Application and Comparison of Additive Manufacturing Technology in Rocket Manufacturing

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Abstract. Engineering's most difficult and complex challenges have always been those involving the production of rockets. Rocket manufacturing has benefited greatly in recent years from the three-dimensional(3D) printing technology's quick development. By layering materials, 3D printing technology can produce complicated parts and components with accuracy and efficiency. However, there are certain distinctions in how various 3D printing methods are applied while making rockets. This article will introduce several common 3D printing technologies and their applications in the manufacturing of key rocket components and discuss their advantages in rocket manufacturing and their comparison with traditional manufacturing. Despite certain difficulties, there are still many potential applications for 3D printing technology in the manufacture of rockets because to ongoing technological progress and advancement. By overcoming technical and production challenges, 3D printing technology will support innovation and advancement in the rocket manufacturing industry, delivering more effective, dependable, and affordable solutions for upcoming space exploration.

Keywords: Metal additive manufacturing; Selective laser melting; Directed energy deposition; Rocket components; Traditional manufacturing.

1. Introduction

Due to its potential to change the production of essential rocket components, additive manufacturing technology, also known as 3D printing, has attracted a lot of attention in the rocket manufacturing industry. It will concentrate on two 3D printing techniques in this article, Selective Laser Melting (SLM) and Directed Energy Deposition (DED), and how they are used to produce essential rocket parts. It will also contrast these technologies with conventional manufacturing techniques and analyze the benefits of each for the production of rockets. It will also go through the potential use of 3D printing technology in the manufacture of rockets as well as any potential difficulties.

SLM, often referred to as laser powder bed fusion, uses a strong laser to layer by layer melt and fuse metal powders, enabling the construction of intricate 3D structures. SLM is used in the manufacture of engine parts for rockets, including nozzles, combustion chambers, and turbine blades. The performance and effectiveness of rocket engines are improved by their capability to design complex geometries and optimize internal cooling channels.

DED technique uses a focused energy source, such as a laser or electron beam, to deposit molten material onto a substrate [1]. DED is employed in the fabrication of rocket casings or shells. Large-scale structures can be built using the layer-by-layer deposition approach with less material waste. DED is useful for producing rocket casings with complex geometries due to its ability to preserve structural integrity and strength.

SLM is the most accurate and detailed of these 3D printing technologies, which makes it the best choice for complex engine components. DED, on the other hand, has advantages for constructing large-scale structures with less post-processing demand, making it appropriate for the production of rocket casings.

The use of 3D printing in the manufacture of rockets has a number of benefits over more conventional production processes like casting and machining. It makes it possible to construct intricate geometries that were previously difficult to manufacture, improving the performance and efficiency of rocket componentry. By judiciously depositing components, 3D printing also lessens material waste, which has advantages for sustainability and cost-savings. More rapid iterations and development cycles are possible thanks to 3D printing's quicker prototyping and production timelines.

However, there are issues with 3D printing in the manufacture of rockets. Extensive material characterisation and qualification are important to assure dependability and safety in printed components. Adopting 3D printing for essential applications is hampered by the absence of established procedures and certification guidelines. Optimizing printing speeds, raising build quantities, and improving process stability are further requirements for scaling up 3D printing for large-scale rocket production.

In conclusion, 3D printing technology has enormous promise for the production of rockets. The production of complex engine components and massive rocket casings, respectively, by SLM and DED technologies, respectively, highlights their importance. To fully reap the rewards of 3D printing in this industry, improvements in material certification and process scalability are required. A future where 3D printing revolutionizes rocket production will allow for more effective, economical, and creative space exploration activities is possible with continued study and development

2. Different 3D printing technologies

2.1. Selective laser melting technology

Selective laser melting (SLM) is a type of metal additive manufacturing that scans metal powder layer by layer, melts the scanned areas, and creates metal components. It uses a high-intensity laser as its energy source. Category belongs to powder bed based process. The basic working principle of SLM technology is to use metal or metal alloy powder as raw material. The laser scanning control system controls the laser beam according to the CAD model. The laser scans the metal powder layer by layer [2]. The metal powder will be melted by huge energy at the moment of contact with the laser. The molten metal powder cools rapidly into a solid and bonds with the previously built layers. When the individual layers of metal powder are scanned, the building platform is lowered, and the laser beam repeats the process until the entire model is printed. Finally, clean up the remaining metal powder and carry out surface treatment to meet the required requirements (Fig. 1).

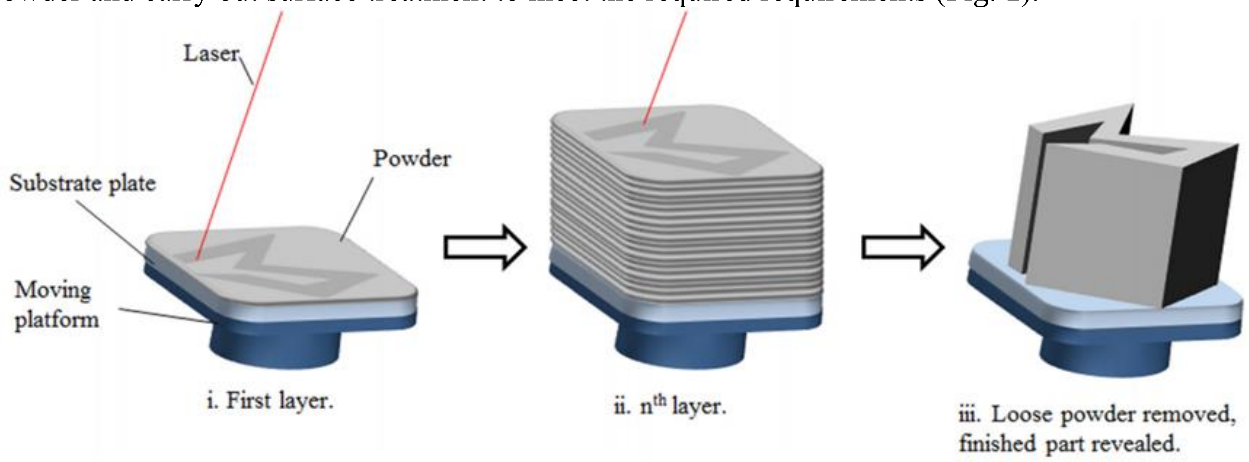

Fig. 1 Concept of SLM process. (i) High-power laser melts selective areas of the powder bed. (ii) Process is repeats for successive layers. (iii) Loose powder removed and finished part revealed [3]

At the same time, SLM technology also needs to meet certain conditions. When melting, laser power, scanning speed, hatch spacing, and layer thickness need to be adjusted, so that the layers can be completely integrated. It is necessary to maintain an inert atmosphere during the printing process, such as filling the building chamber with nitrogen or argon to prevent the metal powder from reacting with oxygen [3] (Fig. 2).

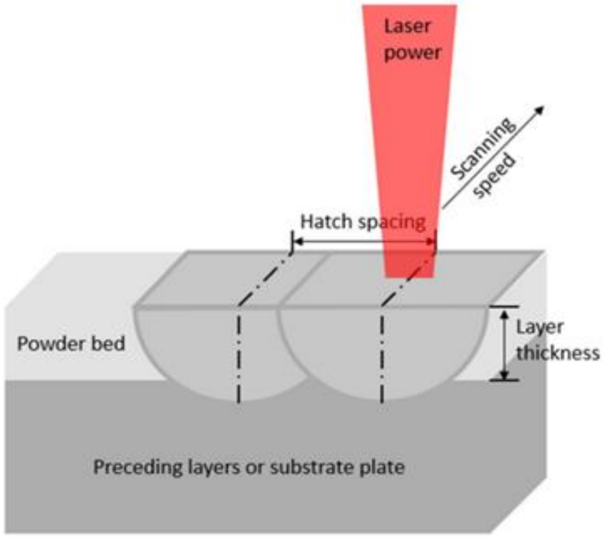

Fig. 2 SLM process parameters: laser power, scanning speed, hatch spacing, and layer thickness [3]

Since the metal powder is printed layer by layer, the model can have a complex and precise internal structure which has potential application prospects in the aerospace industry.

2.2. Directed energy deposition technology

Known also as laser deposition welding (LMD) or laser cladding welding technology, directed energy deposition (DED) technology is a 3D printing process for metal additive manufacturing. During the building process, this is a method of accurately melting and depositing metal by melting metal powder or wire and employing energy sources like laser, electron beam, plasma, or arc [4]. It falls under the umbrella of metal additive manufacturing. DED can be utilized in the production of aerospace and is appropriate for the deposition of high-performance materials like the aluminum alloys and titanium-based alloys described in Table 1 [5-6].

Table 1. Popular commercial alloys available for additive manufacturing [6]

Ni-base	Fe-base	Cu-base	AI-base	Refractory	Ti-base	Co-base	Bimetallic
Inconel 625	SS 17-4PH	GRCop-84	AlSi 10Mg	W	Ti6Al4V	CoCr	GRCop-84/IN625
Inconel 718	SS 15-5 GPI	GRCop-42	A205	W-25Re	TiAl	Stellite 6	C18150/IN625
Hastelloy-X	SS 304L	C18150	F357	Mo	Ti-6-2-4-2	Stellite 21	
Haynes 230	SS 316L	C18200	2024	Mo-41Re		Haynes 188	
Haynes 214	SS420	Clidcop	4047	Mo-47.5Re			
Haynes 282	Tool Steel	Glidcop	6061	C-103			
Monel K-500	Invar 36	CU110	7050	Ta			
C-276	SS 347						
Rene 80	JBK-75						
Waspalloy	NASA HR-1						

It uses a heat source such as laser, electron beam, plasma, etc., to focus on the substrate to form a small molten pool, and the metal powder or wire enters the molten pool and gradually melts and deposits it through the coaxial and transverse type feeding technology. Substrates or previously constructed parts. The deposited metal combines with the base material to form a new layer of metallic material. By repeating the above steps until the entire model is printed.

DED is divided into powder feeding type and wire feeding type. Depending on the raw material, powder uses lasers as heat sources, while wire uses electric arcs, plasma arcs, lasers, and electron beams as heat sources.

DED offers significant benefits in the high-throughput creation of novel materials, the processing of several materials, and the quick manufacture of massive, near-mesh parts with superior mechanical properties [7] (Fig. 3).

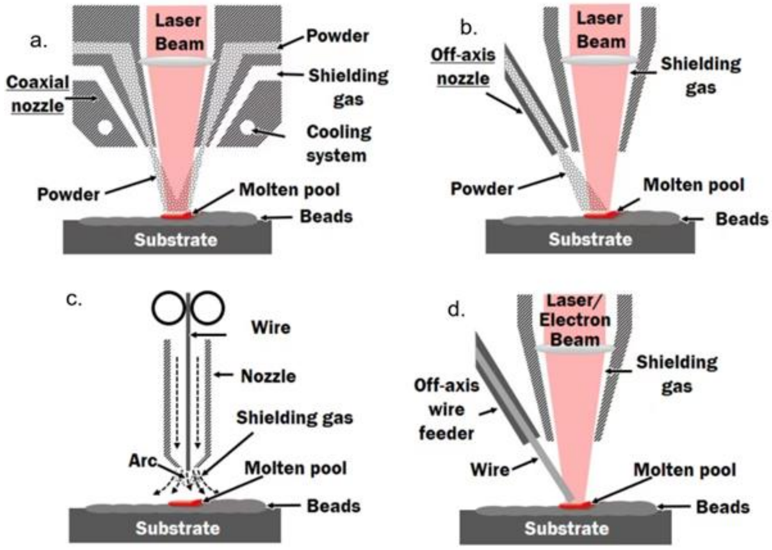

Fig. 3 Powder feeding methodologies of LAM -DED processes (a) coaxial feeding and (b) off-axis feeding; Wire feeding methodologies of DED processes (c) coaxial feeding (WAAM) and (d) off-axis feeding (WLAM and WEAM) [8]

3. Application of AM in Rocket Manufacturing

3.1. Application of AM in Rocket Engine Components Manufacturing

3.1.1 Injectors

AM offers a cost-effective and streamlined solution for manufacturing injectors by eliminating the need for multiple individual components, as well as their processing and assembly. Traditional manufacturing techniques for rocket engine injector systems involve producing numerous components that are later joined through brazing or welding to form a single injector head. This process is both time-consuming and expensive. However, by employing AM techniques, the cost and time required for manufacturing these injector components can be significantly reduced. Additionally, AM enables the production of complex and unconventional designs for manifolds and intricate elements that would be challenging or impossible to achieve using traditional methods.[9]

Since 2012, the Marshall Space Flight Center (MSFC) of NASA has produced injectors using SLM technology. Powder-bed methods have been used to construct and test AM injectors, including a tiny LOX/Propane injector for the Nanolaunch program. Complex characteristics made feasible by AM, such as discretized annulus orifices and intricate manifold routing, were present in the AM injectors. MSFC ran test programs to compare injectors made using traditional methods and those made using an SLM powder bed. Hot-fire testing revealed that the AM process performed on par with more established techniques, demonstrating its suitability for fabricating injectors. For a 35 Klbf engine technology development initiative, MSFC created a follow-on AM injector that included both innovative and core AM features. High exhaust velocity efficiency and steady combustion properties were seen during testing of this injector. The MSFC has built and successfully tested injectors of the shear coaxial and impinging element types while experimenting with other injector designs, propellant mixtures, and thrust classes. The MSFC has created a gas generator application that utilizes a fully atomized and mixed AM impinging injector for liquid oxygen and methane. However, impinging injectors face difficulties arising from dimensional imperfections [9]. Fig.4 shows some examples of injectors produced by MSFC of NASA using SLM technology.

Fig. 4 Examples of injectors produced by MSFC of NASA using SLM technology [9]

Another example is how a German Aerospace Centre, DLR, produced coaxial injectors for an aircraft project using AM technology, notably SML (or L-PBF) processes. The project focused on a small satellite launch vehicle (SSLV) initiative in an effort to lower costs for small satellite manufacturers. Tests on the AM-produced injectors were successful, and they showed promising performance traits [10].

Fig. 5 Injector head made by Ariane Group using EOS technology [11]

Moreover, using EOS Technology, Ariane Group has created a method for fabricating a rocket engine's injector head for an upcoming upper stage propulsion module, which is based on powder bed (or SLM) technology, shown in fig.5. The traditional design of the rocket consists of 248 components, requiring multiple manufacturing steps like casting, brazing, welding, and drilling. These processes can introduce weak points that pose risks under extreme loads. However, with the AM approach, the rocket is consolidated into a single part, maintaining the same functionality while significantly reducing the required time for production [11].

3.1.2 Combustion Chambers

SML technology is also suitable for combustion chambers fabrication. It allows for the production of intricate geometric elements and the integration of complex features such as coolant channels. This overcomes design limitations and enables the creation of chambers with improved efficiency and performance. SLM also provides the capability to achieve smaller feature sizes and ensures the desired finished surface quality [9].

Since 2013, NASA MSFC has used additive manufacturing to create combustion chambers that are channel-cooled. The chambers were constructed via bimetallic additive, hybrid, and SLM powder bed techniques. The SLM AM construction methods produced irregular geometric properties and rough surface finishes when compared to conventional machining. Although it worked well in the

water cooling tests at MSFC in 2013, the resultant channels and surface polish resulted in a coolant pressure loss that was far larger than anticipated. The AM manufacturing technique needed a far shorter timeline than traditional methods and eliminated the need for a separate coolant channel closeout procedure, yet interest continued and a bigger chamber component was sought. NASA has been developing various additive combustion chamber in the following years, as well as taking hot-fire testing. Most of them use SML, except for some that involve the use of DED technology [9].
Similarly, thrust chamber assemblies for Relativity Space's Aeon engines are almost totally produced using SLM powder bed printers [12].

3.1.3 Channel-Cooled Nozzles

Due to the scale and complexity required at these scales, channel-cooled or regeneratively-cooled nozzles as part of an engine system provide a special manufacturing challenge, which is much beyond SLM techniques [9].

NASA is addressing the scale limitations of SLM technology by developing new additive manufacturing methods. One such method is the LWDC (Laser Wire Direct Closeout) procedure, which is a DED-based technology that utilizes open-air localized purging robotic devices to achieve a larger build volume. Nozzles were created using this method and subjected to hot-fire tests, alongside nozzles fabricated using other additive techniques. For instance, some employed wrought stainless for the liner and the LWDC process for coolant channel closeout, while others utilized a combination of DED wire arc-deposition and LWDC, shown in fig.6. In a feasibility hot-fire test conducted in 2017, a directed energy deposition blown powder nozzle with integral coolant channels, fabricated from Inconel 625, demonstrated promising results with a 50% reduction in pressure drop compared to the LWDC technique at similar flow rates. The integrated liner and channel forming process was simplified, involving the welding of manifolds and completing machining steps [9].

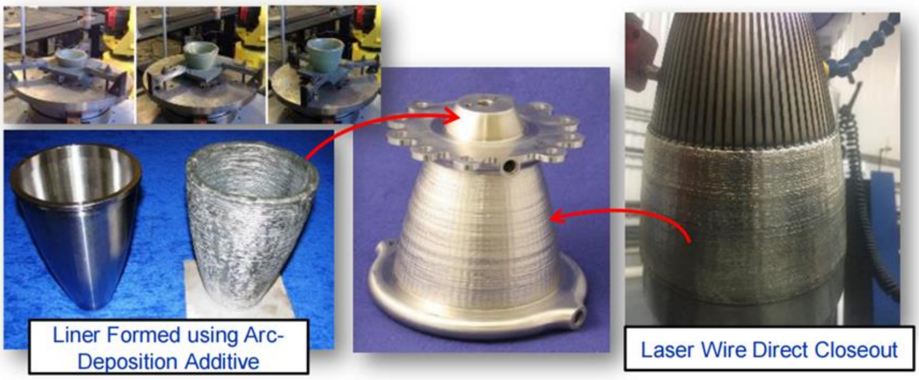

Fig. 6 Arc-based additive deposition and Laser Wire Direct Closeout (LWDC) integrated into channel wall nozzle [9]

3.1.4 Turbomachinery

Compressor blades, turbine blades, inducers, and impellers are a few examples of components with very complicated geometries that can benefit from the use of AM techniques to improve performance. AM technology gives designers more latitude to get around the geometric limitations that come with conventional manufacturing techniques. This independence enables the development of more complex and optimized final components, enhancing performance [6].

NASA has successfully shown the use of additive manufacturing for a variety of complex turbomachinery components in a variety of applications. Among these components are impellers, pump volutes, turbine blisks, stators, exit guide vanes, and nozzles. These AM parts have been shown specifically for liquid rocket engines that use liquid oxidizer (LOX) and liquid hydrogen fuel (LH2) in their turbopumps. Examples of these parts are shown in fig.7 [6].

Relativity Space's Aeon engines also uses SLM powder bed techniques to manufacture oxygen and methane turbopumps successfully, which is another example [12].

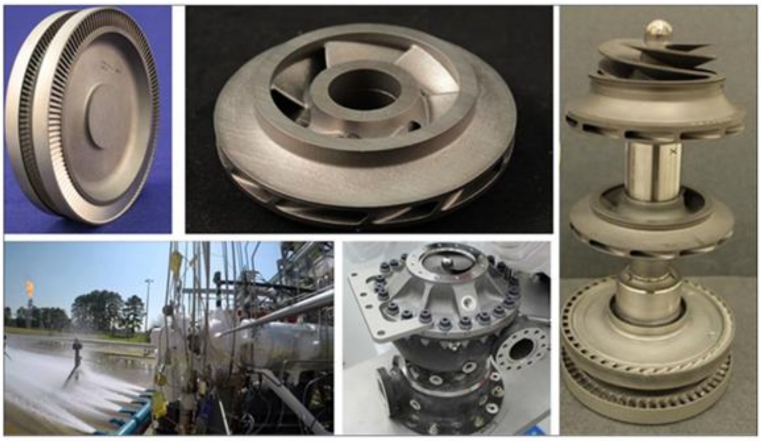

Fig. 7 Examples of liquid hydrogen and liquid oxygen turbopumps using AM at NASA MSFC [6,13]

3.2. Application of AM in Other Rocket Components Manufacturing

Due to advantages of AM, researchers has been developing various techniques in manufacturing different other components of rockets.

Larger liquid fuel rocket components have recently been developed utilizing DED since it is nearly not size-restrictive. Lockheed Martin used EB-DED to develop titanium domes for satellite fuel tanks, reducing material wastage and saving production time [6].

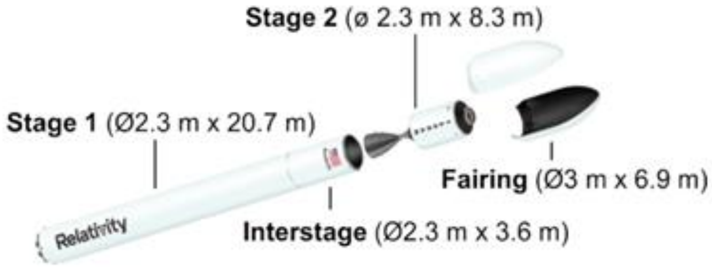

Fig. 8 The Terran 1 launch vehicle by Relativity makes use of 3D printing for practically all of the propulsion components and all of the primary structures [12].

Fig. 9 Relativity's Stargate 3D Printing System producing a Terran 1 first stage tank section [12]

Along with the fuel tanks, the rocket's fuselage can be made using AM techniques. In recent years, Relativity Space has been researching the manufacture of the entire Terran 1 rocket, shown in fig.8, using their proprietary alloy and large format AW-DED printing. With over 90% of the rocket's dry mass being 3D printed, including large fuel tank and fuselage, which showcases a full adoption of 3D printing technology. As is shown in fig.9, Relativity Space's Stargate printers, known for their novel architecture and custom aluminum wire chemistry, can produce flight prints as large as 3.4 meters in diameter and 7.6 meters in height, making them the world's largest metal 3D printing system. The

Terran 1 rocket's payload fairing is printed as a single monolithic structure, expected to be one of the volumetrically largest prints at 6.75 meters tall by 3 meters in diameter. The Terran 1 launch vehicle, standing over 35 meters tall with a diameter of 2.3 meters, is capable of delivering payloads of up to 1250 kg to Lower Earth Orbits. Through simultaneous prints and streamlined integration, Relativity Space aims to achieve a significantly faster production time, turning raw materials into a flight-ready vehicle in less than two months, in contrast to the typical more than 1 year lead times for conventional launch vehicles [12].

4. Comparison of Advantages of Different 3D Printing Technologies in Rocket Manufacturing

4.1. Comparing the advantages of 3D printing technology with traditional manufacturing in rocket manufacturing

Additive manufacturing has made great strides in the aerospace sector, achieving significant benefits through reduced part count, shorter lead times, lighter weight, and lower costs. Part consolidation, such as combining multiple components into a single part, can reduce assembly operations, reduce the use of joining methods (such as bolting, welding, etc.), reduce costs and reduce the need for skilled labor. Additive manufacturing techniques also reduce the tooling required for traditional manufacturing methods and reduce the number of components required for certification and related documentation.

Additive manufacturing can reduce lead times by eliminating the requirement for tooling, whereas traditional manufacturing processes typically demand lengthy lead times and high production process expenses. Additionally, part consolidation eliminates the requirement for manufacturing and storing legacy stock components and minimizes the demand for warehousing and legacy components, huge storage facilities, and component catalogs [6].

Lightweight design has been specifically explored in the aerospace industry, reducing fuel costs by increasing aircraft energy efficiency through weight reduction. Particular attention has been paid to the environmental contribution of aviation, with ICAO aiming to reduce aviation emissions by 50% by 2050. Weight reduction technology is an effective way to improve energy efficiency. For example, reducing the mass of Boeing 787 by 20% can increase fuel efficiency by 10-12%. Additive manufacturing techniques can help reduce costs, shorten lead times, and reduce spacecraft and aircraft component mass.

Lightweight applications bring significant benefits to rotating parts of aircraft and launch vehicle engines. Reducing component mass not only reduces overall mass, but also improves performance, such as reducing moment of inertia. Additive manufacturing has potential in the aerospace industry, enabling lightweight structural components, rapid prototyping, and complex instrument hardware design. Reduce mass to increase payload capacity and reduce launch costs.

Since 2013, NASA has demonstrated multiple applications of additive manufacturing in rocket engine injectors, greatly reducing part counts and shortening lead times. One example reduced the number of parts from 115 to 2 and was tested under full operating conditions with performance comparable to conventional manufacturing [6].

In the aerospace sector, additive manufacturing techniques can also be applied to repair high-value components. Because high-performance components in aerospace applications are often made of high-value materials such as Inconel and titanium alloys, they are often susceptible to harsh environments that can lead to reduced service life. Traditional repair techniques usually cause residual stress and geometric deformation, while additive manufacturing repair has low heat input and can meet structural design requirements and operating conditions.

Some of the unique limitations of employing AM for injector production, such as feature size resolution (especially radial to the build direction) and excessive surface roughness, are being actively addressed by the industry. Their impact has grown over time and is probably going to keep getting better. Another disadvantage of the powder bed method used to make injectors is the need to clean up residual powder from internal passages where the part could have limited access. All powder must be removed before heat treatments (including stress relief), since residual powder can get sintered and become difficult or impossible to remove later. For example, slurry honing has been employed and still is to remove surface effects, even though it is obvious that it cannot free badly blocked passageways. The majority of injector channels now need to be reasonably straight or have access to inlets and/or outputs in order to remove powder while the part is still connected to the build plate [9] (Fig. 10).

Fig. 10 Examples of fully AM thrust chamber assemblies hot-fire tested at NASA MSFC including injectors, combustion chambers, and channel-cooled nozzles, including L-PBF GRCop-84, L-PBF GRCop-42, bimetallic L-PBF and DED, and LP-DED NASA HR-1 [9]

4.2. Comparing the advantages of different 3D printing technologies in rocket manufacturing

4.2.1 SLM

Selective laser melting has high precision and complexity, can achieve high precision and detail resolution, can control the melting of micron-level metal powder layers, and stack them layer by layer to form complex structures. Suitable for manufacturing parts with special design requirements such as complex geometries, internal channels or honeycomb structures. Diversity of materials, SLM is suitable for various metal materials such as stainless steel, titanium alloy, aluminum alloy, nickel-based alloy, etc., providing a wide range of material options to meet different application requirements. Composite structures such as metal-ceramic composites can also be fabricated to provide better performance and functionality. The parts made by SLM have high density and excellent mechanical properties, and the dense bonding is achieved by directly melting metal powder. Excellent performance in strength, hardness and wear resistance, etc., to meet high-demand engineering applications. SLM technology enables a high degree of freedom in design, without being limited by traditional manufacturing methods. Translate complex geometries and internal structures directly into actual part manufacturing. The layer-by-layer stacking manufacturing method realizes rapid prototyping and small batch production, shortening product development cycle and time to market.
The high precision, material diversity, excellent mechanical properties, high degree of freedom and rapid manufacturing of SLM technology make it an important metal 3D printing technology. Widely used in aerospace, medical equipment, automobile and mold manufacturing, etc., to promote the development of innovative design and production methods.

4.2.2 DED

The high-throughput development and processing of new materials using numerous components, as well as the quick production of massive near-mesh pieces with strong mechanical properties, are areas where DED has significant advantages.

DED technology may use a range of metal powders or wires, making it an excellent option for developing and processing novel materials. High throughput new material development and processing for numerous materials. Alloying or customized material preparation can be achieved by mixing different metal powders or wires. This provides greater flexibility and innovation for material scientists and manufacturers to meet the needs of specific applications. DED technology can also combine other functional materials (such as ceramics or composite materials) with metal materials to achieve multifunctional and composite component manufacturing.

Rapid manufacturing of large near net shaped parts has good mechanical properties: DED technology is suitable for manufacturing large near net shaped parts, which usually have complex geometric shapes and large dimensions. By using high-power lasers or electron beams, DED technology can achieve rapid melting of metal materials and precise deposition, thereby achieving faster construction speed. In addition, DED technology can optimize the mechanical performance of parts by controlling temperature gradients and heat treatment during the construction process. This makes DED technology have important application potential in manufacturing large structural components, repairing parts, or conducting prototype production.

In summary, DED technology has major advantages in the development and processing of high-throughput new materials with multiple materials, as well as in the rapid manufacturing of large near mesh parts with good mechanical properties. These characteristics have led to the widespread application of DED technology in many industries, including aerospace, automotive, energy, mold manufacturing, and other fields [7-8].

Selective laser melting (SLM) builds parts by laser melting metal powder layer by layer, with small build diameter limitations and suitable for manufacturing high-resolution features. However, due to the layer-by-layer build, the build rate is slower [1].

Another additive manufacturing method called directed energy deposition (DED) creates items by jetting material into a melting bed of material while it is being built. DED has a high build rate, can accommodate the production of massive parts, and is comparatively free of size restrictions. DED struggles with resolution degradation and is unable to attain the same high precision as SLM.

In DED technology, three methods are currently evolving to bring more options to the manufacturing industry. In addition, DED technology also has the potential to replace traditional casting and forging processes, providing a more flexible and efficient production method for the manufacturing industry [13].

Table 2. Additive Manufacturing vs. Traditional Manufacturing

Scale	Traditional	SLM	DED
Resolution features	√		√
Deposition rates		√	
Reduced part count			√
Reduce waste		√	√
Shorter lead times		√	√
Lighter weight		√	√
Lower costs		√	√
No powder residue	√		√
No post processing	√		

5. Prospects and challenges of 3D printing technology in rocket manufacturing

These 3D printing processes have already made it possible to manufacture many spaceship parts, although there are still certain difficulties. Given the rapid advancements in polymer and metal-based additive manufacturing and the steady development of new technologies, it can be assumed that many of the issues that have recently emerged, such as those related to surface roughness or inadequate mechanical properties, will be resolved in the near future. The projected advancements in the technologies themselves and the creation of techniques for utilizing these technologies to print new metals will address this. A critical aspect that must be considered is the redesign of the particular AM process, taking into account its limitations and employing the increased degrees of design freedom to maximize the mechanical, morphological, temperature-dependent, and other properties of the AM [14]. In order to decrease shape deviations from design and enhance the mechanical qualities of additively created products to the levels attained with forged materials, future research must concentrate on further enhancing the 3D printing procedures detailed here. For materials that are especially suitable for space applications, the printing settings must also be optimized. By doing this, it is possible to cut down on development time and costs as well as the bulk of many components.

There are several applications for hybrid manufacturing, which blends additive manufacturing with traditional production techniques. The AGENT-3D_IMProVe project, created in collaboration with the Fraunhofer IWS team and MTU Aero Engines, shows a hybrid process chain employing DED with wire-filled materials and traditional machining. By cutting down on materials and machining times, the project hopes to lower the costs of semi-finished goods and tooling. The filler material was an alloy with nickel as its foundation called Inconel 718. There are further aerospace instances, such as the utilization of bimetallic structures to create combustion chambers by Virgin Orbit and NASA [6].

Combined machining combines the advantages of DED's high buildup rate and milling's precise surface finish. Alignment of the laser beam, powder stream and TCP is critical for precise additive deposition. With the help of the temporary protrusion concept, parts with cavities, such as rocket nozzles, can be manufactured by DED and milling with smooth surface transitions. Accurate DED processes allow for low oversize during near-net shape manufacturing and thus low stock removal during finishing, important for high-strength materials. An analysis of the accessibility reveals a factor affecting production time in combination machining: Smaller clearances require smaller tool diameters for constant depth of cut, resulting in lower metal removal rates. Alternatively, using a larger tool can result in a smaller depth of cut, requiring an increased number of parts to be built and milled alternately. The disadvantage of combined machining is that the CAM programming effort and cutting time, especially for challenging geometries of narrow, deep and overhanging inner surfaces, can increase significantly. High expenditures may only be justified for parts that require a certain height and cannot be produced using other manufacturing techniques. In the future, the rocket nozzle use case will be further developed using alternating DED and milling to fabricate the combustion chamber as the cavity [15].

6. Conclusion

Different 3D printing techniques, such as SLM and DED, play a vital role in the production of rockets, specifically in the manufacturing of rocket casings and engines. SLM technology utilizes a laser beam to melt and solidify metal powder layer by layer, enabling the production of intricate components like engine nozzles and combustion chambers. On the other hand, DED technology builds up metal powder or wire layer by layer using a heat source, allowing the creation of large-scale shells and structural elements. While DED is suitable for producing massive components, SLM excels in manufacturing small, precise parts with a wide range of materials. Challenges remain in terms of performance, material selection, quality control, and process optimization. However, the potential of 3D printing in rocket production is immense. As technology continues to advance and overcome these challenges, 3D printing is expected to offer more efficient, reliable, and cost-effective solutions for the manufacture of future rockets and the advancement of space exploration.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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