease of scalability, larger build size, and creation & adoption of industry standards are anticipated to result in faster and wider adoption of technology by the aerospace industry.

INTRODUCTION

Additive manufacturing, also referred to as “3D Printing”, has broken the mold both figuratively and literally. The concept of building a part, layer by layer, allows components to be manufactured that were not previously possible by traditional manufacturing techniques.

As seen in Figure 1(a), the worldwide revenue from all additive manufacturing products and services reached $11.9B in 2019 from a level of $9.8B in 2018 [1]. Figure 1(b) shows that the aerospace industry commanded 18.2 % market share in 2017 within the additive manufacturing market space [2].



(a) Worldwide AM-Related Revenue [1] (b) Market Share by Application [2]

Figure 1: Worldwide Additive Manufacturing Related Revenue and Market Share by Application

The aerospace industry has been an early adopter of additive manufacturing. In the mid-1990's, Boeing and Bell Helicopter had begun using polymer additive manufacturing parts for non-structural applications. Since, Boeing has designed and deployed hundreds of unique additive manufacturing parts for 16 different commercial and military aircrafts. Airbus has manufactured thousands of plastic additive manufacturing parts and is now certifying metal additive manufacturing parts for flights [1].

GE Aviation was a key leader in incorporating multiple components into a single additive manufacturing part. In October 2018, GE had additively-manufactured over 30,000 fuel nozzle tips for the LEAP engine since production started at the Auburn Alabama plant in 2015 [3,4]. Subsequently, GE Aviation incorporated around 300 3D printed parts in the GE9X jet engine [5]. Further, GE Avio Aero in Italy has used titanium aluminide to 3D print low-pressure turbine blades on an Electron Bream Melting system for the GE9X jet engine [6].

Honeywell Aerospace, Lockheed Martin, Norhtrop Grumman are also major users of additive manufacturing. Similarly, NASA and ESA (European Space Agency), and SpaceX have been early adopters of metal additive manufacturing to produce igniters, injectors, and combustion chambers for rocket engines [1].

ROLE OF ADDITIVE MANFUACTURING WITHIN LIFE CYCLE OF A COMPONENT

Additive manufacturing has finally found its rightful place as a viable metal manufacturing technology within the aerospace industry. Early adoption of Metal Additive Manufacturing has been for small-volume components, legacy system spare parts, complex shapes, part design simplification, and components specifically designed for additive manufacturing.

The schematic in Figure 2 demonstrates additive manufacturing's potential to becoming an integral part of a product's life cycle from concept to grave. It may not always be the manufacturing technology of choice for the entire life cycle, but it could play a very critical role in reducing the time to market by accelerating product development, component design, creation of prototypes for qualification, and the initial small-volume introduction to the market. For several applications, additive manufacturing might not be viable for large volume production, requiring other metal processing technologies to sustain the product through the "maturity" stage of the life cycle.

A robust product design & development protocol would incorporate this need for an alternate large volume production technology early on in the process. As the product life cycle moves into "decline", potential exists to revert back to additive manufacturing for the remainder of the product life cycle, including the manufacture of spare parts for products in service. The aerospace industry has been actively embracing this cradle to grave concept and have begun to incorporate additive manufacturing into every possible stage of their product design cycle.

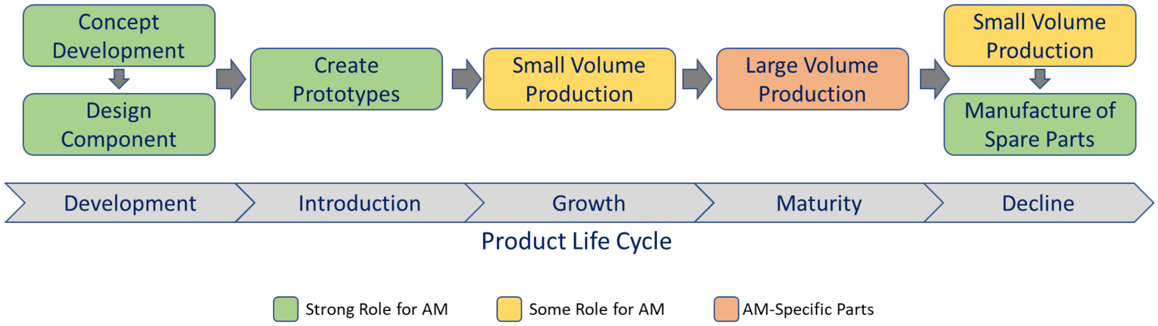


Figure 2: Potential Role for Metal Additive Manufacturing within a Product Life Cycle

METAL ADDITIVE MANUFACTURING FOR AEROSPACE APPLICATIONS

The metal additive manufacturing technologies historically adopted for aerospace and space exploration applications, include: Directed Energy Deposition (DED), Powder Bed Fusion (PBF), and Solid-State Additive Manufacturing. Table 1 summarizes the various metal additive manufacturing technologies being currently used or being evaluated by the aerospace industry [7].

Table 1: Metal Additive Manufacturing Processes Used for Aerospace Applications [7]

Category	Process	Feedstock
Powder Bed Fusion	Laser Powder Bed Fusion	Powder
	Electron Beam Melting	Powder
Directed Energy Deposition	Blown Powder Deposition	Powder
	Arc-Based Deposition	Wire
	Laser Wire Deposition	Wire
	Electron Beam Deposition	Wire
Solid State	Ultrasonic Additive	Foil
	Friction Stir Additive	Rod or Powder
	Cold Spray Technology	Powder

MATERIALS FOR AEROSPACE ADDITIVE MANUFACTURING APPLICATIONS

For aerospace applications, nickel alloys (Inconel 718 and Inconel 625) and titanium alloys (Ti6Al4V) have been historically used due to their high temperature strength and oxidation resistance. Titanium has the added advantage – its low-density, resulting in net weight savings, a very important attribute for aerospace applications.

Other metals being used or considered for aerospace and space exploration applications include: aluminum alloys, cobalt alloys, copper alloys, stainless steels, and tool steels.

A vast range of AM-grade powders, including, nickel and titanium alloy powders, are commonly made using inert-gas atomization, resulting in fairly spherical powders. For certain applications, plasma gas atomization can be used for producing highly spherical titanium powders.

Different additive processes use specifically tailored powder size distributions. For example: binder jetting uses powder that is typically less than 25 mm, powder bed fusion uses a size between 15 and 63 mm, and electron beam process uses slightly coarser powder between 45 and 105 mm.

ADDITIVE MANUFACTURING APPLICATIONS FOR AEROSPACE

Table 2 summarizes the various categories of applications for metal additive manufacturing both for the aerospace (commercial and military aircraft) and space exploration segments of the industry.

Table 2: Categories of Metal Additive Manufacturing Applications for Aerospace

Industry Segment	Current Application	Potential Application
Commercial & military aircrafts	Concept modeling & development Print prototypes & first articles Print small and mid-volume complex parts Print spare or replacement parts Repair of expensive parts	Design for additive manufacturing (DfAM) Print large-volume & complex parts Print aircraft wings & other large parts Print electronics directly onto parts Repair parts on the battlefield
Space exploration	Print specialized parts for space exploration Design & print lightweight components Design & print higher performance parts Rapid concept to deployment cycle	Print on-demand parts or spares in space Print large structures directly in space Print using materials available at destination Effective recycling and reuse of worn parts

Over the last several years, the number of current applications for both aerospace and space exploration have grown tremendously. With advances in technology, the potential for new future applications within this industry also has grown considerably.

GE Aviation's Fuel Nozzle Tip for LEAP Engine

Over a decade ago, when GE Aviation's design engineers designed an optimal highly-efficient fuel nozzle tip for the LEAP engine, the team realized that the new nozzle could not be produced using traditional manufacturing technologies [3,4]. The team re-engineered off the shelf 3D printers to manufacture the part that met the specification. In 2015, GE Aviation started 3D printing the newly designed fuel nozzle tip at their plant in Auburn, Alabama. By late 2018, GE had 3D printed over 30,000 fuel nozzle tips for the LEAP engine [3].

- 95 % Inventory Reduction
- 30 % Cost Efficiency Improvement
- 25 % Weight Reduction
- 20 Components into ONE AM Part
- 5x More Durable

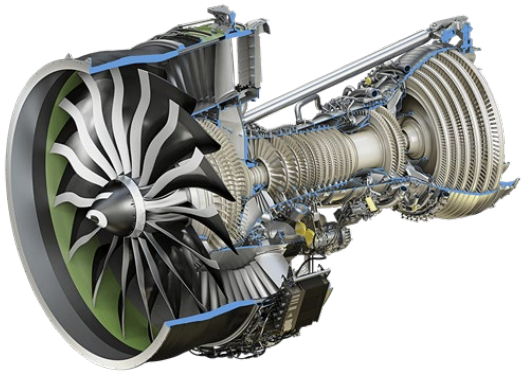
(a) Fuel Nozzle for LEAP Engine (b) By the Numbers

Figure 4: GE Aviation's Fuel Nozzle via Additive Manufacturing [3,4]

The old version of the fuel nozzle consisted of 20 separate pieces welded together. The new AM nozzle tip, shown in Figure 4(a), housed 14 different intricate fluid passages into one single part. As seen in Figure 4(b), when compared to the old design, the new part weighed 25% less than the original, was 5 times more durable, was 30% more cost efficient, and resulted in a 95 % reduction in inventory [4]. This small part, that can be held in the palm of a hand, transformed the metal additive manufacturing industry.

GE Aviation’s GE9X Engine

GE Aviation has continued to expand upon their use of 3D printing with a focus on engine components, creating parts that significantly improve the efficiency of GE engines. GE Aviation started development of the GE9X in 2013; conducted the first on-ground run in 2016; the first test flight was in 2018; and the first Boeing 777X flight in January 2020 [5,8]. The GE9X engine, as shown in Figure 5(a), is regarded as the most fuel-efficient engine in the world.



- 28 Fuel Nozzles & Combustor Mixers
- 16 Particle Separators
- 1 T25 Sensor
- 1 Heat Exchanger
- 228 Stage 5&6 Low-Pressure Turbine Blades
- 10 % Lower Specific Fuel Consumption
- 27:1 Compressor Pressure Ratio

(a) GE9X Engine (b) By the Numbers

Figure 5: Additive Components on the GE Aviation’s GE9X Engine [5,8]

The GE9X incorporates around 300 3D printed parts, including: fuel nozzles, particle separators, temperature sensors, fuel mixers, heat exchangers, and low-pressure turbine blades.

The GE9X delivers a thrust of 598 kN (134,300 lbs. force) with just 16 fan blades, compared to its predecessor GE90 which delivered 569 kN (127,900 lbs. force) of thrust with 22 fan blades. This resulted in a lower build cost, lower ongoing maintenance costs, lower overall weight for the new engine, higher efficiency, and a savings of over 2,650,000 liters (700,000 gallons) of fuel each year [5,8].

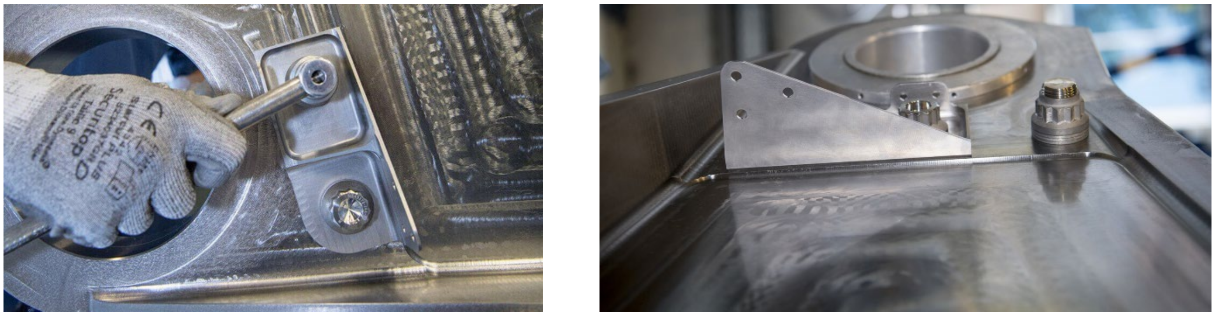
The 3D printed TiAl low pressure turbine blades for the GE9X engine, as show in Figure 6, were designed and manufactured by GE Avio Aero. An ideal alloy for hot environment applications, TiAl is difficult to process via traditional routes and the GE team adopted 3D technology to print this part.

Figure 6: Low Pressure Turbine Blades for GE9X [6]

GE Additive also incorporated the first 3D printed heat exchanger into the GE9X engine. Built using an F357 aluminum alloy, the 163 traditionally manufactured parts were combined into one 3D printed part. The 3D printed heat exchanger was 40 % lighter and resulted in a 25 % reduction in cost compared to the traditional design [9].

Airbus Titanium Bracket

Airbus's first 3D printed titanium bracket took flight on its commercial jetliner in June 2014 [10]. The bracket was installed on the aircraft pylon, the junction section between the wings and the aircraft [11].



(a) Bracket Being Installed at Pylon

(b) Installed Bracket

Figure 7: Airbus's Printed Titanium Bracket [10,11]

Figure 7(a) shows images of the titanium bracket being installed. The deployment of this bracket demonstrated the scope of additive manufacturing – it was possible to retrofit existing aircraft models with 3D printed parts. A key advantage of the 3D printed bracket was that it replaced a heavier part, resulting in significant weight savings. A reduction of even one kilogram can eliminate almost 25 tons of carbon dioxide emissions over the lifespan of an aircraft.

GA-ASI's NACA Inlet

General Atomics Aeronautical Systems, Inc (GA-ASI) began collaborating with GE Additives AddWorks in April 2019 on the design and deployment of a 3D printed NACA inlet part for GA-ASI's SkyGuardian Remotely Piloted Aircraft (RPA) [12,13]. The part, shown in Figure 8, was developed using the "Design for Additive Manufacturing" (DfAM) concept and deployed on its first test flight in February 2020.

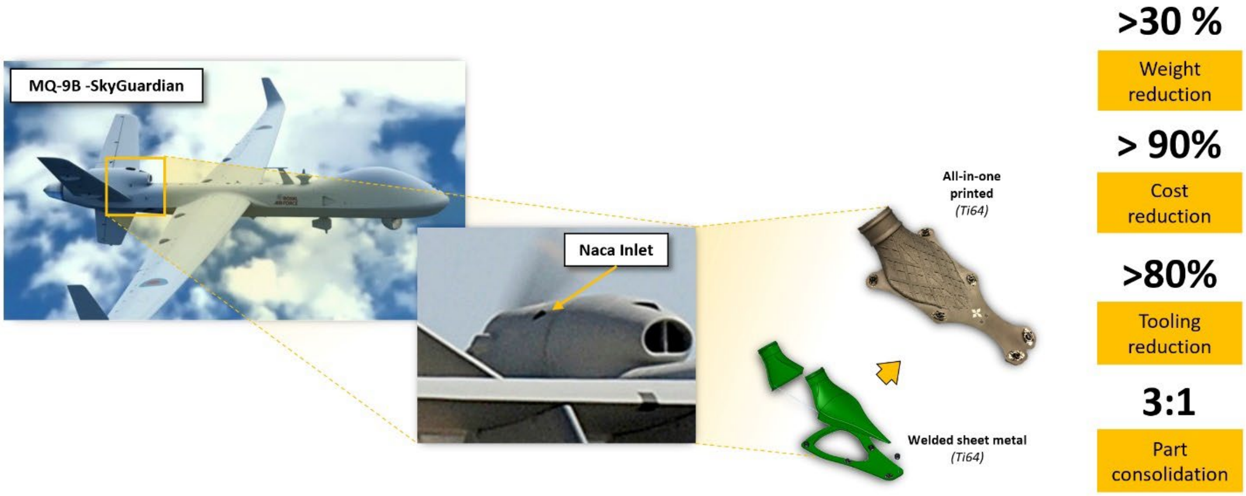


Figure 8: 3D Printed Ti64 NACA Inlet on GA-ASI's SkyGuardian Remotely Piloted Aircraft [13]

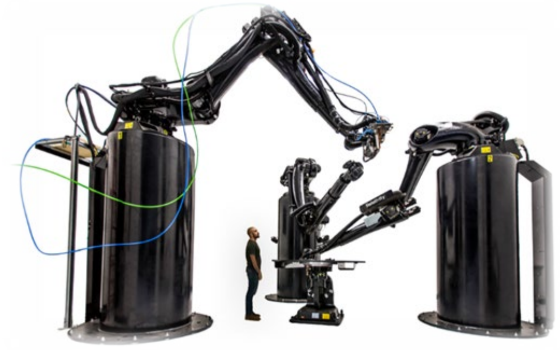
The part was traditionally formed using three titanium sheet metal components that were welded together. These three parts were combined into a single 3D printed part, resulting in over 30 % weight reduction, 90 %

cost reduction, and 80 % tooling reduction. With this success, GA-ASI is launching an aggressive effort to redesign multiple families of traditionally manufactured parts for 3D printing.

Relativity Space's 3D Printed Launch Vehicle & Factory

Rocket design has historically been a time consuming and expensive process. With additive manufacturing, the technology exists today to significantly accelerate design, development, and deployment of space launch vehicles.

Relativity Space have developed the first entirely 3D printed launch vehicle – the Terran 1 [14,15]. Relativity have also established a new factory which allows them to print the Terran 1 launch vehicle from raw materials to launch in 60 days. The machine shown in Figure 9(a) is Relativity Space's custom-built 3D printer – Stargate, with 5.5 m (18 ft.) tall robotic arms. Relativity recently used Stargate to print a 3.4 m (11 ft.) aluminum fuel tank for their rocket launcher. As seen in Figure 9(b), Relativity's mission is to build high quality launch vehicles, with fewer 3D printed parts and a quick turnaround time.



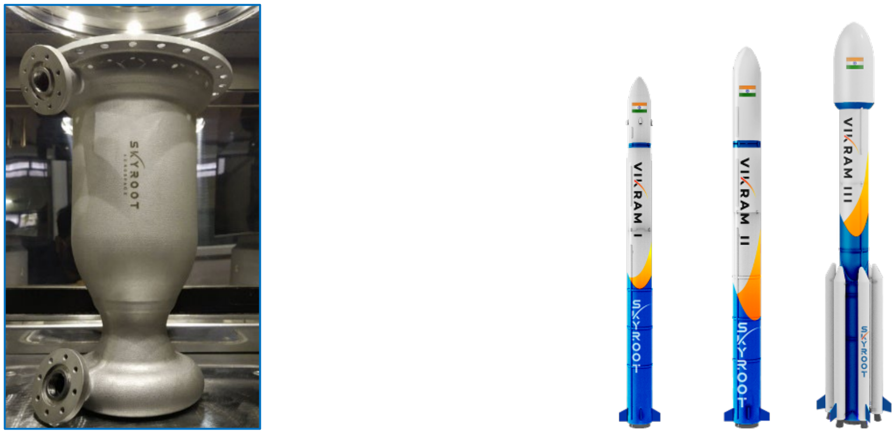
- <1,000 3D printed parts vs. 100,000+ typical
- 2 mth. build time vs. 24 mth. typical
- 6 mth. iteration time vs. 48 mth. typical
- 60 days to build launcher vs. 730+ typical
- No fixed tooling vs. Extensive tooling
- Simple supply chain vs. complex supply chain
- Customized high strength alloys

(a) Stargate 3D Printer (b) 3D Print at Relativity vs. Traditional Manuf.

Figure 9: Relativity Space's 3D Printer for 3D Printing Space Launch Vehicle [14,15]

Skyroot Aerospace's 3D Printed Cryogenic Engine

Skyroot Aerospace, a private aerospace company located in Hyderabad, India, 3D printed a cryogenic engine - called Dhawan-1, shown in Figure 10(a).



(a) Cryogenic Engine Dhawan-1 (b) Launch Vehicles Vikram I, II & III

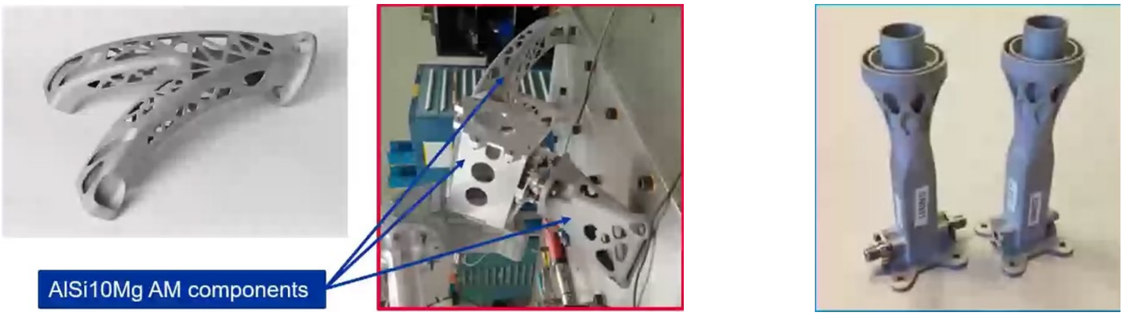
Figure 10: Skyroot Aerospace's 3D Printed Cryogenic Engine for Satellite Launch Vehicles [16]

Skyroot's cryogenic engine will be installed on their satellite launch vehicles - Vikram I, II & III, shown in Figure 10(b). This engine is meant to fuel the upper stage of the rocket and runs on Liquid Natural Gas (LNG) and Liquid Oxygen (LoX) propellants. The fully 3D printed injector in this engine is capable of multiple restarts which will enable the rocket to insert multiple satellites into multiple orbits in a single mission, an area that has seen rapid growth in recent years [16].

Boeing's 3D Printed Parts for Satellite Applications

For the Boeing 702MP satellite system, Boeing incorporated a 3D printed "deployable ion engine mount" as an integrated assembly, as shown in Figure 11(a). These 3D printed engine mounts are now standard on every Boeing 702MP system with xenon ion propulsion. The first such mount was launched in September 2018. The 3D printed AlSi10Mg mount assembly resulted in a 12.7 kg (28 lbs.) weight reduction over the old composite assembly [17].

Similarly, Boeing converted its old multi-piece Command Horn Satellite Antenna into a single 3D printed part, shown in Figure 11(b). The new design was a single-monolithic component and was made from an aluminum alloy powder using selective laser sintering technology. Radio frequency critical features were directly printed into the new part. The Command Horn Satellite Antenna is considered a mission critical application. The new 3D printed part delivered 30 % reduction in weight, 57 % reduction in number of parts, and 90 % reduction in cost. Further it was possible to produce the part in a week compared to around 10 weeks for the old design [17].



(a) Deployable Ion Engine Mounts (b) Command Horn Satellite Antenna

Figure 11: 3D Printing by Boeing of Parts for Satellite Applications [17]

Additive Manufacturing: A Key Element of In-Space Manufacturing (ISM)

NASA's In-Space Manufacturing (ISM) initiative aims to develop the technologies and processes which will enable on-demand manufacturing capabilities during long-duration space missions. The core idea is "Make It, Don't Take It" [18,19]. The initiative encompasses the development of a robust earth-based platform for additive manufacturing technologies and processes; utilizing the International Space Station (ISS) and nearby asteroids as proving ground for the technology; with an ultimate aim to deploy 3D printing in an earth-independent environment such the surface of Mars, where printers would use locally available materials to print structures and components.

Made-In-Space partnered with NASA to create and deploy the first modular 3D printer based on the Fused Deposition Modeling (FDM) technology on the International Space Station [20]. Since 2016, the device has printed over 200 tools, assets and parts for the astronauts while in orbit. In addition, various trials were conducted in microgravity on the ISS and evaluated after the 3D printed parts were returned to earth. NASA concluded that there was no significant impact of microgravity on the FDM process.

COMMON QUALITY CONCERNS FOR 3D PRINTED PARTS

Most 3D printed parts require some degree of post-processing, such as: part separation and support removal; heat, pressure or solution treatment; surface finishing; and quality assurance. Each of these secondary processing steps, add time and contributes to the cost of the part.

Porosity is a problem that plagues most metal additive manufacturing processes, especially powder bed fusion, due the differential cooling experienced within the melt pool [21, 22]. A lack of uniformity in the laser power can result in splattering and uneven cooling of the melt pool. Bubbles get trapped as a result of this temperature disparity and leads to a porous part. Porosity also results in lower than desired part density which can impact performance and the part may not meet established specification.

Another key concern is the residual stress a part goes through while cooling. Residual stress can lead to a number of part defects such as warping and cracking. This can be especially apparent in metal 3D printed parts. During cooling a metal 3D printed part can contract unevenly, the edges of parts cooling fastest and resulting in a tendency for the part to curl or deform if the cooling is done too rapidly. In extreme cases this can result in structural failure and lead to cracks within the part. Frequently, the part needs a secondary finishing operation to meet acceptable dimensional standards.

Thus, it is important to ensure that a high degree of quality control is employed throughout the entire process, starting from the raw material. The quality of powder has a critical impact on the part build quality. Key powder properties include particle size, particle shape, size distribution, flowability, and chemistry. In-situ monitoring and closed-loop feedback during the printing step is becoming more critical to ensuring high quality of the 3D printed part.

ADDITIVE MANUFACTURING INDUSTRY STANDARDS

Industry standards are being rapidly developed to broaden the adoption of additive manufacturing technology. In 2013 ASTM and ISO initiated a joint effort to develop globally accepted standards for additive manufacturing. About 25 standards have been published so far, and another 40+ standards are under development. The following are the key categories for which standards have been or are being developed:

- General AM standards
- Standards for feedstock materials
- AM process and equipment standards
- Standards for finished AM parts
- Application-specific standards

Some key standards for the industry include [23,24]:

- ISO/ASTM52900-15: standard for AM terminology
- ASTM F3122-14: evaluation of mechanical properties of metal AM parts
- ASTM F3049-14: characterization of metal powders used for AM processes

However, only a few standards have been established for the application of metal additive manufacturing within the aerospace industry. Standards relevant to aerospace products include:

- AMS 7001 “Ni Base 625 Super Alloy Powder for Use in Laser Powder Bed Additive Manufacturing Machines”,
- AMS 7002 “Process Requirements for Production of Metal Powder Feedstock for use in Laser Powder Bed Additive Manufacturing of Aerospace Parts”,
- ASTM F2924 “Additively manufactured Ti-6Al-4V components using powder bed fusion such as electron beam and laser melting”.

ECONOMICS OF ADDITIVE MANUFACTURING

Understanding the cost of 3D printing a part is critical to establishing a viable business case for adopting this technology. The best knowledge about the economics of metal additive manufacturing resides with the companies that have successfully adopted the technology at a production scale. However, most companies consider this operational knowledge as proprietary and protect it accordingly. Digital Alloys attempted to gather the data needed to conduct an economics analysis for 3D printing titanium alloy parts based on their own experience; collaboration with customers and industry experts; research from service bureaus; and data gathered from printer vendors and material suppliers [25]. Figure 12 shows the cost of 3D printing titanium parts on dollar per kilogram basis as calculated by the Digital Alloys model.

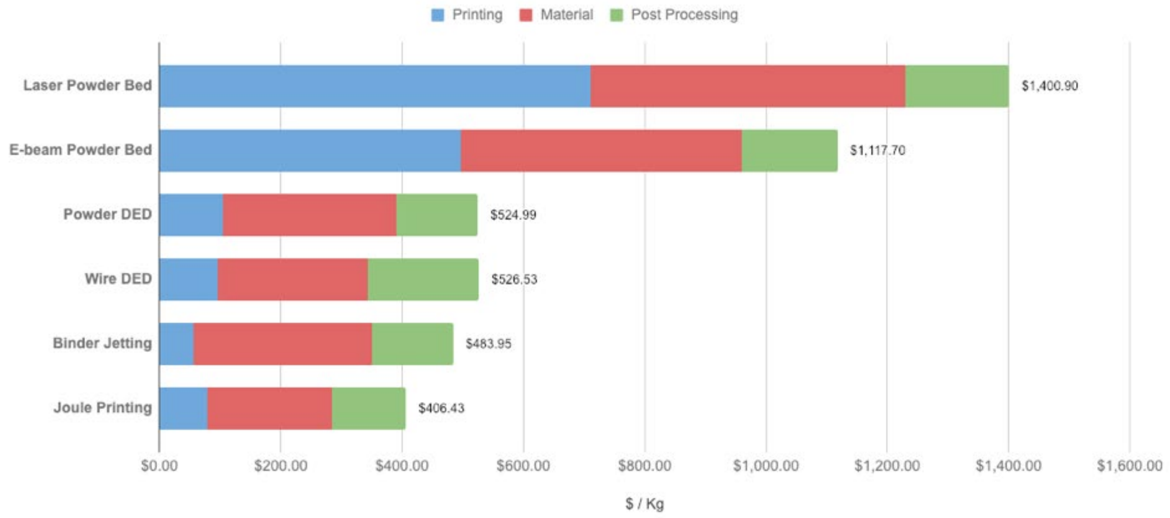


Figure 12: Cost of 3D Printing Titanium Parts, $ per Kilogram [25]

After a part has been designed, there are three main cost drivers:

1) Printing Costs
    a) Per Unit Printing Costs = Operating Costs / Printer Productivity
    b) Annual Operating Cost = Annual Cost of Printer + Maintenance + Labor
    c) Annual Printer Productivity = Print Speed x Annual Printer Utilization

2) Material Costs
    a) Cost of Printed Material
    b) Cost of Waste Material
    c) Cost of Consumables

3) Post-Processing Costs
    a) Part Separation & Support Removal

b) Heat, Pressure or Solution Treatment
c) Surface Finishing
d) Quality Assurance

It should be noted that the above analysis is for demonstration purposes only and was based on a number of assumptions which would be different for each unique application and for each unique company.

CONCLUSIONS

Over the recent years, metal additive manufacturing technology has been proven to be a viable manufacturing option for aerospace applications. As the industry establishes more standards and the technology advances further, Designing for Additive Manufacturing (DfAM) will become the norm within the aerospace and space exploration industries.

In the aerospace industry, the product life cycle is typically measured in decades. Additive manufacturing technology has potential to impact this industry in several areas: (a) shorten the development and introduction stages, significantly reducing the time to go from concept to market; (b) allow faster market growth by expediting delivery of small-volume production parts; and (c) transition back to additive technology for small volume production and manufacture of spare parts towards the end of the life cycle.

For space exploration applications, the product life cycle tends to skip the large-volume production, thus additive manufacturing technology has the potential to be the manufacturing route of choice for the entire life cycle of the part.

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