

Additive Manufacturing of Rocket Propulsion System: A Review

Nishesh Bista^{1*}, Surya Abhyas Gampa², Vishesh Dharaiya³

Abstract

In recent years plenty of research is going on to produce effective manufacturing techniques which can produce complex unique designs with reduced cost and lead time for aerospace applications. In this aspect, Additive manufacturing is getting a wide range of popularity in the aerospace manufacturing domain due to its vast applications and advantages. In terms of geometric flexibility and processing time, additive manufacturing outperforms conventional manufacturing processes. Additive manufacturing has found its place in aerospace, defence, biomedical and automotive industries. However, new application areas like space technology are opening up. This method reduces the demand for industrial infrastructure and produces decentralized products. In this study, we have reviewed the manufacturing of rocket propulsion systems through additive manufacturing techniques Wire-arc additive manufacturing and powder bed fusion are the key areas of focus for us (WAAM). These techniques help produce fewer weight components with part consolidation, reducing tooling and assembly requirements. Combustion chambers and nozzles produced using this method meet the performance requirements, they also demonstrated significant cost and schedule savings for hardware delivery. The components in rocket engines operate in extreme and harsh environments. Thus, special materials and complex geometries are required to achieve high performance. Additive manufacturing techniques can enable this, which in turn enables designer freedom from geometric constraints commonly found using traditional manufacturing techniques. Many other components such as injector systems in rocket engines can be made using additive manufacturing within less time and into a single injector head without traditional welding and joining many components A review discusses manufacturing processes, materials used and properties. It also discusses various challenges faced by additive manufacturing.

Keywords: Additive manufacturing, Powder-bed-fusion, Wire-Arc Additive Manufacturing (WAAM), rocket engine, stereolithography.

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INTRODUCTION

In the manufacturing process known as additive manufacturing (AM), materials are deposited one at a time to produce a three-dimensional object or part. Additive Manufacturing significantly reduces the manufacturing cost and time over traditional manufacturing processes. The materials that are difficult to process by other methods can also be processed or manufactured easily by AM method. The other advantage of AM is that it can be used to manufacture lightweight components and it also reduces complexities.

On the opposite hand, materials which aren't excessively damaged by the tough conditions in space can even be printable easily using AM. The

system for the rocket engine is manufactured using additive manufacturing like Laser Bed Based Fusion (LBBF), Directed Energy Deposition (DED), solid-state, material extrusion, sheet lamination, etc. supported the supply of the materials for additive manufacturing, materials are classified as Ni-base, Al-base, Fe-base, Cu- base, Ti-base, MMC, PMC, Refractory, Bimetallic, etc. materials are used [1].

Different methods such as materials extrusion, selective laser sintering (SLS), stereolithography, or direct laser metal sintering (DLMS), are widely used to create the individual parts, and assembling them gives a complete product (Figure 1). The additive manufacturing method allowed us to embed electrical systems, sensors, antennas, and other parts into the product. This will reduce the complexity of the product and increase the space or room for other components [2].



Figure 1. Orbex's 3D-printed rocket engine [Image credit: Orbex].

POWDER BED FUSION

In the additive manufacturing process known as powder bed fusion (PBF), materials are melted and joined one layer at a time using an electron beam, heat, or laser (Figure 2). In the realm of manufacturing, the powder bed fusion has several benefits, such as:

- wasteful use of materials and low manufacturing costs.
- low-volume item manufacture and quick prototyping
- Full customization of parts on a batch-by-batch basis,
- Good resolution and smoothness when compared to other additive manufacturing processes
- Recyclable and reusable un-melted powder
- Improvement in production and development times

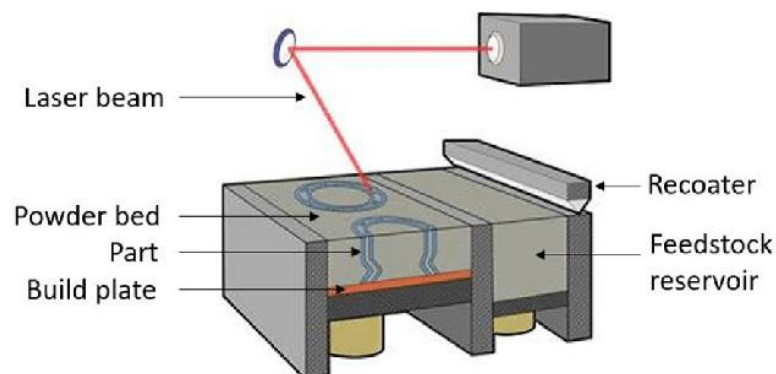


Figure 2. Schematic of powder bed fusion process. Credits: NASA.

WIRE ARC ADDITIVE MANUFACTURING

The manufacturing process known as "Wire Arc Additive Manufacturing" (WAAM) uses Direct Energy Deposition (DED). WAAM uses welding techniques such as gas metal arc welding, gas tungsten arc welding, plasma arc welding, etc. Wire arc additive manufacturing is a widely used additive manufacturing (Figure 3) method and has the following advantages over other manufacturing processes:

- It can be used to produce parts with larger dimensions.
- It is cost-effective as it has a higher deposition rate and the initial set-up cost is also less.
- The materials used in wire arc additive manufacturing are easily available.
- It produces less waste.
- Parts can be manufactured by a combination of wire arc additive manufacturing with other manufacturing processes.

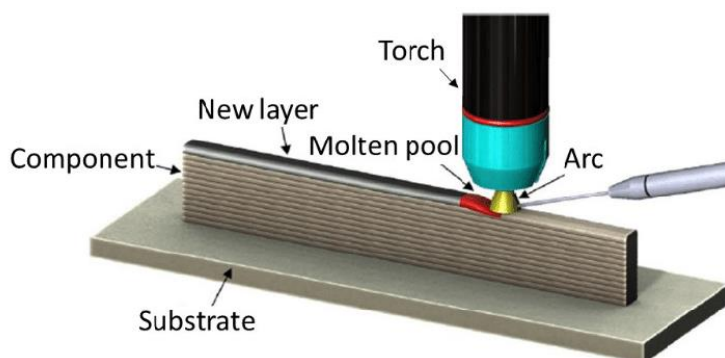


Figure 3. Schematic of wire arc additive manufacturing.

William M. et al. [1]. have studied on manufacturing of CubeSat propulsion systems using additive manufacturing. During the additive printing process, they employed a concept created by the University of Texas at Paso (UTEP) to embed the electronic parts and sensors right into the metal. Antennas for electrical systems can now be built into the CubeSat frame thanks to this idea. Because it can be neatly packaged, supporting structures can be easily printed, electronics can be incorporated, and it has enough propelling power for RCS, the authors chose the Micro Pulsed Plasma Thruster (PPT) as their propulsion system (Reaction Control System). The materials having dielectric strength (i.e., polycarbonate) of 80 V/mil are selected to print μ PPT, as μ PPTs require high voltage (~ 1.5) across electrodes to operate. The embedding of a PPT into a polycarbonate sample panel was tested as a "proof-of-concept." The sample panel was printed embedding μ PPT, wires, and sealed with further printing over μ PPT while the ramp feature routed wires from the thruster down to body connections. At Busek, a thruster fire test is performed under vacuum (10⁻⁵ torr) while being run at 800-1500 V, 2J, and 2Hz. The authors have concluded that μ PPT can be embedded in a printed structure and still operates with no degradation of materials near the thruster exit. It demonstrates that this propulsion system can be incorporated into a CubeSat body, and is cost and time effective [2].

Fabio Kerstens et al. described the design of additively manufactured rocket engines. Laser powder bed fusion and powder-based and wire-based directed energy deposition techniques are used for the fabrication of thrust chambers. L-PBF thrust chambers generally use either monolithic superalloy and refractory alloys or a highly conductive copper alloy. Refractory alloys are used in radiatively cooled applications, while superalloys are used in combination with cooling film. The DED process is more suitable for large thrust chambers, radiatively cooled nozzle extensions or bimetallic thrust chambers. The arc-wire DED, also known as wire arc additive manufacturing, is also used for a very high deposition rate (Figure 4). The end-to-end additive manufacturing process includes chamber design and selection of AM process, feedback quality verification, production of the chamber and witness coupons, and powder removal, followed by non-destructive and destructive evaluation. The authors

have concluded that additive manufacturing is taking a prominent position in the fabrication of thrust chambers of liquid rocket engines. However, the study has the limitations that the AM production process is influenced by the commercial availability, cost, and quality of materials. Additionally, there are size limitations for L-PBF machines [3].



Figure 4. 3D-printed injector head for Ariane-6 launcher [Image credit: EOS].

Teddy Zhang and Colin Miyamoto have presented the feasibility of 3D printing a low-thrust liquid-fuelled rocket engine. 3D printing is to be utilized for the entire engine. The parts are produced using direct metal laser sintering, selective laser sintering, and electron beam melting. The author suggested that this method is cost, time, and design effective and the engine designs can be scaled up or down to fit various roles. Cobalt, chromium, and molybdenum are selected materials for printing. The authors have concluded that the injector elements chosen are a blend of, unlike doublet and triplet, and the inlet plate features 8 sets of elements. Oxidizer and fuel manifolds are designed in such a way to decrease the turbulent flow and regenerative cooling is also provided utilizing RP-1. However, there is a limitation that regenerative cooling is only utilized to cool the throat, and nozzle and film cooling is sufficient for the chamber, but the rocket is overdesigned since it is “proof of concept” [4].

Paul R Gradl et al. have presented the paper on manufacturing and hot-fire testing of liquid rocket engine combustion engine devices such as thrust chamber injectors, combustion chambers, augmented spark igniters, and channel-cooled nozzles using an additive manufacturing process. Powder bed-based manufacturing processes such as selective laser melting (SLM), Electron beam melting (EBM), direct energy deposition (DED), manufacturing processes such as blown powder deposition, arc-based deposition(wire), laser wire deposition, electron beam deposition(wire) are applicable combustion device fabrication. The additive manufacturing process has advantages to these combustion devices such as reduction of cost, number of parts, and manufacturing schedule [5].

S. Soller et al. have provided a comprehensive approach to applying additive manufacturing to liquid rocket engine injectors. A powder bed and a method of selective laser melting are used to create the samples. Inconel 718, stainless steel 316 L, and CoCr are materials selected for engine injector development because of their high temperature and high-strength requirements. In the beginning, the injector design concept is established, followed by a single-element flow check, a subscale hot-fire test, full-scale design manufacturing, and a non-destructive inspection test. The authors have concluded that additively manufactured samples are less susceptible to hydrogen embrittlement and have a 20% higher level of tensile and ultimate strength than samples made from cast. The pressure drops of liquid rocket injector setups made from additive manufacturing due to wall roughness and their hydraulic characteristics can be accurately predicted by using CFD modelling [6].

Research on hybrids rocket fuels and components made via additive manufacturing has been compared by Cagri Oztan and Victoria Coverstone. They mentioned using additive manufacturing techniques to create fuel grains with intricately formed composite fuel grains or fuel grains with complex port geometries. Scaffolds were then printed and a second fuel material was added. Other than the fuel grains, additive manufacturing technology is also useful for the fabrication of hybrid rocket components by reducing the part count and hence the manufacturing cost and time. In this review, the types of material used, comparison of the performance, and the direction of future hybrid rocket technology using additive manufacturing are also mentioned. Additive manufacturing on the microstructure of the printed parts impedes the mechanical properties, standardization, and certifiability of the process. However, the process has limitations in that printed fuels made from the same materials are reported to have different combustion properties from each other in different works [7].

Morgan C. et al. have presented details of manufacturing a bipropellant rocket engine. The engine mass can be reduced by the use of additive manufacturing. The stainless steel 17-4PH was used to make the regeneratively cooling part. Using the additive manufacturing method, a chamber-nozzle was designed and built which is having cooling channels. Computational Fluid Dynamics (CFD) was used to help the design of the chamber (Figure 5) [nozzle. Regenerative cooling was preferred over film cooling in the rocket engine. The regenerative cooling can keep the walls and nozzles of engines within their operating temperatures [8].



Figure 5. 3D-printed bimetallic lightweight thrust chamber assembly before hot-fire testing at NASA's Marshall Space Flight Center in Huntsville, Alabama [Image credit: NASA].

Jan Fessl Jet al. presented the processes that are involved in the additive manufacturing of a regenerative and film-cooled liquid rocket engine. The Computational Fluid Dynamics (CFD) models provided the expected pressure and thermal regimes under regenerative and film cooling. The issues related to overhangs, surface roughness, and shrinkage; aspects related to post-print processing, and the need to minimize machining are discussed. Through the different progress made, they concluded that additive manufacturing is advantageous compared to conventional manufacturing methods. However, additive manufacturing methods have limitations in that some critical features such as scaling surfaces, threading, etc. still rely on traditional milling methods [9].

Carl P. Jones et al. described that rocket engine design and development could be advanced using additive manufacturing. Additively manufactured rocket engines could save cost, lead time, fabrication time, number of parts etc. Another benefit of it in design is more efficient packaging and larger design space. They utilize Powder bed fusion, a new technology for aerospace applications. They concluded that with additive manufacturing the geometry of the parts can be customized with varying thicknesses to maintain the strength and structural integrity of the materials. The use of additive manufacturing enhances the effectiveness and trustworthiness of the products during final installations [10].

When developing a bi-propellant, pressure-fed liquid rocket engine, Nihar Patel et al. demonstrated how additive manufacturing may be used effectively while also focusing on subsequent post-processing and machining work. An extra effort is taken to take into account factors such as early restrictions on engine design due to DMLS (Direct Metal Laser Sintering) printing requirements, as well as post-printing operations including wire EDM (Electric Discharge Machining), heat treatment, and ultrasonic cleaning. They created a Balerion development engine, which may serve as the starting point for acquiring priceless expertise in the area of additive design and production [11].

James Catina et al. presented that in the engineering industry, additive manufacturing is a powerful and effective tool of manufacturing. The engineer can use and improve new advancements with the help of this technology. They made use of SolidWorks for the computational designing and analysis of injectors and computational fluid dynamics (CFD) was done using CFD software. They have concluded that additive manufacturing is a reliable engineering tool that allows for flexibility of the design, lower costs for manufacturing, more accurate testing, and allows for real-world analysis of the engineering design [12].

Deepak M. et al. aimed to prove that by utilizing the benefits of additive manufacturing, rocket engines will provide a significant reduction in time and weight, as seen through the development and future testing of Ignus. They have concluded that the designing, printing, and successful testing of full development of liquid rocket engines proved that only the technology has the potential to redefine how engines are designed and manufactured in the future. Direct Metal Laser Sintering (DMLS) has become more refined and the layer resolution is precise so more homogenous products can be produced [13].

Due to additive Manufacturing, manufacturing the nozzles with the push of a button on Laser Powder Bed Fusion printers, replacement parts do not need to be stocked anymore. The process chain is shorter and more accessible than the conventional manufacturing route using a lathe or a milling machine. Findings by R. Bernhard et al. proved that additively manufactured nozzles are possible. Subsequently, the next generation of sophisticated Additive Manufacturing nozzles will include an additional annular opening for shale gas. In consequence, the powder stream size can be adjusted by the variation of the shape of gas flow [14].

Shapiro et al. mention that the future of Additive Manufacturing relies on the continued development of existing metallic and ceramic materials, as well as expansion into new alloys or

combinations of materials. The future lies in not simply applying additive manufacturing techniques to existing designs but to design with additive in mind, obtaining the maximum benefit from the technology. As designs are no longer limited by traditional manufacturing, software optimization strategies can be used to obtain better geometries simultaneously reducing mass [15].

Nasa Successful Testing of Additive Manufactured Rocket Engine Injectors at NASA GRC Rocket Combustion Lab for Aerojet AR-1 Rocket Engine, which benefited in reducing the cost to 70 percent less and fabrication time from 1 year to 4 months. Nasa also used Additive Manufacturing to manufacture the Rocket Engine Turbopump with 45% fewer parts [16].

Additive manufacturing has been playing an important role in the fabrication of thrust chambers by reducing manufacturing time and weight. It also offers the easy fabrication of complex internal parts of the combustion chambers and nozzles in liquid rocket engines. Gradl, Paul et al. stated that NASA is working on a project called Rapid Analysis and Manufacturing Propulsion Technology (RAMPT), which will enable the large-scale production of multi-alloy thrust chambers, reducing weight and manufacturing costs [17].

Gradl, Paul et al. investigated the technological advancements in the manufacturing of channel wall nozzles. The regeneratively cooled nozzle in liquid rocket engines must withstand high temperatures and pressures and is thin-walled to maintain temperature. Therefore, additive manufacturing techniques can easily produce these nozzles, reducing manufacturing costs and design complexities. Additive manufacturing techniques such as direct energy deposition, laser wire direct closeout etc. are used for the fabrication of channel walled nozzles. NASA has conducted fabrication and hot-fire tests on subscale channel wall regeneratively cooled nozzles, and large-scale fabrication and testing are ongoing based on the results [18].

Nasa is conducting wide research on the development of materials which can be used for the Additive manufacturing process. The regeneratively cooled combustion chamber and nozzles that will be employed in hostile situations use GRCo-42, a copper alloy with excellent conductivity and high strength. Combustion chambers and nozzles were manufactured of GRCo-42 using powder bed fusion and selective laser melting. Several Hot fire tests were run on the GRCo-42 nozzle manufactured using LPBF. The material gives good results at high temperatures. It has been concluded that GRCo-42 can reduce manufacturing time and is easily additively manufactured. GRCo-42 additive manufacturing continues to be developed by NASA, and commercial printing of GRCo-42 is also available [19].

Another unique technology called hybrid laser powder-bed fusion is also being used for manufacturing nozzles. Using micro-milling and laser powder bed fusion (L-PBF), this method combines the research difficulties of two production technologies. A new distortion predicting model for hybrid L-PBF was created using finite element techniques by S. Afazov et al. to produce nozzles with high precision using a hybrid laser powder-bed fusion process. The produced model contained 60% less distortion and good finishing. However, additional study is required to determine the cost-effectiveness of the micro-milling process as well as the cutting tool wear at high spindle speeds [20].

The use of AM in the manufacturing of complex satellite propulsion systems is widely increasing. Meisel et al. detailed the redesign of NASA's pencil thruster using additive manufacturing techniques that had previously been produced using a traditional subtractive manufacturing technique. For processing materials like Inconel 718 alloy to produce end-use components, they used the powder-bed fusion technology, known as laser powder bed fusion (LPBF), to develop nickel alloy nozzles and compared the performance of the nozzles to nozzles fabricated by conventional techniques. To study the flow through the nozzle, computational fluid dynamics (CFD) is used. They found that LPBF-based nozzles are limited in that the nozzle experiences a shock wave at the nozzle expansion cone,

and thrust losses are also high compared to conventionally manufactured nozzles, despite geometry, surface finish, etc. being similar [21].

Wermuth, Loreen et al. have processed and analyzed the noble metal alloy platinum rhodium powder, tantalum and tungsten powder, to prepare specimens using Powder bed laser processing. The use of additive manufacturing technologies such as additive layer manufacturing and selective laser melting has aided in the new material composition. They are primarily focused on applying additive manufacturing techniques to develop the next generation of spacecraft thrusters using noble materials and alloys [22].

San Gregorio et al. with the assistance of additive manufacturing i.e. Selective Laser melting (SLM) fabricated molybdenum grids and keeper electrodes in an ion thruster. The process of fabricating these parts using conventional manufacturing methods would be more expensive and time-consuming. These variable geometry parts can be easily manufactured using additive manufacturing. Although these parts are manufactured by the SLM process, the surface smoothing of the product must be done by post-processing [23].

CONCLUSION

Additive manufacturing is now widely used in the manufacturing of different parts of the propulsion system in rockets. Additive manufacturing is becoming more and more popular. The additive manufacturing method is more economical, can generate any 3D shape, has no need to prepare a mold, and can produce unique parts than the conventional manufacturing methods.

Finally, Additive Manufacturing (AM) also accelerates production as it eliminates the time-consuming toolmaking and fabrication process. Additive manufacturing is the most reliable, economical and time-saving approach to manufacturing in today's world. AM technologies are also being applied including tooling in spare parts and fixtures for conventional manufacturing machines.

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