Materials & Design 209 (2021) 110008

Contents lists available at ScienceDirect

Materials & Design

journal homepage: www.elsevier.com/locate/matdes

Metal additive manufacturing in aerospace: A review

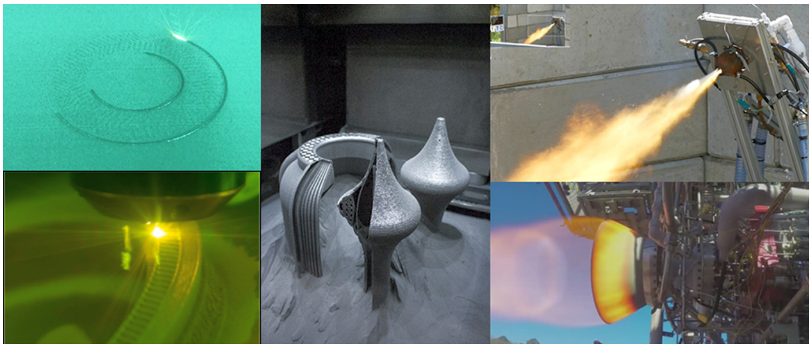
Byron Blakey-Milner [a,c], Paul Gradl [b], Glen Snedden [c], Michael Brooks [c], Jean Pitot [c], Elena Lopez [d], Martin Leary [e], Filippo Berto [f], Anton du Plessis [a,g,*]

[a] Research Group 3D Innovation, Stellenbosch University, Stellenbosch 7602, South Africa
[b] Component Technology Branch, NASA Marshall Space Flight Center, United States
[c] Aerospace Systems Research Group (ASReG), Discipline of Mechanical Engineering, University of KwaZulu-Natal (UKZN), Durban, South Africa
[d] Fraunhofer Institut für Werkstoff und Strahltechnik (IWS), Dresden, Germany
[e] School of Engineering, RMIT University, Melbourne, Australia
[f] Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology, Richard Birkelands vei 2b, Trondheim, Norway
[g] Department of Mechanical Engineering, Nelson Mandela University, Port Elizabeth 6001, South Africa

HIGHLIGHTS

- Metal additive manufacturing in aerospace comprehensively reviewed.
- Discussion of advantages and benefits of metal additive manufacturing in aerospace.
- Limitations and challenges described in context of current technology.
- Successful examples of metal additive manufacturing in aerospace demonstrated.
- Future growth potential and promising areas discussed.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 30 March 2021
Revised 10 June 2021
Accepted 23 July 2021
Available online 24 July 2021

Keywords:
Metal additive manufacturing
Laser powder bed fusion
Directed energy deposition
Topology optimization
Lattice structures
Aerospace
Lightweighting
Electron beam powder bed fusion

ABSTRACT

Metal additive manufacturing involves manufacturing techniques that add material to produce metallic components, typically layer by layer. The substantial growth in this technology is partly driven by its opportunity for commercial and performance benefits in the aerospace industry. The fundamental opportunities for metal additive manufacturing in aerospace applications include: significant cost and lead-time reductions, novel materials and unique design solutions, mass reduction of components through highly efficient and lightweight designs, and consolidation of multiple components for performance enhancement or risk management, e.g. through internal cooling features in thermally loaded components or by eliminating traditional joining processes. These opportunities are being commercially applied in a range of high-profile aerospace applications including liquid-fuel rocket engines, propellant tanks, satellite components, heat exchangers, turbomachinery, valves, and sustainment of legacy systems. This paper provides a comprehensive review of metal additive manufacturing in the aerospace industry (from industrial/popular as well as technical literature). This provides a current state of the art, while also summarizing the primary application scenarios and the associated commercial and technical benefits of additive manufacturing in these applications. Based on these observations, challenges and potential opportunities are highlighted for metal additive manufacturing for each application scenario.

1. Introduction

The aerospace sector encompasses commercial and military aircraft, space launch and in-space systems, missiles, satellites

---

* Corresponding author at: Research Group 3D Innovation, Stellenbosch University, Stellenbosch 7602, South Africa.
E-mail address: anton2@sun.ac.za (A. du Plessis).

https://doi.org/10.1016/j.matdes.2021.110008
0264-1275/© 2021 The Author(s). Published by Elsevier Ltd.

and general aviation. The recent COVID-19 pandemic has had a substantial negative impact on aerospace sector revenue, with a decline from $342.2 billion in 2019 down to $298 billion in 2020 [1]. This decline was primarily caused by air travel restrictions, social distancing protocols and other restrictions imposed on the commercial aviation industry during the ongoing COVID-19 pandemic. Despite this challenge, the aerospace sector is expected to grow to $430.87 billion revenue by the year 2025 [1]. This growth is primarily due to the long-term demand for new commercial aircraft, increased global military expenditure, high market activity in the space sector and substantial research and development ongoing throughout the pandemic [1].

Manufacturing in the aerospace sector is subject to numerous interacting technical and economic objectives of: *functional performance, lead time reduction*, *lightweighting, complexity, cost management,* and *sustainment*. Each of these objectives have strong relationships to one another and considerations from each factor must be considered carefully when selecting an optimal design solution. The relative importance of these objectives depends on the specific aerospace application, but in general terms these objectives can be described as follows:

- The aerospace sector requires the delivery of safety–critical components that must operate in their intended environment *(functional performance)* in small production volumes with relatively inflexible delivery schedule. *Lead time reduction* is therefore highly relevant to the aerospace sector as this allows rapid product certification and retains flexibility in design of high value components.
- *Lightweighting* is relevant to the technical and economic performance of aerospace structures. Specifically, the technical performance and allowable mission-defined payload of aerospace structures is physically limited, meaning that system mass reduction directly relates to enhanced economic and technical performance, including reduced fuel costs, lower emissions, larger payloads and increased range.
- The objective of lightweighting is tempered by the economic constraints of *cost management*, whereby a specific financial resource is available for a specific design objective. Cost management, lightweighting and lead time reduction objectives are interrelated, whereby the allowable system cost generally increases for solutions that are able to achieve lightweighting or lead time reduction objectives. Cost management applies to all aspects of component use, including certification and maintenance, and opportunities for cost management by reduced certification risk.
- A critical challenge to metal additive manufacturing (AM) applications in aerospace is the hurdle of *certification*; requiring that regulatory bodies be confident that the AM systems are fundamentally well understood, and can be repeatably designed and inspected such that reliability and safety expectations can be satisfied. These certification requirements vary according to the criticality of the proposed AM system as being safety or mission-critical or otherwise. Practical certification requires connection with existing standards for traditional manufacturing as well as to standards emerging for AM processes.
- Aerospace structures are generally *high-complexity*, low volume systems, where the challenges associated with *sustainment* can become substantial. Sustainment challenges include part availability for aging aircraft, remanufacture and repair, and recertification of existing aircraft for alternate uses.
- *Complexity* is inherent to the designs where often hundreds, or thousands of parts make up systems and subsystems to achieve the desired *functional performance* in the intended environment. These systems are integrated into the overall flight system that can often exceed millions of components. These components are high in complexity to allow for functional performance (structural, flow, thermal, reliability, durability, compatibility, etc.) as well as weight reduction [2,3].

In the drive to improve efficiency continuously through cost, lead time reduction and attempts to lower the mass of flight components, high-performance materials are used, with increasingly complex designs. This must be done within a reasonable cost and schedule to meet commercial orders or mission requirements. Traditional manufacturing systems and strategies have been developed over many decades to accommodate these aerospace design objectives for numerous application types; however AM is and will continue to have a profound impact on the design and manufacturing. This AM digital transformation, often touted as Industry 4.0, will increase its market size in the aerospace sector to $3.187 billion by the year 2025 with an average compound annual growth rate (CAGR) of 20.24% [4]. Research into AM in aerospace has also seen exponential growth over the last decade.[1] In addition to this scholarly literature, much relevant work exists in the form of technical reports, popular literature and publicity articles from commercial aerospace suppliers, with technical details sometimes restricted for commercial reasons.

Additive manufacturing, unlike conventional subtractive manufacturing techniques, utilizes layer by layer manufacturing based on a common feedstock, typically powder or wire that is melted or fused by a heat source and solidifies to produce the final geometry based on a digitally defined heat source trajectory [5]. The advantages of the use of additive manufacturing for aerospace components are the reduced lead time and associated cost, the ability to design and manufacture complex geometries that enable lightweighting, consolidation of multiple components and improvements in performance; within cost and timeline constraints, hence offering improved programmatic and technical risk management [6,7]. By utilizing the design freedom of metal AM, it is possible to optimize the material distribution, reducing mass while maintaining the mechanical and other performance requirements of the component. It is also possible to combine components, reducing risk and cost for multiple components and reducing potential failure modes across joints. Additionally, enhanced performance (above that of conventional manufacturing) is possible by utilizing mechanical, thermal and other optimization approaches for the design of complex parts that were previously impossible to manufacture, incorporating internal features such as conformal cooling channels on combustion chambers or turbine blades, for example [8,9]. While the reduced lead times are the present main driver for the use of AM in aerospace applications, specific manufacturing scenarios give AM advantages over traditional manufacturing as schematically illustrated in Fig. 1 and discussed below.

The *complexity* afforded by the AM process is a large advantage of this technology, as new designs can be realized for enhanced mechanical and thermal performance and reduced system mass, not possible by other manufacturing methods. The inherent capacity for complexity within AM design enables *lightweighting* by both the consolidation of multiple components into one and by the opportunity for increased technical efficiency. Despite persistent misconceptions regarding the constraint-free nature of AM technologies, they are highly compatible with high complexity outcomes; thereby enabling lightweighting by deploying material as required for the technical response (structural, vibratory or thermal) rather than as constrained by the associated manufacturing process. A systematic review of AM design constraints is provided

---

[1] Scopus listed publications with the keyword *aerospace* combined with either *3D printing* or *additive manufacturing* have increased from 15 in 2010 to 490 in 2020.

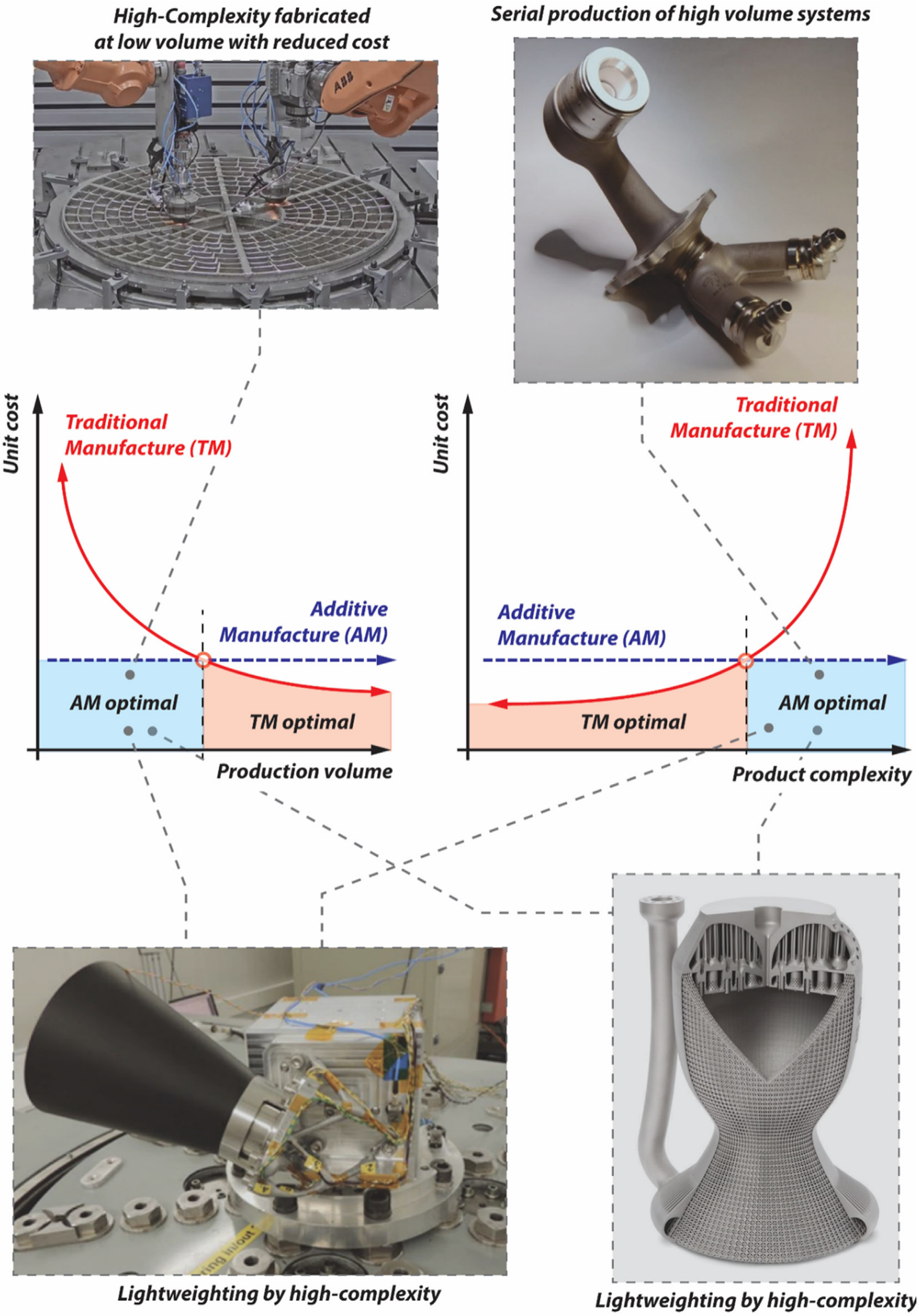


Fig. 1. Unit cost versus production volume and production complexity identifying economically and technically optimal scenarios further developed in this monograph. Note the possibility for a specific application to satisfy multiple opportunities, such as high-complexity and low-production volume; these scenarios are especially valuable for commercial AM applications. Images courtesy of Fraunhofer, European Space Agency and GE Additive Copyright: ©SLM Solutions/ CellCore, [10–13].

in [14]. It should be noted that the complexity should be appropriately traded within the design and throughout the lifecycle of AM components as it can add additional post-processing operations or unintended operational challenges if not fully understood. Algorithmic design methods, often referred to as generative design and opportunities for topology optimisation are reviewed in [15].

Part consolidation refers to the re-design of multiple interacting components as a single integrated system, thereby enabling substantial enhancement in technical performance. The integration of multiple components enables removal of mating surfaces and structures, thereby increasing structural efficiency and reducing the costs associated with inspection and certification of mating structures. Furthermore, the consolidation of multiple parts may substantially reduce overall fabrication costs. This cost reduction is enabled by the direct reduction of manufacturing lifecycle costs as well as the reduction in non-recurring costs associated with design, certification and risk-management of the failure modes that are associated with part interactions.

The aerospace sector relies heavily on machined forged and billet structures for high-value structural systems. This manufacturing methodology provides high certainty in final component quality, as billet materials are readily certified for porosity and microstructure, but adds substantial direct manufacturing costs and induced costs due to high production lead times. Forging requires the expensive design, manufacture and trialling of preforming dies and billet machining is inherently expensive with typical buy-to-fly ratios[2] estimated at 20:1. For example, a final product with a mass of 10 kg would require 200 kg of stock materials as discussed in [16]. Others claim this ratio is closer to 40:1 [17]. The unused material is waste and is recycled or reprocessed if possible, adding extensive costs to all projects.

By the nature of the layer-by-layer manufacturing process, AM produces little to no waste with buy-to-fly ratios of between 1:1 and 3:1 [18,19]. Using far less stock material by mass compared to traditional manufacturing techniques, AM has the potential to reduce the cost of manufacturing aerospace components substantially all while simplifying the recycling and reprocessing processes, subject to proper precautions. Many aerospace alloys can have long lead times to produce the required wrought starting stock material. Since many AM processes start with a powder or wire feedstock, which is readily available for common alloys, this lead time can be substantially reduced for commercially available materials. Additional costs and lead time in processing of aerospace components can include specialty tooling and fixturing [20]. Currently, the significant reduction in lead times is one of the major advantages of AM in this industry.

Historically, AM was used extensively for rapid prototyping in the form of part representation and initial functional testing before infusion into commercial end-use applications. While flight use of AM has roots back to the early 2000s, the decade from 2010 to 2020 expanded the use of AM to include final production, including mission-critical components [21]. This digital transition in manufacturing focus has been successful due to improvements in the underlying technology and in the improved understanding of the technology and its supply chain, as well as the rigor being applied to standardization and certification [22].

The basic principle of AM is to build up components layer-by-layer directly from 3D model data created using Computer-Aided Design (CAD) to near net or final shape. This is a complex procedure as a large multitude of process parameters have possible effects on the quality of produced components [14,23]. Continued improvements in the understanding of these parameters has steadily lessened the associated quality impacts, however. The process parameters including the power, scan speed, hatch spacing or overlap between tracks, scan strategy (e.g. use of contours, angle change of hatch tracks per layer, etc.), among many other parameters may influence the process and thus the quality and properties of the manufactured components. This includes surface roughness, porosity, residual stress and associated cracks or warping of components, unique microstructures, as well as anisotropy of the material. This traces back to the roots of materials characterization and allowing an understanding as part of the Process-Structure-Properties linkages ultimately leads to better performance [24]. Further disadvantages of AM include limited materials, uncertainty in material properties, specific design constraints inherent to AM, post-processing requirements, waste generation (used powder, build plates, failed builds), increased requirements of design skills to allow lower-mass components with feasible complex designs, often utilizing time-consuming topology optimization software workflows, as well as the need for strict quality control and certification of the process [25]. While accessibility to AM machines is increasing, the technology is not as readily available as traditional manufacturing techniques so the supply chain requires maturation. Post-processing is an area that challenges AM, requiring specialized and custom-developed or optimized thermal treatments, part cleanliness, and surface enhancements to improve rough surfaces.

All aerospace manufacturing is subject to strict quality controls such as Quality Systems - Aerospace SAE AS9100 and Standard for Additively Manufactured Spaceflight Hardware MSFC-STD-3716, NASA Standard 6030 [14,26–31], but this is further exacerbated by the complexity of the AM processes and many possible influences on component quality. This is especially true as the technology has matured only recently and many studies have reported widely disparate mechanical properties [32–34], especially fatigue performance [35–37]. This leads to uncertainties in the material performance and in the required controls which may be different from traditional manufacturing. Various international standards are currently under development to address this [14]. With appropriate quality controls and optimization procedures, the issues mentioned above can all be mitigated or minimized [14,38]. Significant post-processing is generally required such as powder removal, thermal processing, supports and baseplate removal, hot isostatic pressing (HIP), surface polishing, and often final machining.

Despite the disadvantages mentioned, specific scenarios exist where AM is well suited to aerospace applications, with clear technical advantages over traditional manufacturing methods. This paper provides a comprehensive review of applications of metal AM in the aerospace industry, thereby also providing a review of the current state of the art. Through demonstrating these successful examples, the benefits of AM and the challenges associated with AM in aerospace are systematically documented; thereby promoting the further application of AM in this sector, taking into full consideration the challenges and requirements.

2. Key concepts related to AM for aerospace

2.1. Additive manufacturing technologies

Additive manufacturing, outlined by the international standard ISO/ASTM 52900 [39], comprises seven process categories which include directed energy deposition (DED) and powder bed fusion (PBF), both allowing the fabrication of metal components with near full density. Other process categories are not discussed in detail as they are still evolving and still at lower technology readiness levels (TRL). Metal AM is reviewed in more detail in [40], including an overview of the processes, resulting structure/microstructure, and properties of manufactured materials. In particular, laser powder bed fusion (L-PBF) is gaining traction in industry due to its high resolution, high-quality part production capabilities, combining fine feature sizes with adequate build volumes for many part sizes required [14]. Once the process is optimized, the resulting components produced can boast mechanical properties exceeding those of conventional manufacturing techniques with proper procedures in place [34,41]. AM methods, key technologies and relevant materials for aerospace applications are briefly described below.

---

[2] Buy-to-fly ratio refers to the ratio of billet material purchased to material in the production component.

2.1.1. Powder bed fusion processes

(a) Laser Powder Bed Fusion

The L-PBF technology utilizes high power laser(s) to melt and solidify individual layers of metal powder [14,42]. The L-PBF process involves powder feedstock delivered and coated onto a platform where the powder is selectively melted and solidified according to the CAD design. The laser scanning strategy and layer thickness, inert atmosphere and gas flow, and various other parameters are selected by the user and need to be optimized for the particular material and system used [14]. This is the most common form of metal AM with options for machines from a host of manufacturers and a large collection of materials such as aluminium alloys, steel alloys, copper alloys, nickel and iron superalloys, precious metals, refractory metals, titanium alloys and many more. Although L-PBF is known to produce fully dense components with high precision in a relatively short time [43], the manufacturing process is relatively expensive and is only applicable in industries with high-value components and where higher performance can result in cost reduction, such as the aerospace industry. Typical minimum features sizes of ~ 0.2–0.4 mm with maximum part size of about 300–400 mm cover a range suitable for most small-medium part size requirements [14]. Larger systems are now becoming available using multiple laser sources for enhanced productivity and with build volumes up to 500 × 280 × 850 mm [44]. Even larger systems (>1 m) are being developed but not commercially available or widely accessible yet.

(b) Electron Beam Powder Bed Fusion

Electron beam powder bed fusion (EB-PBF) is an AM process that uses a high-energy electron beam to melt metal powder layer by layer to fabricate fully dense solid components. The components are manufactured in a vacuum due to the electron beam requiring a vacuum. This reduces impurities in oxygen sensitive materials. These systems often use preheating by rapidly scanning the electron beam across the powder prior to melting of a layer, assisting to minimize residual stresses. Mechanical properties of components manufactured through EB-PBF can be similar to that of cast materials, demonstrating the suitability of components manufactured through this process as compared to traditional manufacturing methods [45]. The maximum build sizes are similar to that of L-PBF, with latest models having circular build diameter 350 mm and height 380 mm. These systems typically use larger feedstock powder sizes, which results in larger roughness values. However, the systems are well developed and offer relatively short build times due to the high power and rapid scanning of the electron beam.

2.1.2. Directed energy deposition processes

Dissimilar to powder bed processes, in directed energy deposition (DED) techniques, the stock material is deposited locally using powder or feeding wire feedstock directly into the meltpool which is created by an energy source, e.g. electrical arc, lasers or electron beams [41]. Since DED does not rely on a powder bed, it has some benefits in geometrical freedom compared to other AM techniques and is not limited to build size restrictions. Very large components can therefore be manufactured with this technique. DED machines are commonly used in the repair of high value existing components such as turbine blades. DED has a poorer resolution (minimum feature sizes of about 1 mm) [46,47] compared to that of powder-bed based technologies and is therefore used for larger components with reduced resolution [48], or where post processing machining operations can be performed.

There are various forms of DED techniques that each have different advantages and disadvantages. Laser Powder DED (LP-DED) is one of the most common using a laser as the energy source and a powder feedstock. The deposition head is attached to a robotic or gantry system and uses a local inert or fully purged chamber. In LP-DED the powder is blown into the melt pool and joined with the previous layer creating a freeform structure. An alternate DED method is Laser Wire DED (LW-DED), which uses the same concept, but the feedstock is wire. The wire feedstock may be off-axis or co-axial and has an advantage with high material efficiency, but at a reduced resolution. Other systems such as Arc Wire DED (AW-DED) and Electron Beam DED (EB-DED) use wire but with an electric arc or electron beam as energy sources, respectively. Each of these processes has differing feature resolution and deposition rates, which can result in varying heating and cooling rates and subsequent variance in metallurgical characteristics and in mechanical and thermophysical properties [49–52].

2.2. Materials for AM aerospace

Distinctive materials for AM in aerospace are aluminium alloys, stainless steel, titanium alloys, nickel-and iron-based superalloys, copper alloys, cobalt alloys, refractory alloys, and steels, among other metallic materials. Most of these are used in pre-alloyed powder form, most often produced by gas atomization, or in wire form depending on the process [5,40].

Aluminium alloys have been an integral material since the inception of the aerospace industry. Their low cost, light weight, high strength to weight ratio and ease of manufacturing characteristics have resulted in aluminium being the most widespread material in aerospace until recent advances in composite technologies [53,54]. However, aluminium alloys suffer from poor elevated temperature capabilities, and in some high strength aluminium alloys, corrosion resistance is poor, thus limiting their applications.

Stainless steels are used in several aircraft and space components due to the high strength to weight ratio, excellent durability, hardness and good mechanical properties at elevated temperatures. Various classes of stainless steels are often used with AM including austenitic, precipitation hardened (PH), and maraging (martensitic and aged) [55,56]. These forms of stainless steel are used across components for engine and exhaust systems, hydraulic components, heat exchangers, landing gear systems, and structural joints. Stainless steels also exhibit high corrosion, oxidation, and wear resistance depending on the environments [57,72,73].

Titanium alloys have been the subject of much interest in aerospace applications due to their high specific strength, excellent corrosion resistance and high-temperature stability [58,59]. Titanium alloys are also electrochemically compatible with polymer matrix-carbon fiber composites (PMCs) which are extensively used in modern aircraft [60]. Titanium alloys see substantial use in aircraft due to their high-temperature stability and specific strength [60]. Cryogenic applications, commonly found in rocket propellant tanks, are also potential use-cases for titanium alloys since they exhibit no ductile to brittle transition at low temperatures [60].

Nickel- and iron-based superalloys have become key materials for the manufacturing of disks and blades in high-pressure turbines for gas turbine engines. They are also used in many high temperature and cryogenic applications such as valves, turbomachinery, injectors, igniters, and manifolds [61,62]. Their excellent mechanical properties under extremely high temperatures, high pressures and in corrosive environments improve the efficiency of modern aircraft engines substantially [63]. Currently, over 50% of the mass of an advanced aircraft engine is comprised of nickel-based superalloys [64]. Iron-based superalloys are commonly used in high pressure hydrogen applications such as rocket engines to mitigate hydrogen environment embrittlement [65].

Copper-alloys are commonly used in heat exchangers, such as for combustion chambers for liquid rocket engines. This high heat flux environment requires a high strength and high conductivity alloy to properly cool the walls of the thrust chamber with a high pressure propellant or oxidizer. Common AM copper alloys used include GRCop-42, GRCop-84, C18150 (Cu-Cr-Zr), C18200 (Cu-Cr), and GlidCop [66–71].

Other metal alloys that can be used in aerospace applications include refractory materials such as niobium, tantalum, and tungsten and alloys such as C-103 [74]. These are used in extreme temperature applications such as in-space radiatively-cooled thrusters. Other materials such as Cobalt-based alloys including Co-Cr and Stellite are also used for a variety of elevated temperature applications [75,76].

Many of these materials exist as feedstock for metal AM machines and have seen varying levels of research into the material characteristics and properties produced using AM methods, with demonstrations of mechanical properties equal to, and sometimes exceeding those associated with typical manufacturing methods [77–80]. For this to be achieved, the process parameters and post-processing operations must be optimized to minimize porosity, residual stress, crack propensity and includes optimized post processing steps as required to enhance the material properties, including optimized heat treatments and HIP. For more information on AM materials and related issues, the reader is referred to [40] and Table 1 summarizes the more popular materials for AM in aerospace. Some of the alloys highlighted in this table include variations such as Metal Matrix Composites (MMC), including Al-MMC and Ni-MMC. Many of these alloys have also been used in test and flight applications as discussed later in Table 2 and Table 3.

2.3. Development of new alloys

Early adoption of AM techniques used materials that had traceability to common alloys manufactured by traditional processes. Many of these alloys are not the best-fit alloys for the applications in question, and have challenges in AM processing due to cracking or susceptibility to porosity formation, oxidation or other unwanted properties. AM offers a significant opportunity to introduce new and custom alloys that allow for more optimized processing to reduce cracking or to mitigate other challenges, while being further optimized for the end application. Examples of this include the introduction of custom aluminium alloys such as 7A77, 6061-RAM2, AlSi10Mg, Scalmalloy, and many others that offer high strength and successful AM builds with otherwise crack-prone alloys [82–86]. NASA also recognized the need for advanced alloys in AM and initiated development of the GRCop-84 and GRCop-42 copper-alloys for use in high heat flux applications, in addition to the iron-based superalloy NASA HR-1 alloy for use in high pressure hydrogen environments [87]. Many other examples of custom superalloys, aluminium, refractory metals and others being designed specifically for AM processing are being addressed as the industry need for more materials has been identified [88–91]. Beyond monolithic alloys, AM also provides the opportunity to create custom bimetallic and multimetallic material solutions, adding material locally within a design for optimization of thermal or structural loads. These can include a discrete material transition or a function gradient material [92–96].

2.4. Reduction in processing time

One of the key motivations for use of AM in aerospace is the significant cost reduction and improved lead times achievable compared to traditional manufacturing [97]. Aerospace components are complex to manufacture and often require unique alloys that have long procurement lead times in a wrought form and can also take significant processing time to form, machine, build, or assemble during the transition from the starting stock to a final part or subsystem. This lead time is compounded due to the various inspections and traceability requirements of material and parts throughout the process. The parts must follow a rigid process to ensure they are fabricated safely and meet standards and certifications while also meeting the design intent. AM is no different and must still follow strict requirements to be flown safely in aerospace applications, but the lead time can be drastically reduced and the supply chain simplified. This is true for new part designs, but probably more important for spares or replacements that are out of production. This simplified supply chain and reduction in lead time, including logistical benefits, presents a substantial opportunity to reduce cost [98]. There are several examples that have demonstrated cost reductions of 50% and lead time reductions of 50% or more [9].

2.5. Process certification

Additive manufacturing requires strict control of the entire process from powder through AM build and post-processing. This includes a detailed understanding of the process parameters that impact the microstructure and subsequent mechanical and thermophysical material properties. This certification process must be determined early in the design process to include both a methodology and traceability throughout all stages of AM. This includes implementation of adequate non-destructive evaluation (NDE) techniques, surface enhancements to improve fatigue performance, optimization of thermal processing, and other pre-, build and post-processing operations. Methodologies described by standardization and government organizations require strict control of machine parameters, powder lots, and include a detailed understanding of variations in powder or off-nominal build operations to ensure that parts meet the intended design and metallurgical characteristics.

Metal AM processes derive their flexibility and low-production costs to their fundamental unit material inputs (either powder, wire or sheet) which are then additively joined to generate the required as-manufactured geometry (including additional supporting structures) which are then post-processed as required to generate the final component. The production capabilities inherent to metal AM technologies allow previously unachievable system efficiency, however the fundamental certification challenge for these high-complexity AM components and systems is commensurately high. AM production phases are not compatible with aviation certification protocols derived for traditional manufacture [41,99], consequently the certification of these components is challenging; for applied engineering of AM products it is therefore necessary either to accommodate *existing* certification protocols or to actively engage with *emerging* protocols for AM structures.

Existing certification protocols are derived as a function of criticality and associated failure modes, consequently, the challenge for metal AM certification is lower for non-safety critical applications, and for applications that are subject to monotonic failure modes (such as static deflection) rather than for complex failure modes such as corrosion cracking or multiaxial fatigue. Therefore the certification challenge for a statically loaded assembly fixture may be less than for a non-safety critical structure, than for a dynamically loaded structural safety–critical component.

Emerging standards are under active development from government entities, industry groups, and standard organizations. These emerging protocols seek to find practical certification strategies that allow the benefits of emerging AM technologies to be applied without undue risk to safe aircraft or space vehicle operation. These emerging protocols include a combination of:

- Detailed understanding of material, process and design inputs on critical failure modes, potential defects and the classification of parts [100].

Table 1
Popular commercial alloys available for additive manufacturing [81]

Ni-base	Fe-base	Cu-base	Al-base	Refractory	Ti-base	Co-base	Bimetallic
Inconel 625	SS 17-4PH	GRCop-84	AlSi10Mg	W	Ti6Al4V	CoCr	GRCop-84/IN625
Inconel 718	SS 15–5 GP1	GRCop-42	A205	W-25Re	γ-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	SS 420	Glidcop	4047	Mo-47.5Re			
Haynes 282	Tool Steel (4140/4340)	CU110	6061	C-103			
Monel K-500	Invar 36		7050	Ta			
C-276	SS347						
Rene 80	JBK-75						
Waspalloy	NASA HR-1						

- Post processing standards, including for example, the application of HIP to ameliorate the criticality of internal defects to component function and to improve the material microstructure and anisotropy [59,101].
- Safe-life design methodologies that presume the existence of internal crack-like defects and based on minimum critical flaw size calculations an allowable service life is defined [102].
- Non-destructive testing protocols, for example the application of computed tomography to quantify the existence and geometric attributes of internal defects [103].
- Material certification protocols and systematic quantification procedures to determine the consistency and fitness-for-purpose of metal AM inputs, especially for powdered metal.
- Developing fundamental requirements for process controls and part production including qualification of material processes, equipment controls, personnel training, and material property development.
- Allowable design and data management protocols to ensure geometric data is not corrupt and is appropriately encrypted and that appropriate file management procedures are followed.
- In-situ data acquisition provides an opportunity for increased confidence in internal AM structural integrity as well as potentially identifying geometric “high risk” regions that require enhanced resolution NDE or Non-Destructive Testing (NDT).
- Standards for witness coupon design and deployment to destructively validate integrity of a manufactured AM batch without damage to production AM components.

2.6. Topology optimization & lattice structures

Topology optimization (TO) refers to a mathematical design method often used to optimize material layout in structural applications for given boundary conditions and a given set of loads and constraints [104]. The method is based on simulations and iterative shape optimization, realized in different forms in commercial software packages. Traditional TO utilizes the finite element method (FEM) to improve design performance [104] and was first popularized by Bendsøe and Kikuchi in 1988 [105]. The method has seen extensive development over the last three decades and has been a popular topic of continued research and development, for all manufacturing processes. It finds particular application in AM due to the manufacturing freedoms of the AM technologies, allowing optimization of shape and geometry for highly efficient designs with internal components and intricate features that are not feasible otherwise [106,107].

Lattice structures are porous cellular architectures that typically refer to a network of solidly interconnected struts forming the faces or edges of cells [108]. Cellular porous material architectures are common in a wide variety of materials such as wood, bone, metals, and other microscopic structures. The conventional manufacturing of cellular porous structures includes direct foaming, spray foaming and vapour deposition techniques [109]. Both random stochastic structures and periodic designs exist as low-density cores in sandwich panel designs which are used in many industries. Additively manufactured cellular structures (or lattice structures) can mimic the geometry of these random stochastic and periodic structures, on both the macro and micro scale, creating new opportunities for complex designs with unique properties to be realized using the materials available for AM.

Metal lattice structures demonstrate high mechanical performance, offering high specific strength, good energy absorption capacity and robust thermal characteristics [110]. Periodic lattice structures typically exhibit better performance characteristics with respect to specific strength and energy absorption [111]. However, these periodic lattice structures typically have manufacturing constraints and therefore higher costs over stochastic structures [112,113]. L-PBF in particular can produce complex geometric structures at a high resolution with limited flaws and this shows potential for the manufacture of both periodic and stochastic cellular lattice structures for excellent performance components, with precisely controlled properties [114].

While these lattice structures allow for designs with interesting lightweight, thermal, acoustic and energy absorption properties, parameters for manufacturing still need to be improved to reduce common issues such as strut micro-porosity, surface roughness inconsistencies and poor mechanical properties that can occur [112]. These manufacturing errors and the overall choice of cellular geometry influence the fatigue performance of such structures, which is key for their use in aerospace and is discussed in more detail in [108].

2.7. Advantages of AM for aerospace applications

While the concept of lightweighting design exists in many industries, aerospace industry applications are particularly well explored due to the reduced fuel costs achieved through mass reduction on aircraft and spacecraft. Recently, a specific focus on the contributions of the aviation industry to the climate change phenomenon and environmental pollution has prompted ongoing efforts to increase the energy efficiency of aircraft for the reduction of emissions.

With the target of 50% reduced aviation emissions by 2050, the International Civil Aviation Organization has invoked widespread technology development in more efficient aircraft systems. One of the most effective methods of increasing the energy efficiency of aircraft is through mass reduction techniques. For example, reducing the mass of a Boeing 787 by 20% would improve the fuel efficiency by between 10% and 12% all while improving the acceleration and other performance characteristics [115].

Additive manufacturing techniques have been shown to help reduce cost and lead times and also for reducing the mass of components aboard spacecraft and aircraft. Many popular publicized examples of AM applications in aerospace boast mass reductions, among many other benefits. While this is an attribute that holds much promise, lightweighting is currently still not the primary driver for AM in aerospace. Lead time reduction is currently the main benefit, which can be significant for complex aerospace components often taking months or years of (traditional) fabrication time for complex systems. For example, the manufacturing freedoms offered by using AM techniques to manufacture the A320 nacelle hinge bracket, shown in Fig. 2, enabled the TO design to reduce the CO_2 emission for the entire operational lifecycle of the nacelle hinges by 40% utilizing the mass reduction benefits of AM and TO [116]. The optimized design achieved a mass reduction of 64% from the original component, although the use of Ti-6Al-4V instead of the original HC101 steel accounts for about half of this mass advantage [116].

Rotational components in aircraft and launch vehicle rocket engines also benefit highly from the application of lightweighting. While the reduction in mass of these components decreases the overall mass of aircraft and spacecraft, they have the added benefit of reducing rotational inertia which improves performance characteristics such as starting torque reduction, braking torque reduction and a lower interaction moment between the rotational components and the axle structures [118].

As demonstrated in [119], the potential for lightweighting of structural components, rapid prototyping in the design chain and complex designs of instrumentation hardware are all compelling applications for AM in the space industry. With more recent improvements in AM technology, new manufacturing opportunities have arisen for even the most technically demanding components. The technology synergises with space applications serving low quantities of components that exhibit mass and cost reductions crucial for increased development in space. With mission costs for space exploration exceeding €20,000 per kilogram, every gram saved translates to an increased payload capacity per launch and a consequent reduction in launch costs [120].

Besides lightweighting, part consolidation is another prominent benefit for the application of AM techniques in aerospace applications with nearly every example displaying massive reductions in part counts. Part consolidation, the act of consolidating multiple components into one piece without assembly operations, has widespread benefits across all industries where it is applied. For example, the Ariane 6 rocket injector head built through AM techniques achieved a part consolidation count of 248 individual components manufactured as a single component compared to traditional manufacturing methods all while reducing the mass of the injector head [121]. NASA has also demonstrated multiple applications of AM to rocket engine injectors since 2013 that significantly reduce part count and lead time [62]. One such example demonstrates a reduction from 115 parts to 2 parts and tested at full operational conditions with high performance equivalent to traditional manufacturing [122,123].

Part consolidation has the primary benefits of reducing the assembly operations and minimizing the usage of joining methods such as bolting, welding, brazing, soldering and chemical bonding methods [124]. Minimizing the use of these manufacturing methods in the production process drastically decreases the need for skilled labour throughout resulting in cost reductions [125]. The tooling necessary to manufacture components through traditional manufacturing methods is also reduced by using part consolidation through AM techniques. Another advantage is the reduced number of components requiring certification and associated documentation. Risk mitigation is inherent in component consolidation as fewer joins and fewer processes are involved in the manufacturing process. The certification process is still a strict requirement though with AM and is being evolved across various organizations.

Tooling for traditional manufacturing techniques typically induces long lead times for manufacturing components and adds significant costs to the production process. AM techniques notably reduce the need for tooling to manufacture components. This has the benefit of improving lead times for manufactured components since tooling lines often take months, if not years, to set up. An example of this is the Pratt & Whitney stator blades which claim a lead time reduction of 15 months when compared to traditional manufacturing methods all while reducing the mass of the blades by 50% [126]. The design flexibility of AM machines also allows engineers to potentially manufacture multiple components on a single machine, sometimes in the same build process. This enables the tooling and assembly requirements to be reduced even further since multiple, already part consolidated components can be manufactured on a single machine. An example of a stator from a NASA liquid oxygen (LOX) turbopump can be seen in Fig. 3, from [127].

Another benefit to part consolidation is the reduced need for warehousing for components and legacy components, including components no longer available. Reducing part counts through part consolidation directly reduces the need for large storage facilities and cataloguing of components. Furthermore, manufacturing and storing legacy stock components for future use is all but eliminated since AM machines can produce components from a digital catalogue when they are needed. This is especially useful for unpredictable maintenance related components and legacy components that can be manufactured on demand, thereby eliminating the need for stagnant production lines [128].

Heat transfer device applications have a strong potential to disrupt traditional aerospace manufacturing processes by using AM techniques, due to complex designs and internal features required. Manufacturing these devices through AM allows for vast improvements in part count reduction, lead time reduction, lightweighting and cost reduction. For example, the GE9X heat exchanger boasts a

Fig. 2. TO and AM of Airbus A320 nacelle hinge bracket. Left: TO design process. Right: Original bracket (top) and final TO optimized design (bottom) [116,117]. Original steel bracket = 918 g; TO and AM bracket in Ti6Al4V = 326 g. Copyright: Airbus.

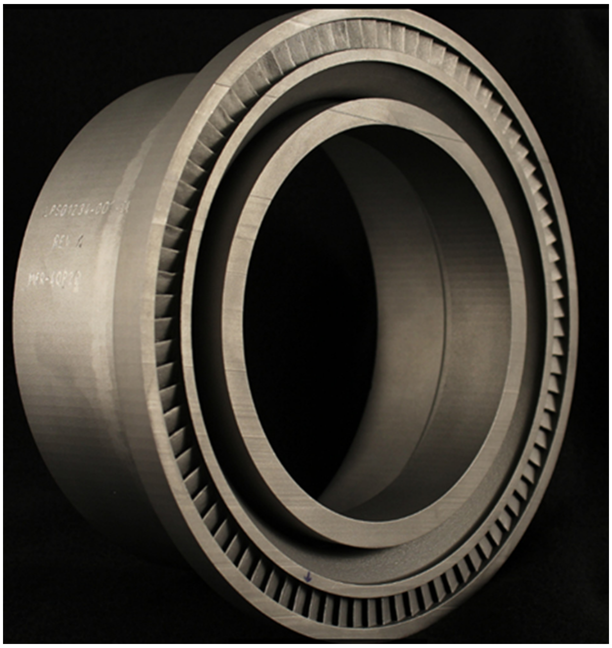


Fig. 3. Additive Manufacturing Demonstrator Engine Liquid Oxygen (LOX) Turbopump Stator. Courtesy: NASA [127].

40% mass reduction, 25% cost reduction all while consolidating 163 components into a single part using AM techniques compared to traditional manufacturing methods [129]. Manufacturing heat transfer devices using AM also has performance benefits when compared to traditional manufacturing methods. As shown by Saltzman et al [130], replicating a traditionally manufactured aircraft oil cooler using AM techniques improved the heat transfer performance by up to 15% due to the improved design with larger surface area. Integrating heat transfer devices into structures and other components also benefits from the use of AM techniques. As shown in [131], the incorporation of a thermal anti-ice system into the structure of the leading edge of aircraft aerofoils has the potential to improve the performance of anti-ice systems. Advanced complex high-performance components and structures also see beneficial applications in aerospace using AM. The manufacturing demonstrator AM rocket engine design by Cellcore, shown in Fig. 4, demonstrates the ability to produce a complex thrust chamber assembly in IN718 with integrated lattice internal cooling channels [13,132].

NASA has established significant use of AM for heat exchangers, such as liquid rocket engine combustion chambers and channel-cooled nozzles. Various applications have been reported including combustion chambers using copper-alloys such as GRCop-42, GRCop-42, C18150, and also Inconel 718 and Bimetallic Copper-Superalloy structures that have accumulated over 30,000 s and 400 starts of hot-fire time. Channel-cooled nozzles in various alloys including JBK-75, NASA HR-1, Inconel 625, Haynes 230, and bimetallic (Copper-Superalloy) structures have also been demonstrated by NASA and accumulated over 11,000 s and 250+ hot-fire tests [133]. While these combustion chambers and nozzles meet performance requirements, they also demonstrated significant cost and schedule savings for hardware delivery [134]. An example of combustion chambers and nozzles for liquid rocket engines can be seen in Fig. 5 [135–137].

Repairing high-value aerospace components using AM techniques also presents a major benefit to AM applications in aerospace. The high-performance components present in aerospace applications such as impellers, turbine blades and airfoils are typically expensive due to the use of high-value materials such as Inconel and Titanium alloys. These components are often subject to harsh environments such as corrosive environments, impact events, thermal cycles and high stresses which all contribute to reduced service life [138]. Traditionally these components were repaired through welding processes which impart residual stress formation and geometric distortion in the repaired components [139,140]. Using AM techniques to repair aerospace components has the benefits of inducing a lower heat input during the repair process compared to the traditional repair techniques and can meet all structural design margins and operational conditions when applied properly [141].

Hybrid manufacturing, i.e. combining AM with traditional manufacturing methods is widely used in different permutations. One good example is demonstrated in the AGENT-3D_IMProVe project, where the Fraunhofer IWS team and project partner MTU Aero Engines have developed a hybrid process chain using DED with wire filler material and conventional machining. The project focuses on saving semi-finished product costs by reducing both material quantities and machining times in order to cut tool costs. This was achieved by way of precise AM using DED on the conventionally produced substrate body. The project partners used a nickel-based alloy (Inconel 718) as a wire filler material. Several other examples have been provided across aerospace including bimetallic structures reported by Virgin Orbit and NASA to form combustion chambers [142].

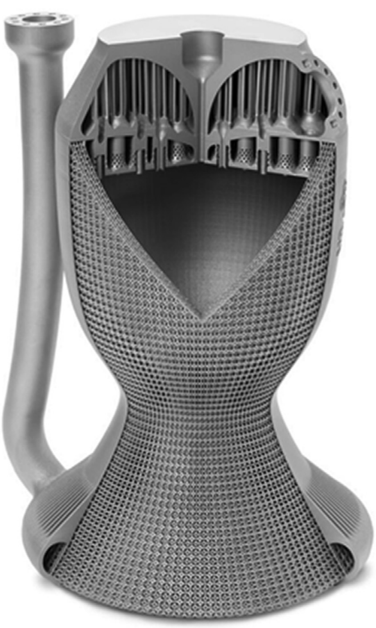


Fig. 4. Cellcore prototype rocket nozzle featuring internal cooling channels. Copyright: ©SLM Solutions/ CellCore [13].

3. Distinct applications of AM in aerospace

3.1. Structures and brackets

Complex designs for AM of load bearing structures and brackets are often unconventional, seemingly organic geometries with exceptional strength to mass ratio characteristics. While these can be applied successfully, a thorough understanding of full load paths and environments must be well understood to take full

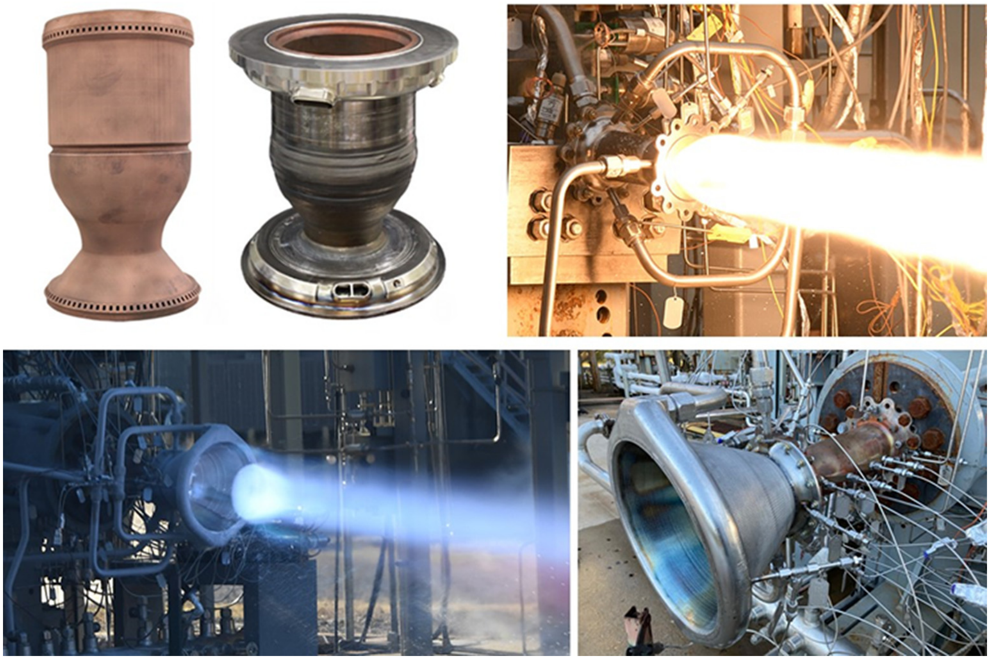


Fig. 5. Examples of fully AM thrust chamber assemblies hot-fire tested at NASA MSFC including injectors, combustion chambers, and channel-cooled nozzles, including L-PBF GRCop-84, L-PBF GRCop-42, bimetallic L-PBF and DED, and LP-DED NASA HR-1. (Courtesy: NASA) [135–137]

advantage of the technology. Metal AM enables the manufacture of components of complex design within the build limits of the AM technology being used, in a variety of materials and with different design methodologies [143]. Brackets, structures, and frames are common examples of applications for AM and TO in aerospace. The production of organic lightweight structures was previously performed by conventional manufacturing methods with serious manufacturing constraints such as casting directions, symmetry, size, and tool path limits. Compared to typical manufacturing techniques, AM allows higher design complexities which can be utilized fully through TO to further reduce the mass of components in aerospace applications [115,144].

3.1.1. Aviation structures and brackets

The recent growth of metal AM and TO methods gave rise to a host of new projects to potentially reduce the mass of components by using TO together with AM without applying typical manufacturing constraints. The synergy of TO and AM techniques saw great success throughout many aerospace application areas in recent years [115,144]. One of the first examples of a structural, TO, AM component being used for the interior on a commercial aircraft is the A350 cabin bracket connector. Airbus utilized TO and AM to produce the bracket, as shown in Fig. 6, from Ti-6Al-4V using L-PBF in 2014 [10,145,146].

A Norwegian company Norsk Titanium, in 2017, was the first company to receive approval from the FAA to manufacture AM components, using DED techniques, that would experience in-flight stress loads [147]. These components, manufactured from Ti-6Al-4V, were the first structural AM components present on the Boeing 787 Dreamliner. Later in 2017, Airbus began production and installation of a titanium critical support bracket to be used on the A350 XWB. The component, manufactured via AM techniques, is part of the aircraft pylon, the junction between the wings and the engine [148].

A joint study between EOS and Airbus Group Innovations was carried out on the Airbus A320 nacelle hinge bracket shown in Fig. 2 [116]. The component, to be manufactured from Ti-6Al-4V using L-PBF techniques, is intended to replace the current hinge brackets on the engine inspection nacelles with the goal of mass and cost reduction over current designs [116]. This study showed that compared to a conventional casting process, using L-PBF based AM techniques produced distinct advantages in mass reduction [117].

Fig. 6. TO and AM of Airbus A350 XWB cabin bracket connector [10,145,146], by L-PBF of Ti6Al4V. Copyright Airbus.

Mass reduction techniques have seen widespread adoption in the aerospace industry due to their inherent performance benefits. TO can be used as a powerful design tool for large scale structural components of aircraft for overall shape and mass optimization, when the appropriate environmental and combined loads are known. An early and popular application of TO is seen in the design of the A380 Droop Nose Ribs. Airbus UK, in partnership with Altair Engineering, used compliance-based TO intending to provide more stability to the existing Droop Nose Rib designs which resulted in a shear-web and truss design [117].

Recent applications of TO adaptation have allowed for shape preservation under given inputs which allow designers to optimize both for mass and, for example, warping deformation [115,144]. A good example of this is the cockpit windshield design. While the front fuselage of an aircraft has much potential for TO for mass reduction, damaging effects from bird strikes and extreme weather conditions need to be mitigated [117]. A study was performed which maintained warping deformation of the windshield to avoid cracking by constraining the windshield local strain energies [117,144]. The TO design with shape preservation dissipates the strain energies on critical loading from the elements surrounding the windshield [117,144]. The biggest challenges in incorporating TO into the design and manufacturing workflow for aerospace are the lack of well-defined inputs for loads and constraints, and the increased uncertainty in manufacturing quality for increasing complexity components – an area that will see much future development before AM techniques are used more routinely in aerospace applications.

3.1.2. Spacecraft structures

The space industry commonly refers to economic activities related to orbital launch vehicles, manufactured components that go into Earth's orbit and beyond and other related services [149]. The space industry has often been reliant on new, advanced technologies to continue to push exploration and new missions. As discussed in [119], early applications using AM showed potential advantages in design and manufacturing for space applications. The first AM spacecraft structures were launched on the Juno mission to Jupiter in 2011. The components, a set of eight brackets, were used to attach the waveguide, which is used to transmit radio frequency signals between components [150]. Since then, AM technology continued to mature and confidence in metal AM throughout the aerospace industry increased significantly resulting in AM taking a larger role in the manufacturing of components for launch vehicles and satellites [150,151]. The Sentinel satellites, a series of earth observation missions from the European Space Agency (ESA), set out to develop AM solutions for the latest editions of the mission, the Sentinel-1C and Sentinel-1D [139,140]. The Sentinel-1A and Sentinel-1B, launched in 2014 and 2016 respectively, both utilized conventional manufacturing techniques which allowed a set of new brackets, developed by RUAG and Altair, produced using AM techniques to be compared to the traditional design. Working together with EOS and Altair, RUAG designed and produced an optimized version of an existing Antenna bracket shown in Fig. 7 [139,140].

RUAG in collaboration with Altair then went on to design and produce a star tracker camera bracket using TO and AM techniques. The precursor bracket, manufactured using typical subtractive methods, saw mass reduction advantages using TO and AM on the updated design. The bracket was manufactured in an EOS M290 L-PBF machine from AlSi10Mg. The bracket, in its testing configuration shown in Fig. 8, underwent various testing procedures such as Computed Tomography (CT) scans, geometric analysis, tensile, microscopy and structural response testing [10].

The manufacturing of mirror components for satellite applications often push limits on several length scales. Besides the optical or sensor devices, the corresponding supporting structures are affected by high technical requirements as well. At the ESA L class ATHENA (Advanced Telescope for High ENergy Astrophysics) mission, Silicon Pore Optics (SPO) need to be aligned and carried by a supporting structure with a diameter of several meters. AM has been used at Fraunhofer IWS to print those supporting structures which require high process flexibility and scalability. Tailored processes and technologies are indispensable for overcoming the accompanied manufacturing restraints. A hybrid AM process has been developed in a cooperation between Fraunhofer IWS, ESA and Airbus merging the high flexibility of Laser Metal Deposition (LMD), another name for LP-DED, with the precision of cryogenic machining for the manufacturing of large volume titanium components. So far a demonstrator of 1.5 m in diameter has been manufactured to demonstrate the feasibility of the whole process chain for this application, shown in Fig. 9 [12].

3.1.3. Lattice structures

Recently, lattice structures have gained widespread interest from engineers and scientists for their multi-faceted design advantages [152]. Over the past decade, TO has seen commendation among designers to optimize patterns of both *meso*-structures and macro-structures, and sometimes including novel cellular (or lattice) structures (CSs) [153]. While lattice designs previously saw use in rectangular forms in heat exchangers and filter elements, it is now possible, using computational algorithms such as TO, to design far more complex structures and internal geometries using open-pored cellular / lattice structures [154]. While there is a lot of potential for these structures, they have numerous design and manufacturing constraints that need attention, limiting their application so far, this is discussed in depth in [108].

CubeSats are types of miniaturized satellites designed to be manufactured and deployed in a modular system which allows for increased accessibility to space for small satellite manufacturers. These satellites are designed to be both lightweight and small enough to be carried as secondary payloads by satellite launch providers. Mass reduction of CubeSat structures presents the opportunity to increase the number of small satellites per payload and reduces the costs of launching these satellites to orbit. nTopology, in collaboration with the U.S. Air Force Institute of Technology (AFIT), completed a case study on the application of AM and lattice techniques for CubeSat bus structures. Built from Inconel 718 on a L-PBF machine, the structure has the goals of reducing mass, part count, lead times and increasing stiffness. The structure, shown in Fig. 10, achieved a mass reduction of 50% and consolidated 150 components to less than 25 components which results in 6 times less possible failure locations [155].

Thales Alenia Space, in collaboration with the European Space Agency (ESA), also used the combinations of AM, TO and lattice structure techniques to develop a solar panel deployment mechanism. The mechanism, intended for a satellite solar panel deployment application, uses TO to reduce the mass of the supporting structure and then further reduces the mass by lattice insertion techniques [156]. The structure, shown in Fig. 11a, reduced the mass of the design by a factor of 5, the costs by a factor of 4, and reduced the total component count by 10 through part consolida-

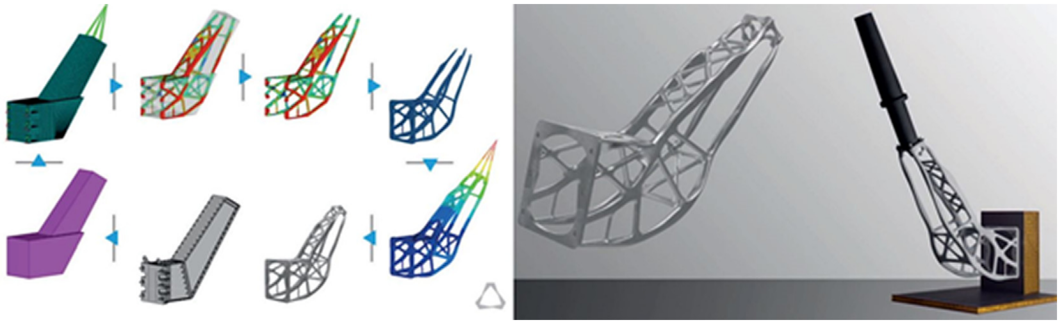


Fig. 7. TO process of an antenna bracket for the Sentinel-1C and Sentinel-1D. Photo courtesy of Altair Engineering [140].

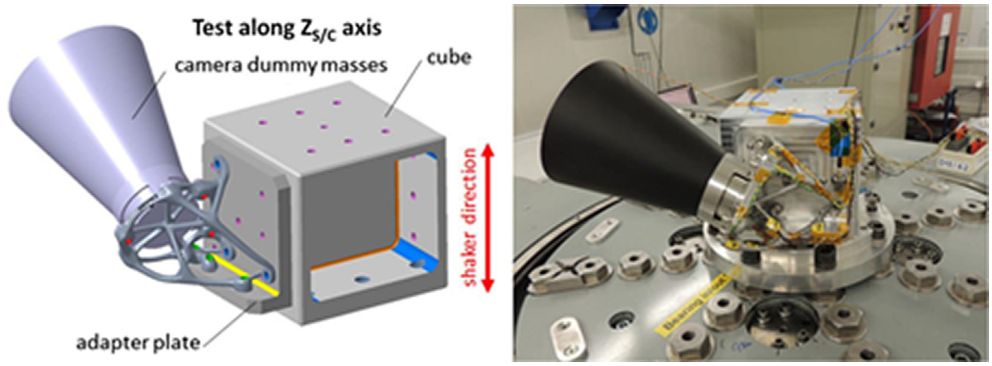


Fig. 8. Test configuration of the bracket with adaptor plate and dummy masses. Copyright: The American Institute of Aeronautics and Astronautics (AIAA), Inc. [10].

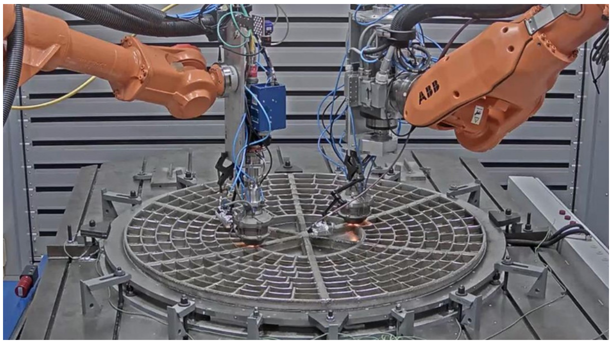


Fig. 9. Example of 1.5 m mirror support being manufactured as technology demonstrator (image courtesy of Fraunhofer and European Space Agency)[12].

Fig. 10. nTopology and AFIT lattice CubeSat bus structure. Credit: nTopology [155].

tion [156]. Another example of lattice use, in this case for thermal application, is shown in Fig. 11b.

A collaborative project by Airbus, APWorks and Autodesk was created with the task of reducing the mass of a partition wall of the A320 series of aircraft. The Bionic Partition Project sought out to utilize modern manufacturing techniques such as AM, TO and lattice optimization to improve the partition design over existing designs. The new partition used generative design similar to TO to formulate an initial strut structure with the objectives of reducing mass while maintaining maximum displacement constraints [158]. Further mass optimization was then applied by converting the initial TO geometry to lattice beams, resulting in further mass reduction [159].

Combinations of conventional manufacturing and AM techniques present an interesting opportunity to reduce the impact of imperfect parameterization currently in metal AM solutions. Autodesk used both AM techniques and conventional metal casting processes to produce a lightweight frame design for aircraft seats. Using Autodesk's Netfabb software package, the geometry for an aircraft seat was produced using lattice and surface optimization, algorithms similar to TO techniques. These technologies were combined, producing positive molds for the seat frames containing complex lattice geometry, printed in plastic to reduce costs and time, and used to create ceramic casting molds in a similar method to the "lost wax" process. Finally, the frame was cast in magnesium allowing for the vast production quantities necessary for aircraft seat manufacture [160,161].

An obvious but less widely reported application of cellular lattice structures in metal AM is for internal fill geometries of components. TO techniques for AM applications can be further improved by shelling components to further reduce the mass, but this presents the challenges of internal voids which require internal support structures for any overhanging sections and can trap unprocessed powder increasing mass [108,112]. This challenge is often solved by using internal lattice geometry in printed components which replaces internal support structures with functional cellular lattice structures with load-bearing capabilities [162]. However, these internal lattices often do not eliminate all the unprocessed powder and holes need to be placed in a design to release this powder. Fig. 12 demonstrates the applications of using an internal lattice fill to reduce internal mass. The branches of internal macro lattice designs are usually designed such that their angles did not exceed the minimum build angle of 45° common to metal AM machines [118]. Such mass reductions on impeller components reduces the rotational inertia and increases the performance.

3.2. Static and dynamic engine components

The static and rotational components present in both aircraft and spacecraft rocket engines are subject to both extreme performance requirements and harsh environments such as elevated pressures, temperatures, and corrosive or embrittlement conditions. These performance requirements often lead to highly complex part geometries and special materials being used. Since components such as compressor blades, turbine blades, inducers and impellers have highly complex geometries, AM techniques

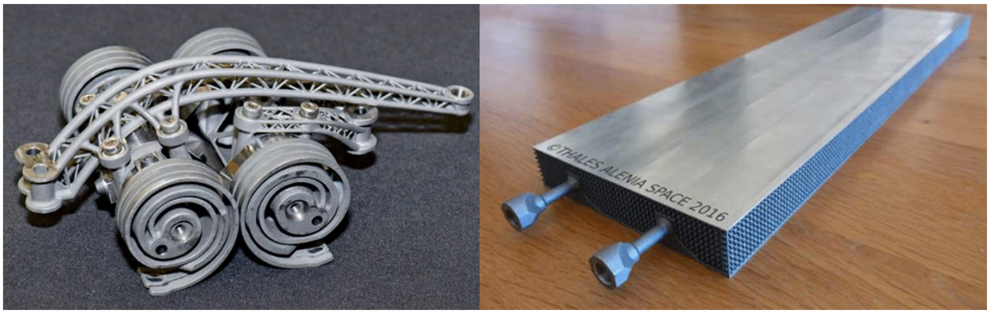


Fig. 11. Thales Alenia Space examples including AM lattice structure usage: (a) satellite solar panel deployment mechanism – "Adel'light hinges for solar arrays of satellites" and (b) satellite sandwich panel "Diphasic heat spreader". Courtesy of Thales Alenia Space [156,157].

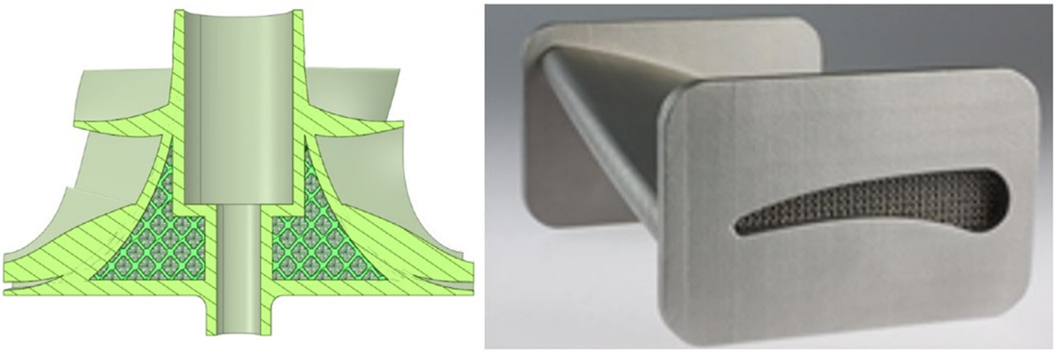


Fig. 12. AM built impeller with internal lattice – design concept from [118] and a similar manufactured physical part with internal lattice from a different study [Courtesy: SLM Solutions].

can be used to increase their performance [16]. As complexity increases, traditional manufacturing techniques are limited by their constraints and part complexity is effectively restricted. However, AM technology enables more designer freedom from geometric constraints commonly found using traditional manufacturing techniques allowing for more intricate final components [138,97]. There are limitations of the AM process though in producing some of these geometries in build angles and also rougher surfaces than traditional machining. Typical build angle constraints limit overhangs to maximum 45° relative to the vertical, with variation of surface roughness depending on the overhang angle. Down-facing surfaces often have rougher surfaces with excess material and irregular surface morphology. The build angle change affects the local thermal history as underlying powder (in powder bed fusion) does not conduct heat away, leading to higher temperatures in these regions. The inclusion of support structures may alleviate this and reduce the possibility for residual stress and warping, but this requires post process support removal and this may be difficult in complex components. These and other limitations are being solved incrementally by various researchers and manufacturers, to improve the quality of metal AM components to remove some design constraints.

An early case study in this domain was reported by Allison et al in 2014 [163] showing the potential for AM applications on turbomachinery components such as an impeller. The impeller, manufactured from Inconel 718 using AM techniques, demonstrated promising results functioning as predicted during testing. Interestingly, during testing, the impeller test rig consisted of multiple other components manufactured through AM techniques. Both the inlet guide vane assembly and the aluminium volutes were manufactured using SLS with Duraform HST and 3D-printed sand casting molds respectively.

General Electric's next-generation GE9X engine, which made its maiden flight in January 2020 aboard the new Boeing 777X, is the largest and most powerful commercial jet engine ever produced [164]. The GE9X, a high-bypass turbofan engine, features a large number of additively manufactured components integrated directly into the core structure of the engine. Notably, 228 low-pressure turbine blades are manufactured from TiAl using EB-PBF manufacturing techniques for each engine with the express goal of mass reduction [129].

A case study by Siemens highlights the manufacturability of turbomachinery by the means of AM. Siemens, after initial investments in AM in 2009, installed their first AM components in gas turbines in 2013, began to work on hot gas path blades which were successfully printed and installed in 2017. They then went on to assess the viability of commercial applications of closed radial impeller wheels for turbo-compressors using AM techniques such as L-PBF and EB-PBF. Depending on successful testing and regulatory approval, the radial impeller wheels show promising results to improve the efficiency of turbomachinery [165]. While these are not directly aerospace examples, they are a good indication of the potential and capability for high performance components.

Engine maker Pratt & Whitney has produced more than 100,000 prototype components using AM over the last 25 years and currently produces compressor stator blades and ring synch brackets for the PW1500G engines which are part of the Bombardier C Series aircraft. These stator blades are used to guide airflow through the compressor of aircraft engines [126].

While still in their infancy, lattice structures are gaining interest into turbomachinery components to increase performance. A recent study done by [118] demonstrates the application of internal lattice structures on compressor impellers to reduce the mass and moment of inertia. Manufactured using AM with Ti-6Al-4V, the internal lattice impeller design attempts to both improve the performance of the impeller, and the AM manufacturing process by reducing residual stress build up in the printing process.

Large modern aircraft engines typically consist of tens of thousands of components and, while not all components are feasible to manufacture through AM techniques, many components besides the core turbine and compressor blades can be reasonable applications for AM. Honeywell Aerospace completed a study into various turbomachinery components for applications in their HTF7000 series of aircraft engines. The study details not only high-pressure turbine applications for AM but also designs for a tangential on-board injector, a second stage high-pressure turbine nozzle, an atomizer shroud, an inlet booster rake, and an engine mount. This demonstrates that a large quantity of aircraft engine components have the potential to be manufactured using AM [166].

Probably the most well-known AM component application in aerospace is the General Electric LEAP engine fuel nozzle. Beginning production in 2015, over 30 000 nozzles were produced by the year 2018 and it is still in production [167]. Utilizing L-PBF with a Cobalt-Chrome alloy, the fuel nozzle, shown in Fig. 13, is installed on multiple engines currently in service on commercial aircraft.

After the success of the LEAP engine fuel nozzle, GE then went on to produce a myriad of AM components for the new GE9X engine series [129]. The GE9X engine boasts 304 additively manufactured components across seven multi-part assemblies resulting in over one-third of the components on the GE9X series engines being produced using AM techniques. The engine will feature 28 of the LEAP engine fuel nozzles, 228 low-pressure turbine blades, a T25 sensor housing, a combustion mixer, 8 cyclonic inducers and a heat exchanger all manufactured using AM. All these components, except for the LPT blades and the heat exchanger, are manufactured from a Cobalt-Chrome (Co-Cr) alloy using L-PBF processes.

DED is being used to fabricate overhanging large scale metal structures. These structures can be built through multi-axis orientation systems that orientate the constructed component so that layers are always built with no overhangs. A five-axis DED system produced by The Welding Institute (TWI) is used in the production of an Inconel 718 helicopter engine combustion chamber with effective overhang angle constraints of close to 90° [97,168].

Additive manufacturing techniques have been extensively applied to repair existing components [97]. Damaged components can be repaired using AM instead of replacing and scrapping them, this can result in significant cost savings for expensive components commonly found in aerospace applications, not only for saving on the cost of new components but also on the requirements for spare components inventories and new part manufacturing lead time savings [169]. This is also relevant to legacy and aging aircraft for which components might not be available at all. Further studies have shown that restoration through AM has, compared to traditional methods, a substantially lower environmental footprint [170]. Restoring the structural integrity of integrally bladed rotors, also known as Blisks, provides cost-effectiveness since these components can cost tens or even hundreds of thousands of dollars to manufacture. The T700 Blisk, made from AM355 steel suffers from erosion on its leading edge. This led to a case study by Optomec which utilized Stellite® 21, an erosion-resistant cobalt-based material to repair the leading edge. Passing spin and low-cycle fatigue tests, the repaired blisk showed positive metallurgical, tensile and erosion qualities enabling its certification [171]. Fig. 14 shows the repair process using LENS AM (LENS is a DED process) where (A) shows the LENS system repair process, (B) shows the T700 blisk after leading-edge repair and (C) shows the repaired blisk after finishing [171,172].

Fig. 13. The GE LEAP Fuel Nozzle. Courtesy of GE Additive [167].

The ability to produce impeller and airfoil components through the use of DED processes with high-quality mechanical properties compared to typical manufacturing techniques was demonstrated in [173]. They illustrate the ability of DED to repair turbine blades and a fuel nozzle swirler using Inconel-718, which is usually a difficult material to deposit using typical welding processes or laser deposition processes without causing cracks [173].

Complex turbomachinery has been demonstrated in various applications by NASA [174–177]. Impellers, pump volutes, turbine blisks, turbine stators, turbine exit guide vanes, and the turbine nozzle have all been demonstrated for an AM liquid rocket engine within a liquid hydrogen fuel (LH_2) and liquid oxidizer (LOX) turbopumps (see Fig. 15). The liquid hydrogen fuel turbopump was successfully manufactured with 45 percent fewer parts than traditional manufacturing and completed spin and engine testing operating at more than 90,000 revolutions per minute. A LOX pump demonstrated the use of AM within relevant test environments as well. It was noted that process improvements were required for these AM components include surface finishing, material properties, application of support structures during build, and dimensional tolerances [178].

3.3. Thermal devices

Advanced heat transfer devices manufactured employing AM techniques have strong potential to reduce manufacturing time and improve the performance characteristics of heat exchangers (HXs), heat sinks (HSs) and heat pipes (HPs) mainly when used to manufacture complex free-form internal geometries [179]. In particular, HXs are crucial for components in aerospace applications such as the performance of aircraft and spacecraft engines, while HSs are typically used in crucial electronic applications present on both aircraft electronics and spacecraft electronics. Conventional manufacturing techniques for HXs and HSs typically include brazing techniques and CNC milling techniques respectively [180]. While brazing is an effective manufacturing method for HXs, it typically consists of a high amount of time-consuming skilled labour work, high tolerances for achieving reasonable gaps in joining, and often expensive materials which increases the cost of components. Furthermore, HSs are limited by the complexity achievable through the use of CNC milling techniques. For these reasons, AM techniques are being used to improve the performance of HXs and HSs by increasing their complexity and providing flexibility for designers to improve the surface area to volume ratios, all while eliminating the brazing process. Moreover, brazing techniques are typically limited to the materials compatible with the process while AM allows for a wider variety of materials to be used on these devices, although new material developments are a significant growth opportunity for AM. Gobetz et al, performed a study to demonstrate the feasibility of using AM

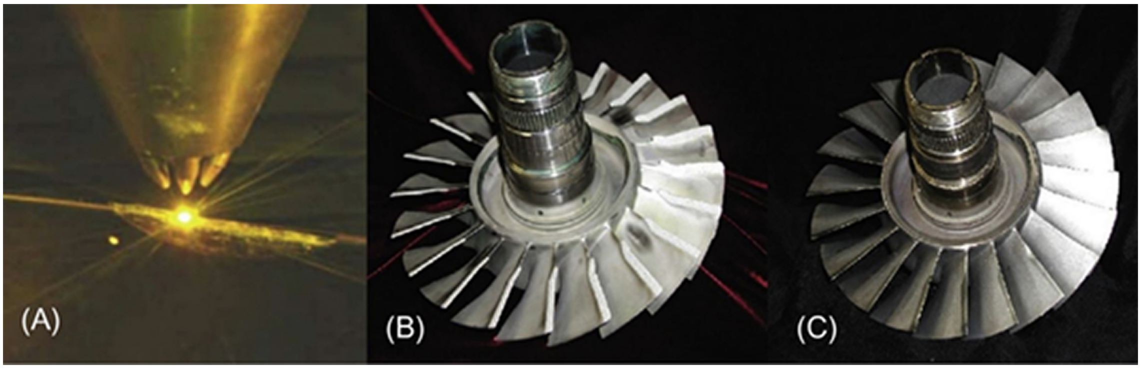


Fig. 14. Blisk repair solution using LENS AM. Photo Courtesy of Optomec [171].

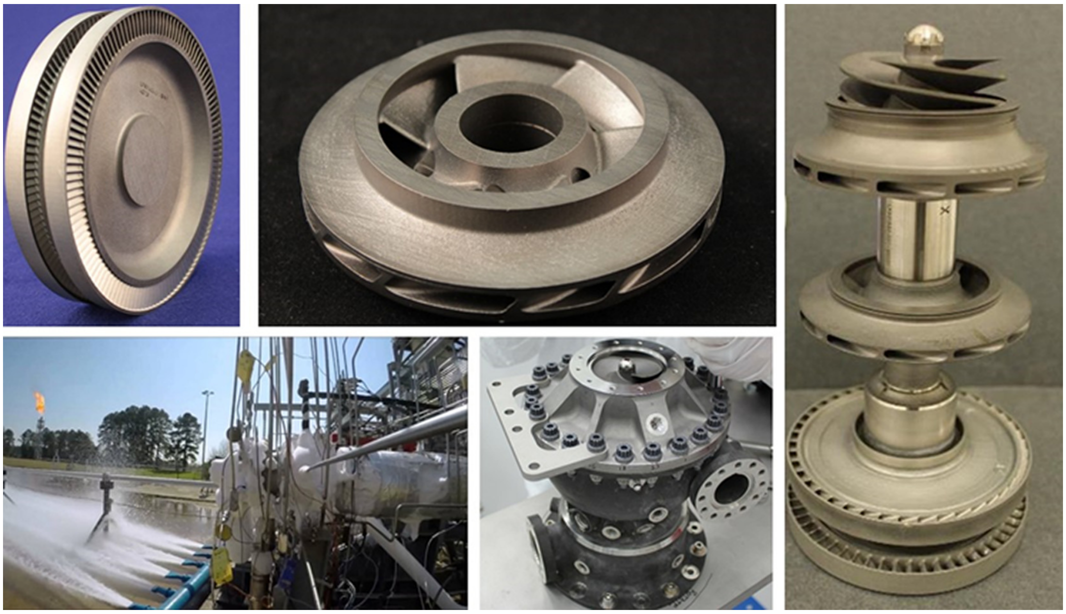


Fig. 15. Examples of AM used within liquid hydrogen and liquid oxygen turbopumps at NASA MSFC. (Courtesy: NASA) [127].

techniques in a heat exchanger for aerospace applications with the goals of more direct manufacturing as opposed to the traditional manufacturing and assembly techniques present in current applications of HXs. Built from Al-10Si-0.5 Mg on an EOS M280 L-PBF machine, the HX functioned effectively under an air-to-air testing setup after successful manufacturing [181].

A case study done by [130] highlights the ability for AM to be utilized on typical aircraft HX applications. The study compares the AM HX functionality relative to conventionally manufactured HX components with an example of an aircraft oil cooler. The component in question was manufactured as a direct copy of an existing conventionally manufactured HX. Using L-PBF techniques, the component was realized with AlSi10Mg. Although the AM manufacturing process produced some defects in the component, under testing the AM component performed significantly better than the baseline, conventionally manufactured component demonstrating the functionality of AM HX in realistic applications.

More notably, General Electric has incorporated an AM HX into their latest GE9X engine series currently in operation [129]. Manufactured from Aluminium alloy (F357) on an L-PBF machine, the HX functions as a vital component in the engine with the goals of reducing size, reducing mass, reducing costs, and improving durability.

NASA's latest mission to Mars saw the delivery of yet another rover to Martian soil. The rover, called Perseverance, has the task of finding signs of ancient life and to collect samples of regolith and rock for future return missions to Earth. The rover, which landed on Mars in February 2021, carries 11 components fabricated using metal AM techniques. Of these 11 components, 6 are AM built heat exchangers used in the Mars Oxygen In-Situ Resource Utilization Experiment, or MOXIE. These heat exchangers are exposed to the Martian atmosphere and have to withstand temperatures of over 800° Celsius for extended periods of time. This resulted in nickel-based superalloys being used for the heat exchanger structures which simplified and improved the capabilities of the MOXIE system compared to if they were built using conventional techniques. Besides the 6 heat exchangers, the Perseverance rover features 5 other AM built components on its Planetary Instrument for X-ray Lithochemistry, or PIXL. To reduce the mass of the PIXL, AM was used to fabricate a two-piece titanium shell, a mounting frame and two supporting struts which all resulted between 3 and 4 times less mass compared to components manufactured through traditional methods [182].

Since AM techniques provide an unprecedented amount of complexity in components compared to traditional manufacturing methods, often there are limitations on design capability to fully optimize devices such as HXs and HSs. Optimization tools are gaining traction for their application in HXs and HSs through the application of AM techniques in the form of thermal TO methods. A paper by de Bock et al [183] exhibits the potential performance of using hybrid analytical thermal TO (HAATO) on an HS application. While still in their infancy, these optimization techniques have the potential to drastically increase the performance of HSs and HXs by increasing their geometric complexity. Fig. 16 displays the incredible internal complexity of their AM HX designs intended for motorsport applications [184]. The highly complex structure is optimized for large surface area, enhancing the heat exchange. While this is not an aerospace example, the principles and advantages are the same for aerospace components.

Examples of internal cooling channels are present in cylinder blocks of internal combustion engines and internal cooling channels in high-pressure turbine blades in aircraft. These integrated systems are generally constrained by typical manufacturing techniques such as joining, brazing, casting, and CNC milling processes. AM techniques offer vastly more design complexity for these components for placement options for internal cooling channels and micro-lattice structures and related designs. Cobra Aero, a small UAV designer and manufacturer, sought out to improve their UAV engine using AM, optimization techniques and lattice structures with the goals of reducing mass and optimizing heat transfer characteristics [185]. Using AM, they produced a cylinder block leveraging multi-physics simulations which accounted for thermal, flow characteristics, stress and pressure factors resulting in an optimally designed cylinder block that was more thermally efficient than designs realised through conventional manufacturing methods (Fig. 17).

Thermal anti-ice is a widely used anti-ice system present on commercial aircraft that limits the ice build-up on the leading edges of aircraft airfoils. Bici et al [131] explored the application of lattice structures to a multi-functional panel intended for this application. The design focusses on a single piece airfoil, manufactured via AM techniques, with an internal lattice structure that distributes hot air to the leading edge of the airfoil to prevent ice build-up. Furthermore, the design mitigates structural stresses by using lattice structures to reduce the mass of the leading edge.

HiETA, an engineering company based in the United Kingdom, uses AM techniques such as L-PBF to produce a variety of products for the aerospace market with a particular focus on heat exchanging and cooling devices [186]. In particular, they produce an internally cooled radial turbine wheel and housing using AM techniques. The turbine wheel, manufactured from CM247 LC or Inconel alloys, features complex internal cooling channels that enable higher operating temperatures for turbine engine applications all while reducing the mass of components.

Fig. 16. Conflux sectioned F1 heat exchanger application. Picture Courtesy of Conflux Technology [184].

3.4. Liquid fuel rocket components

Space-based activities have seen rapid increases over the last two decades in the form of space exploration, scientific endeavours, communication satellites, earth-observation satellites, permanent human presence on the International Space Station (ISS) and many other missions. All this increased activity has been assisted by programs such as NASA's Artemis program and many private companies entering the orbital launch capabilities market [187–189]. With so much competition among launch providers, innovation has soared and advanced manufacturing techniques such as AM are widespread among space launch systems and satellites. Satellites, space stations and space launch systems boast the most expensive man-made objects in existence with the ISS costing $160 Billion alone and more sections are still being added [190]. The benefits of AM in cost reduction compared to conventional manufacturing methods has the potential to make space-based activities more accessible.

As launch systems provide the infrastructure to access space, the efficiency of these systems is vital to reducing costs for all space-based systems. At the core of these systems is the Liquid Fuel Rocket Engine which is widely used in most launch vehicle applications. This complexity is leveraged through the use of AM techniques in more modern rocket launch systems to increase the performance of the system. With unofficial reports suggesting the in-development SpaceX Raptor engine contains as much as 40% by-mass AM fabricated components [191], space launch systems are proving to be one of the primary applications for AM built components.

Injector systems on rocket engines typically consist of hundreds of individually manufactured components which are then brazed or welded into a single injector head [121]. These injector heads are generally time-consuming and expensive to manufacture through traditional manufacturing techniques. However, AM techniques can be employed to drastically reduce the cost and time needed to manufacture these injector components. Ariane 6, set to be launched in 2020, is the latest rocket in production by the Ariane Group and as part of their RAMS (Reliability, Availability, Maintainability and Safety) guidelines, they are looking for innovative manufacturing solutions. With an overall goal of 40–50% lower production costs over the Ariane 5, AM was employed throughout the project for increased cost efficiency and performance [121]. This injector core was produced with Inconel 718 on an EOS M 400–4 system utilizing 4-laser technology to rapidly decrease production time. The injector core is shown in Fig. 18.

Copenhagen Suborbitals, an entirely crowdfunded and non-profit space company, has been assessing the feasibility of utilizing AM components into their workflow to reduce costs [192]. Their latest AM case study, swirlers for a coaxial swirl injector, have been manufactured using Digital Metal's proprietary binder jetting metal AM technique. A project was completed by DLR, a German Aerospace Centre, also involving coaxial injector applications of AM in aerospace [193]. The project was based on a small satellite launch vehicle (SSLV) program with the aims of reducing costs to orbit for small satellite producers. After being manufactured using L-PBF techniques, the injector was tested successfully showing good performance characteristics and is set to pave the way for further development at DLR. NASA has also demonstrated and reported hundreds of successful injector hot fire tests in a variety of fuels for liquid rocket engine applications [62].

At NASA's Marshall Space Flight Center (MSFC) in Alabama, much research and development is being performed into AM applications for rocket engine components. NASA, in collaboration with Stratasys Direct Manufacturing, developed and tested an injector system using L-PBF AM techniques [194]. The injector, manufactured out of Inconel 625, allowed for unique flow characteristics

Fig. 17. Cobra Aero AM and lattice cylinder block design. Courtesy of Cobra AERO [185].

Fig. 18. Injector core for the Ariane 6 Rocket. Photo via Ariane Group/EOS [121].

only achievable through AM technologies. The MSFC then went on to manufacture and test a demonstrator rocket engine that was comprised of 75 percent AM built components [194]. NASA has since developed and tested a myriad of AM components since 2010 such as copper alloy (GRCop-42 and GRCop-84) combustion chambers, liquid hydrogen and liquid oxygen fuel pumps, maintenance port cover on J-2X and the pogo accumulator assembly with integral pogo z-baffle [195]. Some of these components are set to be installed on the upcoming RS-25 liquid rocket engines respectively under the Space Launch System (SLS).

Aerojet Rocketdyne, an American rocket and missile propulsion manufacturer, has also been evaluating applications of AM in their new line of rocket engines, the AR-1 series. Intended to replace the currently used Russian-made RD-180 engine, the AR-1 utilizes AM methods for its pre-burner. The pre-burner is manufactured from Mondaloy™, a proprietary burn resistant nickel-based superalloy which eliminates the need for elaborate metal coating processes currently in use on oxygen-rich engines such as the RD-180 [196]. This is not the first component Aerojet Rocketdyne has manufactured and tested using AM techniques. In 2017, the space company manufactured and tested a copper combustion chamber for their RL-10 rocket engine using AM and has developed significant qualification criteria for AM in space applications [197].

Arianne group recently manufactured and completed hot-fire testing of a full scale, demonstrator rocket engine with AM built components integrated. The engine featured a L-PBF built injector head and combustion chamber using the materials of a nickel-based alloy and stainless steel respectively [198]. As part of the Arianne 6 development program, these new AM built components are set to fly aboard the new variant of the Arianne rocket family in 2022.

Additive manufacturing applications are sometimes limited by the build area constraints of the L-PBF based machines which can only produce components as large as their maximum build volume (typically 300–600 mm cubed for single-laser commercial systems, although larger systems are in development). Built under conventional manufacturing conditions, rocket fuel tanks and aircraft fuselages are often built in several sections using thin-skinned supported structure designs called Isogrid [199]. The process of traditionally manufacturing these structures generates a lot of material waste in space structure applications since entire Isogrid designs are commonly machined, using milling techniques, from a thicker plate of stock material. This process results in extremely expensive components due to the high wastage of stock material and the long-lead plate stock material needed for larger rocket fuselages.

Since DED techniques are not limited by size, larger liquid fuel rocket components have recently seen development using DED. A specific application area is to use DED to manufacture entire fuel tanks, which typically also act as the structure for rockets. Using DED techniques, it may be possible to print entire rocket fuel tanks in a single piece or far fewer pieces with significantly less material wastage and much fewer tooling requirements which could significantly reduce the costs of these components. Lockheed Martin recently developed and tested a titanium dome for satellite fuel tanks built using EB-DED. The 1.16-meter diameter domes serve as caps for variable size fuel tanks aboard the LM 2100 satellite buses currently in production. Using these manufacturing techniques, Lockheed Martin is saving valuable production schedule time all while reducing material wastage significantly [200]. Relativity Space, an American aerospace company, plans to build their entire Terran 1 rocket using AM techniques from a proprietary alloy. Notably, the company plans to build the 2-meter diameter, dual-purpose fuel tank and fuselage using AW-DED, significantly reducing wasted materials and has demonstrated and ground tested pathfinder units [201]. With no theoretical limits to the height of components being produced using these methods, the component could potentially span the entire fuel tank section which is over 10 m tall.

SpaceX, after successfully developing and launching an AM built main oxidiser valve aboard their Falcon 9 rocket, went on to develop the SuperDraco engine series that is used in their Dragon V2 spacecraft [202]. The SuperDraco engines are used for the mission-critical launch escape system designed to carry astronauts to safety if an emergency occurs during the launch sequence of the Dragon spacecraft. Featuring an AM built engine chamber made of Inconel, the SuperDraco is one of the earliest applications of crucial AM built components aboard human-occupied spacecraft which has had two successful missions launching astronauts to the ISS on the Demo-2 and Crew-1 missions [203]. Fig. 19 shows the assembled Superdraco rocket engine and the engine on a testing stand in a hot-fire test.

Using AM techniques for manufacturing primary engine components has seen large-scale adoption at the California-based aerospace company, RocketLab. The company, a small satellite launch provider, has used AM technology to manufacture all of their primary rocket engine components aboard their Rutherford rocket engine since 2013. Aboard their Electron launch vehicle, the Rutherford rocket engine features a combustion chamber, injector, pumps, and main propellant valves among other components all manufactured using EB-PBF techniques and has been tested, manufactured, and launched on 18 missions to date [206].

Usually built using multiple materials and thousands of components, the combustion chamber, nozzle, and injector assemblies have garnered much interest recently for AM applications of single-piece manufacturing. An example of AM techniques being used for single-piece manufacturing is the Aeon 1 rocket engine built by Relativity Space. The Aeon 1 engine, to be launched on the upcoming Terran 1 launch vehicle, features its injector, ignitor, combustion chamber and nozzle all manufactured as a single component using AM techniques [207]. Another company, the New York-based Launcher Inc., plans to build the highest performance rocket engine in the small satellite launcher class using predominantly AM built components. Their rocket engine, the E-2, will be the largest single part combustion chamber, injector and nozzle assembly all built using L-PBF techniques from a C18150 (Cu-Cr-Zr) alloy [208].

More recently, NASA has been developing new materials and application areas for AM for liquid fuel rocket engine components using a variety of AM methods. Prominent examples of this are development under NASA's Rapid Analysis and Manufacturing Propulsion (RAMPT) project and Space Launch System (SLS) projects evaluating new materials, GRCop-42 and NASA HR-1 developed at NASA's Glenn Research Center (GRC) and NASA MSFC, respectively. These materials, namely the GRCop-series of copper-chrome-niobium alloys and iron-nickel NASA HR-1 superalloy, were developed primarily for rocket combustion chamber and nozzle applications using AM. A 7k-lbf coupled-design features a GRCop-42 (Cu-4 at.% Cr-2 at.% Nb) L-PBF built combustion chamber with integral channels and a NASA HR-1 LP-DED integrated nozzle built directly onto the chamber to eliminate the manifold and joint. Combining these AM techniques and materials allows for tailored material characteristics in the combustion chamber, nozzle, and integrated cooling channels which could improve the performance and reduce mass of rocket engines substantially while using AM techniques. The 40k, shown in Fig. 20c, is built using a L-PBF GRCop-42 combustion chamber liner and a DED HR-1 jacket [209].

NASA has also demonstrated many applications of large scale DED, specifically LP-DED. The focus at NASA has been rocket engine components, such as large scale channel wall nozzles and powerhead components. The nozzle has design similarities to combustion chambers with fine feature channels being incorporated to eliminate braze joints and extensive tooling often involved during assembly. NASA MSFC along with industry partners recently demonstrated a 65% scale RS-25 engine integral channel LP-DED nozzle at 1.52 m in diameter and 1.78 m in height [210]. Prior nozzles were also demonstrated with LP-DED integral channel features at smaller scales and several completed hot-fire testing with high duty cycles [47,211]. The nozzles demonstrate the potential to reduce part counts of the traditionally built nozzles from over 1100 components to fewer than 10 components on full-scale designs [212]. Other components have been demonstrated using LP-DED including various large scale manifolds and complex components such as the RS-25 powerhead half shells. Many of these components were typically fabricated using forgings or castings with extensive machining operations and have shown significant cost and schedule savings with short deposition times using DED. Examples of these components can be seen in Fig. 21.

Recently, there have been investigations in the use of AM and lattice structures in rocket nozzle components. Thrust chamber assemblies see various integrated mechanical, thermal, and integrated environments loads which presents difficulties in optimization. A collaboration between Cellcore and SLM Solutions produced an integrated thrust chamber design utilizing L-PBF to show potential applications in the aerospace industry [13]. The thrust chamber, as seen in Fig. 4, features a structural lattice in its walls which has a second purpose as the cooling jacket for the engine. The one-piece engine is manufactured in just over three days on an SLM 280 printer. The design uses Inconel 718, a particularly difficult to machine material, and features very little post-processing avoiding costly tool wear, saving considerable costs while producing an extremely lightweight structure. The design also features a fully integrated injector further reducing the total part count and complexity of the final rocket design [132]. While this design shows an example of the potential integration of multiple parts, the overall loads must be well understood in the full environment to incorporate TO and also the entire AM process, including post-processing for successful application.

Due to the complexity present in the regenerative cooling channels of most rocket engines, thermal and structural optimization techniques have been gaining interest in applications for rocket engine designs. In one example, Hyperganic, a developer of AI-driven design software similar to TO, demonstrated optimization applications on a concept rocket nozzle using a top-down approach, integrating several components such as the combustion chamber, nozzle, and cooling channels into one single component [213]. The nozzle is designed to be printed using metal AM techniques allowing for a high complexity in design. The prototype, shown in Fig. 22, is designed to be manufactured from Inconel 718 on an EOS M400-4 printer. The nozzle features a gyroid minimal surface lattice design on its outer surface. These lattice structures are found in nature and are often self-supporting and feature zero average curvature at any point on their surface, making for more even distribution of stresses within the structures [112]. These examples demonstrate some of the potential, but these designs are still not widely tested or adopted in flight components and currently are still in design and proof of concept phases.

3.5. Summary of applications of AM in aerospace

Many applications of metal AM exist throughout the aerospace industry. Table 2 and Table 3 present a collection of prominent examples appearing in non-technical literature (Table 2) and a comprehensive list of articles, books, reviews, and conference proceedings appearing in technical literature (Table 3) in recent years. Table 2**** alphabetically lists the company involved, the application, the design approach, the material used, technology used and reference for further reading. Table 3 chronologically lists the studies and includes information on the author/s, the title, the application area, the publication year, and reference for further reading.

4. Challenges and opportunities

4.1. Overview

Metal AM technologies show great potential for technical and commercial advantages for aerospace applications, as is evident from the applications reviewed in the previous sections. Despite the technical and commercial opportunities enabled by metal AM, these technologies are subject to unique challenges for implementation in aerospace applications. This section highlights some of the current major challenges and some future opportunities.

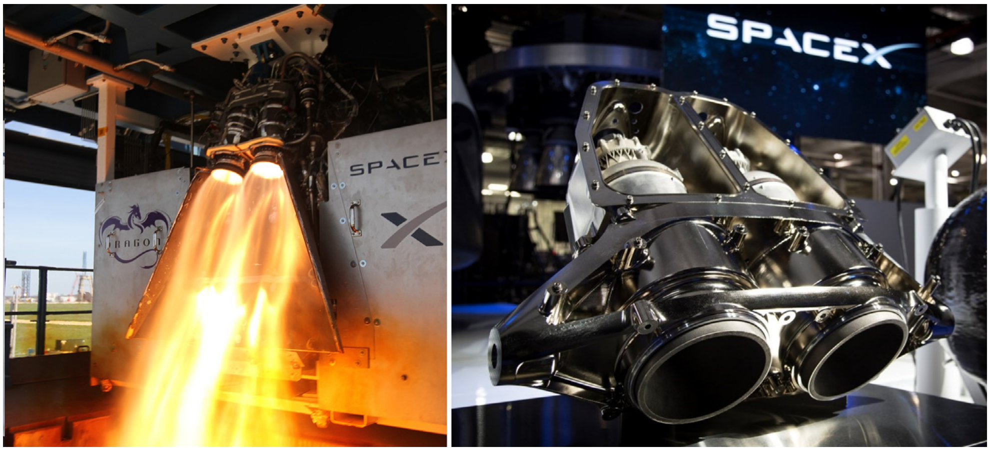


Fig. 19. SpaceX AM built Superdraco rocket engine. Left: SuperDraco Test Fire by SpaceX [204]. Right: SuperDracos by SpaceX [205].

Fig. 20. a: Bimetallic 7k Coupled Chamber using L-PBF GRCop-42 with HR-1 DED Integrated Nozzle (b: complete with manifolds). c: Bimetallic 40k Chamber built using L-PBF GRCop-42 liner and HR-1 DED Jacket. (Courtesy: NASA)[209].

4.2. Certification & standards

A major current challenge is the lack of technological standards and certification approaches present for metal AM in the aerospace industry, which is caused by the rapid growth in AM technologies over the last decade. These standards need to be refined and agreed upon across industry to assure the repeatability, reliability and quality of AM components for aerospace sector applications. Major governing bodies such as the European Union Aviation Safety Agency (EASA), NASA, European Space Agency (ESA), and Federal Aviation Administration (FAA) are imposing increasingly strict testing protocols and certifications that are required for the use of aerospace components in service for both mission-critical and non-critical applications [99]. These certification processes generally involve the repeatability of production processes and consistency in the quality of manufactured components which are both considerable challenges currently in the metal AM industry, especially when producing components in larger quantities. The primary challenge for the certification process of AM built components is the lack of prior knowledge, complete understanding and traceability of the AM process, detailed characterization and AM property databases, and data regarding the failure mechanisms. While materials with traditional processes are well understood and significant databases exist, AM materials lack a large database and agreed upon properties. Currently, ISO and ASTM develop a range of AM standards, described in more detail in [14]; these standards are evolving, and new standards are emerging, to accommodate the certification and design requirements for AM applications in the aerospace sector. A list of relevant current certification-related standards is provided in Table 4.

4.3. Structural integrity

Structural integrity is of paramount importance for mission-critical aerospace applications and integrity includes dynamic loading in both high cycle and low cycle modes, thermal cycling and impact loading. Fatigue response to dynamic loading is of particular concern for AM aerospace applications. The static mechanical properties of metallic AM built components are relatively well researched, with hardness and strength matching and exceeding that of traditionally manufactured material properties [77–80]. However, dynamic mechanical properties such as fatigue and creep have seen relatively less research and there remains a lack of test data reporting among aerospace companies [40]. The existing AM fatigue literature demonstrates test results that indicate porosity, residual stress and surface roughness are the largest concerns for high cycle fatigue (HCF) and low cycle fatigue (LCF) testing scenarios with overall fatigue properties generally substandard compared to conventional manufacturing processes [34,40,41]. Much progress has been made in mitigating these issues, allowing the improved performance of components with minimized defects, and achieving mechanical performance (including fatigue performance) on par with traditional manufacturing techniques [14].

Residual stress during AM builds result in possible part warping, cracking and reduced mechanical properties, and this build-up depends on the material used, the process parameters used, and the geometry and orientation in the build chamber, amongst other factors (specific thermal histories during the build). Similarly, porosity formation is strongly dependent on the process parameters as well as on local changes during the build. Various mechanisms for porosity formation in metal AM have been identified, which result in lack of fusion and keyhole porosity, with varying extent and 3D distributions depending on various factors [344–347]. The presence of porosity reduces the ductility of the material but is especially critical in fatigue loading as pores can act as stress concentrators and hence crack initiation locations, resulting in premature failures [348–350]. The surface roughness of the as-built components are generally irregular and vary with build orientation, process parameters and other factors – these also act as stress concentrators and crack initiation locations [100]. The obtained material microstructure is often anisotropic and the grain orientation depends on the building direction, affecting the mechanical properties. Appropriate post-process heat treatments and HIP are required to improve this.

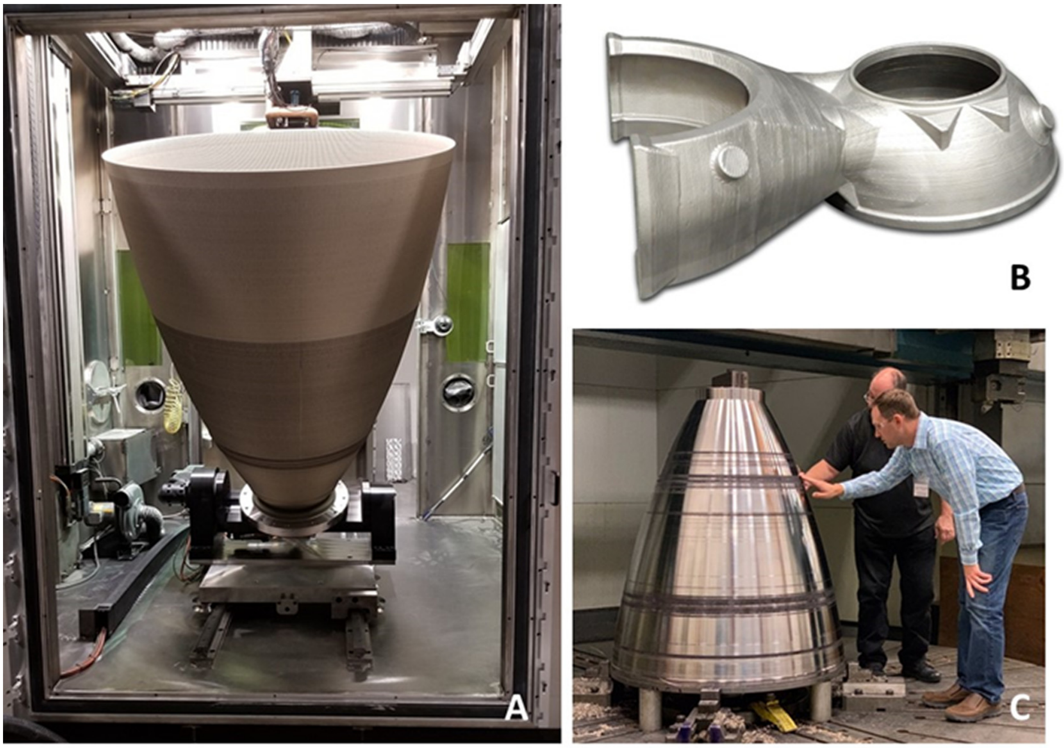


Fig. 21. Examples of Large Scale DED at NASA. A) LP-DED integral channel nozzle 60″ (1.52 m) diameter and 70″ (1.78 m) height with NASA HR-1 alloy deposited in 90 days, B) Powerhead half shell using Inconel 718, and C) LP-DED JBK-75 Nozzle (no channels) that is ½ scale RS-25. (Courtesy: NASA)[212].

Fig. 22. Hyperganic prototype rocket nozzle featuring internal cooling channels and an external lattice. Photo courtesy of Hyperganic [213].

All of these manufacturing-specific defects remain an issue to actively mitigate and be cognizant of, and therefore require extensive quality control across all stages of the AM process, from powder feedstock to ambient gas purity, process parameter control, process optimization, in-situ monitoring and post-processing for each individual process and feedstock combination required. Despite optimal processes and material quality, unexpected errors may still occur which require post-process inspection and often some kind of machining and further post processing is needed. All of these operations add cost to the produced components, but bypassing these steps leads to a loss in performance and reliability. HIP has been widely adopted in aerospace, and in AM in particular it is very useful for closing pores [101], homogenizing the microstructure, and improving the ductility of components. This also leads to greatly improved fatigue performance of metal AM components [351,352], leading to its wide adoption in aerospace manufacturing [34].

4.4. Design for AM

Design for AM (DfAM) can be used to optimize the design for the best manufacturing quality, minimizing support structures and post processing requirements [143]. This can also be done in combination with build simulations to determine optimal orientation of the part on the build platform, help determine build strategies to minimize residual stresses and resulting distortion, and minimizing support structures. Such simulations and DfAM methods are time consuming and dependant on the engineering skill of the AM engineer, and on the computing power of the computer used, but may be necessary. Simulations also require well defined

Table 2
Non-technical literature example list.

Non-Technical Literature					
Manufacturer or Author	**Application**	**Design Approach**	**Material used**	**Technologies used**	**Reference**
Aerojet Rocketdyne	Thrust Chamber	AM	Copper Alloy	L-PBF	[197]
Aerojet Rocketdyne	AR1 Preburner	AM	Mondaloy 200™	L-PBF	[196]
Airborne Engineering	C18150 copper chamber	AM	Copper Alloy	Not Stated	[214]
Airbus	Reflector Bracket	AM	Titanium	L-PBF	[215]
Airbus	A350 Cabin Bracket Connector	AM & TO	Ti-6Al-4V	L-PBF	[216]
Airbus	A350 XWB Pylon Bracket	AM	Titanium Alloy	L-PBF	[217]
Airbus & 3D Systems	RF Filter	AM	AlSi10Mg	L-PBF	[218]
Airbus & EOS	Aircraft Door Locking Shaft	AM	Ti6Al4V	L-PBF	[219]
Airbus, APWorks, Autodesk	Bionic Partition wall Project	AM, TO, Lattice	AlMgSc	L-PBF	[220]
Amaero Engineering, Safran	Aero-Engine	AM	Al7SiMg, Hastelloy X, Ti6Al4V	L-PBF, EBM, CS	[221]
Ariane Group, EOS	Ariane 6 Injector head	AM	Inconel 718	L-PBF	[222]
Ariane Group, ESA	Rocket Combustion Chamber	AM	Copper Alloy	L-PBF	[198]
Autodesk	Lattice Aircraft Seat	AM, TO, Lattice and “lost wax” casting	Magnesium	N/A	[223]
Betatype	Rocket Nozzle	AM, Lattice	Stainless Steel 316L	L-PBF	[224]
Blue Origin	BE-7 Engine	AM	Various	Not Stated	[225]
Blue Origin	BE-4 rocket engine boost pump	AM	Aluminium alloy, Monel	L-PBF	[226]
Copenhagen Suborbitals	Coaxial Swirl Injectors	AM	Not Stated	Binder Jetting	[192]
DLR & 3D systems	Liquid Rocket Engine Injector	AM	Ni718	L-PBF	[227]
EOS & Airbus	Borescope Bosses	AM	Not Stated	L-PBF	[228]
EOS & Airbus	Hydraulic spoiler manifold	AM	Titanium	L-PBF	[229]
EOS & Vectoflow	Flow Measurement Probe	AM	Nickel-Chromium Alloy	L-PBF	[230]
EOS, Sogeti and Airbus	Vertical tailplane bracket	AM & TO	AlSi10Mg	L-PBF	[231]
Frustum & 3D Systems	GE Aircraft Bracket	AM & TO	Titanium Alloy	L-PBF	[232]
General Electric	LEAP engine Fuel nozzle	AM	Cobalt-Chrome Alloy	L-PBF	[11]
General Electric	GE9X Engine Additive Components	AM	Various	EBM, L-PBF	[129]
General Electric	Sump Cover	AM	Cobalt-Chrome Alloy	L-PBF	[233]
General Electric	NACA inlet	AM	Ti-6Al-4V	L-PBF	[234]
GKN Aerospace	Rocket Engine Turbines	AM	IN718	DED	[235]
GKN Aerospace	Turbine exhaust casing	AM	Not stated	L-PBF	[236]
GKN Aerospace	Bracket	AM	Ti6Al4V	EBM	[237]
GKN Aerospace	Intermediate compressor case bosses	AM	Ti-6Al-4V	DED	[238]
GKN Aerospace	Optical ice protection probe	AM	Not stated	Not stated	[239]
Hieta	High and Low temperature heat exchangers	AM	Inconel 718/625 or CM247 LC	L-PBF	[186]
Hyperganic	Rocket Nozzle	AM, Lattice	Inconel 718	L-PBF	[213]
Launcher & EOS	E-2 Rocket Engine	AM	C18150 Copper-alloy	L-PBF	[208]
Lena Space and Oerlikon	Propulsion system Impeller	AM	Not Stated	Not Stated	[240]
Liebherr-Aerospace & Airbus	Landing Gear Sensor Bracket	AM	Titanium Alloy	L-PBF	[241]
Lockheed Martin	Satellite Fuel Tank	AM	Titanium Alloy	EB-DED	[200]
NASA	Rocket Combustion Chamber	AM	GCop-84	L-PBF	[242]
NASA	Perseverance Heat Exchangers and structures	AM	Titanium Alloy, Nickel-based superalloy	L-PBF	[182]
NASA	7k and 40k coupled chamber and nozzle	AM	GRCop-84, GRCop-42, NASA HR-1, Inconel 625	L-PBF, EB-DED, DED	[209]
NASA	Rocket Injector	AM	Inconel 625	L-PBF	[194]
NASA	Rocket Engine	AM	Various	Not Stated	[243]
NASA	LPS Fuel Turbopump	AM	Various	L-PBF	[244]
NASA	Pogo Accumulator Assembly	AM	Inconel 718	Not Stated	[245]
NASA	Maintenance Port Cover	AM	Not Stated	L-PBF	[246]
NASA	RS-25 Pogo z-baffle	AM	Inconel 718	L-PBF	[195]
nTopology & Cobra Aero	Cobra Aero uses multiphysics simulation to optimize UAV engine	AM, Lattice	AlSi10MG	L-PBF	[185]
nTopology & USAF	Air Force optimizes cubesat using Architected Materials	AM, Lattice	Inconel 718	L-PBF	[155]
Oerlikon	Turbine Blade	AM	Not Stated	Not Stated	[247]
Oerlikon	Double Nozzle	AM	Inconel 625	L-PBF	[248]
Optomec	T700 Blisk repair	AM	Stellite® 21	LENS	[141]
Orbex	Rocket Engine	AM	Not Stated	L-PBF	[249]
Orbital ATK	Hypersonic Engine Combustor	AM	Not Stated	L-PBF	[250]
Parabilis Space Technologies	Multi-Material Nozzle	AM	Copper Alloy, Isomolded Graphite, Inconel 718	Various	[251]
Parabilis Space Technologies	RCS Thruster	AM	Not Stated	Not Stated	[252]
Pratt & Whittney	Compressor Stators	AM	Ti-6Al-4V	L-PBF	[126]
Relativity Space	Terran 1 Fuel Tank	AM	Not Stated	DED	[201]
Relativity Space	Aeon Engine	AM	Not Stated	L-PBF	[207]
RocketLab	Rutherford Engine	AM & Lattice	Not Stated	EBM	[206]

(*continued on next page*)

Table 2 (*continued*)

Non-Technical Literature

Manufacturer or Author	Application	Design Approach	Material used	Technologies used	Reference
RUAG, EOS, Altair	Sentinel Antenna Bracket	AM & TO	AlSi10Mg	L-PBF	[139]
RUAG, EOS, Altair	Star Tracker Bracket	AM & TO	AlSi10Mg	L-PBF	[253]
RUAG, EOS, Altair	LEROS Engine support bracket	AM & TO	AlSi10Mg	L-PBF	[254]
Siemens	High-Pressure Hydraulic Manifold	AM	Titanium Alloy	L-PBF	[255]
SLM & Cellcore	Rocket Engine	AM & Lattice	Inconel 718	L-PBF	[13]
SpaceX	SuperDraco Engine Chamber	AM, Cert	Inconel Alloy	L-PBF	[202]
SpaceX	Main Oxidiser Valve Body	AM	Not Stated	Not Stated	[256]
SpaceX	Raptor Engine Components	AM	Various	Various	[257]
Spirit AeroSystems & Boeing	Access Door Latch	AM	Titanium Alloy	DED	[258]
Thales Alenia Space & 3D Systems	Antenna Bracket	AM & TO	Ti Gr5	L-PBF	[259]
The Welding Institute	Helicopter combustion chamber	AM	Inconel 718	DED	[260]
ULA	Vulcan Bellows Feedline Housing	AM	Inconel 718	L-PBF	[261]
Virgin Orbit & NASA	Rocket Combustion Chamber	AM	GRCop-84	L-PBF	[262]

Table 3
Technical literature example list.

Technical Literature

Authors	Title	Application Areas	Year	Reference
Godec M.,et al.	Hybrid additive manufacturing of Inconel 718 for future space applications	Spacecraft	2021	[263]
Zhan Z., Li H.	A novel approach based on the elastoplastic fatigue damage and machine learning models for life prediction of aerospace alloy parts fabricated by additive manufacturing	Aerospace, Fatigue	2021	[264]
Van Den Berg P, Jyoti B, Hermsen R	Investigation of Thermal Behaviour of Additively Manufactured Green Bi-Propellant Thrusters in CubeSat Applications Using Transient Thermal Modelling	Spacecraft, Engines	2021	[265]
Waugh I., et al.	Additive manufacture of rocket engine combustion chambers from CuCrZr (C18150) using the DMLS process	Rocket, Engines	2021	[266]
Waugh I., et al.	Additive manufacture of rocket engine combustion chambers using the ABD R −900AM nickel Superalloy	Rocket, Engines	2021	[267]
D'Emilia G.,et al.	Uncertainty assessment for measurement and simulation in selective laser melting: A case study of an aerospace part	Aerospace, Case Study	2020	[268]
Dordlofva C., Törlind P.	Qualification challenges with additive manufacturing in space applications	Qualification, Spacecraft	2020	[269]
Fereiduni E., Ghasemi A., Elbestawi M.	Selective laser melting of aluminium and titanium matrix composites: Recent progress and potential applications in the aerospace industry	Aerospace	2020	[270]
Gao L.,et al.	Study on Arc Additive Manufacturing Process and Properties of 5356 Aluminium Alloy Rocket Booster Module Transition End Frame	Rocket	2020	[271]
Gu D.,et al.	Laser Additive Manufacturing of High-Performance Metallic Aerospace Components	Aerospace	2020	[272]
Hehr, A.,et al.	Hot Isostatic Pressing of Ultrasonic Additive Manufacturing Liquid Cold Plate Heat Exchangers.	Case Study, Heat Transfer	2020	[273]
Jia, D., Li, F., & Zhang, Y.	3D-printing process design of lattice compressor impeller based on residual stress and deformation.	Case Study, Design, Lattice	2020	[118]
Jing L.-L.,et al.	Application of Selective Laser Melting Technology Based on Titanium Alloy in Aerospace Products	Aerospace	2020	[274]
Kuntanapreeda S., Hess D.	Opening access to space by maximizing utilization of 3D printing in launch vehicle design and production	Spacecraft, Design	2020	[275]
Liu F.,et al.	An aerospace integrated component application based on selective laser melting: Design, fabrication and FE simulation	Aerospace, Design	2020	[276]
Manil P.,et al.	Structural optimization, additive manufacturing and vibration testing of titanium alloy supports based on the space detector SVOM-MXT	Spacecraft, Optimization Techniques	2020	[277]
Oyesola M.O.,et al.	Hybrid-additive manufacturing cost model: A sustainable through-life engineering support for maintenance repair overhaul in the aerospace	Aerospace, Repair	2020	[278]
SHI G.,et al.	An aerospace bracket designed by thermo-elastic topology optimization and manufactured by additive manufacturing	Aerospace, Design, Topology Optimization	2020	[279]
Stolt R., Elgh F.	Introducing design for selective laser melting in aerospace industry	Aerospace, Design	2020	[280]
Willner R.,et al.	Potential and challenges of additive manufacturing for topology optimized spacecraft structures	Spacecraft, Structures, Topology Optimization	2020	[281]
Gradl P.,et al.	Lightweight Thrust Chamber Assemblies using Multi-Alloy Additive Manufacturing and Composite Overwrap	Rocket, Engines	2020	[93]
Mireles O., et al.	Additive Manufacture of Refractory Alloy C103 for Propulsion Applications	Rocket, Engines	2020	[282]
Abi-Fadel M.,et al.	Leveraging additive manufacturing to enable deep space crewed missions	Spacecraft	2019	[283]
Barroqueiro B.,et al.	Metal additive manufacturing cycle in aerospace industry: A comprehensive review	Review, Aerospace	2019	[284]
Belfi F.,et al.	Space structures with embedded flat plate pulsating heat pipe built by additive manufacturing technology: Development, test and performance analysis	Spacecraft, Structures, Heat Transfer	2019	[285]
Berrocal L.,et al.	Topology optimization and additive manufacturing for aerospace components	Aerospace, Topology Optimization	2019	[286]
Chekir N.,et al.	Laser wire deposition of a large Ti-6Al-4 V space component the methodology for creating a functional Ti-6Al-4V satellite part using LWD additive manufacturing is	Spacecraft, Structures	2019	[287]

Table 3 (*continued*)

Technical Literature				
Authors	**Title**	**Application Areas**	**Year**	**Reference**
	detailed			
Chougrani L., et al.	Parts internal structure definition using non-uniform patterned lattice optimization for mass reduction in additive manufacturing	Spacecraft, Structures, Lattice	2019	[156]
Diaz A	Surface texture characterization and optimization of metal additive manufacturing-produced components for aerospace applications	Aerospace, Optimization Techniques	2019	[288]
Facchini F., De Chirico A., Mummolo G.	Comparative cost evaluation of material removal process and additive manufacturing in aerospace industry	Aerospace	2019	[289]
Froes F., Boyer R.	Additive manufacturing for the aerospace industry	Aerospace	2019	[172]
Froes F., Boyer R., Dutta B.	Introduction to aerospace materials requirements and the role of additive manufacturing	Aerospace	2019	[290]
Fuchs C.,et al.	Additive Manufacturing for Structural Components in Aerospace Engineering	Aerospace	2019	[291]
Gas M.,et al.	Improving Competitiveness of Additive Manufacturing Aerospace Serial Parts	Aerospace	2019	[292]
Gloria N.,et al.	Performance of a small-orifice rocket injector utilizing additive manufacturing	Rocket	2019	[293]
Gradl P.R., Protz C., Wammen T.	Additive manufacturing development and hot-fire testing of liquid rocket channel wall nozzles using blown powder directed energy deposition Inconel 625 and JBK-75 alloys	Rocket	2019	[47]
Hehr A.,et al.	Selective Reinforcement of Aerospace Structures Using Ultrasonic Additive Manufacturing	Aerospace, Structures	2019	[294]
Hilpert E.,et al.	Design, additive manufacturing, processing, and characterization of metal mirror made of aluminium silicon alloy for space applications	Spacecraft, Design	2019	[295]
Kalender M.,et al.	Additive manufacturing and 3D printer technology in aerospace industry	Aerospace	2019	[296]
Kamal M., Rizza G.	Design for metal additive manufacturing for aerospace applications	Aerospace, Design	2019	[297]
Kohl P.,et al.	Additive Manufacturing Developments for Satellite Antenna Applications from C- to Ka-Band	Spacecraft, Structures	2019	[298]
Kozmel T.,et al.	Additive manufacturing of Ferrium$^{®}$ c64$^{®}$ for aerospace gear applications	Aerospace	2019	[299]
Liu S.-B.,et al.	A Summary of Research on 3D Printing Technology of Titanium Alloys for Aerospace Field	Aerospace	2019	[300]
Mekki, B. S., Langer, J., & Lynch, S.	Genetic Algorithm Based Topology Optimization of Heat Exchanger Fins Used in Aerospace Applications.	Aerospace, Topology Optimization, Heat Transfer	2019	[301]
Murphy T.F., Schade C.T.	Measurement of powder characteristics and quality for additive manufacturing in aerospace alloys	Qualification, Aerospace	2019	[302]
Najmon J.C., Raeisi S., Tovar A.	Review of additive manufacturing technologies and applications in the aerospace industry	Review, Aerospace	2019	[97]
Niu X.-D	3D printing in China's aerospace industries	Aerospace	2019	[303]
Opgenoord M.M.J., Willcox K.E.	Design for additive manufacturing: cellular structures in early-stage aerospace design	Aerospace, Structures, Design	2019	[304]
Oyesola M., Mpofu K., Mathe N.	A techno-economic analytical approach of laser-based additive manufacturing processes for aerospace application	Aerospace	2019	[305]
Patel N.,et al.	Design and additive manufacturing considerations for liquid rocket engine development	Rocket, Design	2019	[306]
Piticescu R.,et al.	Powder-bed additive manufacturing for aerospace application: Techniques, metallic and metal/ceramic composite materials and trends	Aerospace	2019	[307]
Riou A	Metal powders for additive manufacturing in aerospace & land turbines. Trends and challenges	Aerospace, Turbomachinery	2019	[308]
Sacco E., Moon S.K.	Additive manufacturing for space: status and promises	Spacecraft	2019	[309]
Shelton T.E.,et al.	Additive manufacturing: Designing to withstand space launch	Spacecraft, Design	2019	[310]
Tepylo N., Huang X., Patnaik P.C.	Laser-Based Additive Manufacturing Technologies for Aerospace Applications	Aerospace	2019	[311]
Vetrivel, Varun Teja P.,et al.	Potential and scope of additive manufacturing in aerospace industry with reference to India	Aerospace	2019	[312]
Vityaz P.A., Kheifetz M.L., Chizhik S.A.	Synergetic technologies of direct layer deposition in aerospace additive manufacturing	Aerospace	2019	[313]
Withers J.C.	Fusion and/or solid state additive manufacturing for aerospace applications	Aerospace	2019	[314]
YongXin G.,et al.	Optimization Design of Star Tracker Bracket of Small Satellite for 3D Printing	Spacecraft, Structures, Design, Optimization Techniques	2019	[315]
Yusuf S.M., Cutler S., Gao N.	Review: The impact of metal additive manufacturing on the aerospace industry	Review, Aerospace	2019	[151]
Zhang X., Liang E.	Metal additive manufacturing in aircraft: Current application, opportunities and challenges	Aircraft	2019	[316]
Gradl P.,et al.	Bimetallic Channel Wall Nozzle Development and Hot-fire Testing Using Additively Manufactured Laser Wire Direct Closeout Technology	Rocket, Engines	2019	[92]
Gradl P.,et al.	GRCop-42 Development and Hot-fire Testing Using Additive Manufacturing Powder Bed Fusion for Channel-cooled Combustion Chambers	Rocket, Engines	2019	[134]
Gradl P.,et al.	Additive Manufacturing and Hot-fire Testing of Bimetallic GRCop-84 and C18150 Channel-Cooled Combustion Chambers Using Powder Bed Fusion and Inconel 625 Hybrid Directed Energy Deposition	Rocket, Engines	2019	[142]
Gradl P.,et al.	Progress in additively manufactured copper-alloy GRCOP-84, GRCOP-42, and bimetallic combustion chambers for liquid rocket engines	Rocket, Engines	2019	[66]
Allevi G.,et al.	Non-Contact Measurement Techniques for Qualification of Aerospace Brackets Made by Additive Manufacturing Technologies	Qualification, Aerospace	2018	[317]
Bici M.,et al.	Development of a multifunctional panel for aerospace use through SLM additive manufacturing	Aerospace	2018	[131]

(*continued on next page*)

Table 3 (*continued*)

Technical Literature				
Authors	**Title**	**Application Areas**	**Year**	**Reference**
Cailloce Y.,et al.	Additive manufacturing of Ku band horn antennas for telecommunications space applications	Spacecraft	2018	[318]
Eberle S.,et al.	Additive manufacturing of an ALSI40 mirror coated with electroless nickel for cryogenic space applications	Spacecraft	2018	[319]
Fessl J.,et al.	Liquid rocket engine design for additive manufacturing	Rocket, Design	2018	[320]
Fetisov K.V., Maksimov P.V.	Topology optimization and laser additive manufacturing in design process of efficiency lightweight aerospace parts	Aerospace, Design, Topology Optimization	2018	[321]
Gaudenzi P.,et al.	Revisiting the configuration of small satellites structures in the framework of 3D Additive Manufacturing	Spacecraft, Structures	2018	[322]
Gradl P.R.,et al.	Additive manufacturing of liquid rocket engine combustion devices: A summary of process developments and hot-fire testing results	Rocket	2018	[62]
Gradl P.,et al.	Channel Wall Nozzle Manufacturing and Hot-Fire Testing using a Laser Wire Direct Closeout Technique for Liquid Rocket Engines	Rocket, Engines	2018	[323]
Hettesheimer T., Hirzel S., Roß H.B.	Energy savings through additive manufacturing: an analysis of selective laser sintering for automotive and aircraft components	Aircraft	2018	[324]
Maksimov P.,et al.	Numeric simulation of aircraft engine parts additive manufacturing process	Aircraft	2018	[325]
Oyesola M.,et al.	Sustainability of Additive Manufacturing for the South African aerospace industry: A business model for laser technology production, commercialization and market prospects	Aerospace	2018	[326]
Saltzman, D.,et al.	Design and evaluation of an additively manufactured aircraft heat exchanger.	Aircraft, Design, Heat Transfer	2018	[130]
Stolt R., Heikkinen T., Elgh F.	Integrating additive manufacturing in the design of aerospace components	Aerospace, Design	2018	[327]
Vishnu Prashant Reddy K., Meera Mirzana I., Koti Reddy A.	Application of Additive Manufacturing technology to an Aerospace component for better trade-off's	Aerospace	2018	[328]
Vogel D.,et al.	Combining additive manufacturing and biomimetics for the optimization of satellite structures	Spacecraft, Structures, Optimization Techniques	2018	[329]
Gradl P.,et al.	Development and Hot-fire Testing of Additively Manufactured Copper Combustion Chambers for Liquid Rocket Engine Applications	Rocket, Engines	2017	[67]
Cismilianu A.-M.,et al.	End-to-end process of hollow spacecraft structures with high frequency and low mass obtained with in-house structural optimization tool and additive manufacturing	Spacecraft, Structures, Optimization Techniques	2017	[330]
Clinton R.	NASA additive manufacturing initiatives: In space manufacturing and rocket engines	Spacecraft, Rocket	2017	[331]
Cruz M.F., Borille A.V.	Decision methods application to compare conventional manufacturing process with metal additive manufacturing process in the aerospace industry	Aerospace	2017	[332]
Froes F.H., Boyer R., Dutta B.	Additive manufacturing for aerospace applications-part I	Aerospace	2017	[333]
Froes F.H., Boyer R., Dutta B.	Additive manufacturing for aerospace applications-part II	Aerospace	2017	[334]
Gill S.S., Arora H., Jidesh, Sheth V.	On the development of Antenna feed array for space applications by additive manufacturing technique	Spacecraft	2017	[335]
Judalet N.,et al.	Performance monitoring & control for an additive manufacturing factory - A case study in the aerospace industry	Aerospace, Case Study	2017	[336]
Kasim, K.,et al.	Advanced Heat Transfer Devices for Aerospace Applications.	Aerospace, Heat Transfer	2017	[337]
Lindwall A., Dordlofva C., Öhrwall Rönnbäck A.	Additive manufacturing & the product development process: Insights from the space industry	Spacecraft	2017	[338]
Liu R.,et al.	Aerospace applications of laser additive manufacturing	Aerospace	2017	[138]
Munteanu C.E.,et al.	Structural optimization of space components adapted for 3d printing	Spacecraft, Optimization Techniques	2017	[339]
Nagasaki A.,et al.	Additive manufacturing development for rocket engine in Japan	Rocket	2017	[340]
Obilanade D., Kingston J.	Spacecraft designers' guide to using additive manufacturing processes for large metallic spacecraft structures.	Spacecraft, Structures, Design	2017	[341]
Orme M.E.,et al.	Designing for additive manufacturing: Lightweighting through topology optimization enables lunar spacecraft	Spacecraft, Structures, Design, Topology Optimization	2017	[146]
Orme M.E.,et al.	Additive manufacturing of lightweight, optimized, metallic components suitable for space flight	Spacecraft	2017	[10]
Pacurar R., Pacurar A., Bâlc N.	Research on the mechanical behaviour of an airplane component made by selective laser melting technology	Aircraft	2017	[342]
Yakout M.,et al.	The selection of process parameters in additive manufacturing for aerospace alloys	Aerospace	2017	[343]
Gradl P.,et al.	Rapid Fabrication Techniques for Liquid Rocket Channel Wall Nozzles	Rocket, Engines	2016	[180]
Godfrey, D	Additive Manufacturing (AM) and the Honeywell Global Initiative.	Case Study	2015	[166]
Xue, L.,et al.	Laser Consolidation: A Novel Additive Manufacturing Process for Making Net-Shape Functional Metallic Components for Gas Turbine Applications.	Case Study, Turbomachinery, Repair	2015	[173]
Allison, T.,et al.	Manufacturing and Testing Experience with Direct Metal Laser Sintering for Closed Centrifugal Compressor Impellers.	Case Study	2014	[163]
Tomlin M., Meyer J.	Topology Optimization of an Additive Layer Manufactured (ALM) Aerospace Part	Aerospace, Topology Optimization	2011	[116]

Table 4
Certification-related AM standards, including those under development (marked by *).

ISO/ASTM 52942–20	Qualifying Machine Operators of Laser Metal Powder Bed Fusion Machines and Equipment Used in Aerospace Applications
ASTM F3434-20	Installation/Operation and Performance Qualification (IQ/OQ/PQ) of Laser-Beam Powder Bed Fusion Equipment for Production Manufacturing
ISO/ASTM 52941–20	Acceptance Tests for Laser Metal Powder-Bed Fusion Machines
ISO/ASTM AWI 52,937 *	Qualification of Designers
ISO/ASTM CD 52,920 *	Quality Requirements for Industrial Additive Manufacturing Sites
ISO/ASTM AWI 52,935 *	Qualification of Coordinators for Metallic Production
ISO/ASTM CD TS 52,930 *	Installation, Operation and Performance (IQ/OQ/PQ) of PBF-LB Equipment
ISO/ASTM CD 52926–5 *	Qualification of Machine Operators for DED-ARC
ISO/ASTM CD 52926–4 *	Qualification of Machine Operators for DED-LB
ISO/ASTM CD 52926–3 *	Qualification of Machine Operators for PBF-EB
ISO/ASTM CD 52926–2 *	Qualification of Machine Operators for PBF-LB
ISO/ASTM CD 52926–1 *	General Qualification of Machine Operators
NASA-STD-6030	Additive Manufacturing Requirements for Crewed Spaceflight Systems
SAE AMS7032	Additive Manufacturing Machine Qualification
NASA-SPEC-6033	Additive Manufacturing Requirements for Equipment and Facility Control
NASA MSFC-SPEC-3716	Standard for Additivity Manufactured Spaceflight Hardware by Laser Powder Bed Fusion of Metals
NASA MSFC-SPEC-3717	Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes

inputs such as alloy mechanical and thermophysical properties often at the liquidus and solidus temperatures, which is not always available [353–355].

While TO and lattice structures are discussed there are several challenges that exists with these in practical application. Since these techniques often optimize the design based on a known set of inputs and constraints, the load paths for aerospace components must be well understood. These load paths and combined structural, thermal, dynamic, and integrated environments are not always well defined or known for aerospace applications and designs can often include high design margins to account for these uncertainties.

4.5. Powder removal & post processing

Post-processing is a critical step in metal AM that is often underestimated. For complex parts with fine feature sizes, trapped powders can be a challenge to remove. This is compounded by the difficulty in handling such powders due to safety concerns. Typical approaches involve rotational movements, tapping and blowing powders out of surface cavities and channels. Trapped powders can be observed in CT scans, but may be permanently trapped if not removed prior to heat treatment.

Further post-processing steps might involve support removal, surface finishing and other heat treatments. For all post processing steps, care must be taken to prevent damage (e.g. when removing supports) to ensure the part conforms to the design and does not include surface damage. Surface polishing, machining or other processing is further challenged as AM part complexity increase and must be carefully designed for early in the process.

4.6. Non-Destructive testing (NDT)

Due to the many challenges described before, NDT is prescribed for all critical flight components manufactured by metal AM. Various NDT methods used are described in detail in [356]. NDT is important for identifying flaws such as porosity or cracks in critical components and a variety of methods may be used including radiographic testing (RT), dye penetrant, eddy current, ultrasonic testing, amongst others. Some of the new challenges in this type of NDT for AM parts is that the complexity of the parts requires more challenging NDT approaches and some traditional tools are not relevant to such complex parts. In addition, the inherent surface roughness reduces the sensitivity of some traditional NDT tools. Despite these challenges, one method has proven to be able to overcome many of these challenges: X-ray computed tomography (CT). This method has been demonstrated to be successful for inspection of cracks, pores, trapped powders, deviation from design geometry, warping due to thermal processing, and more [103]. One particular advantage of the method is the ability to provide information on the changes in a part over time, with multiple scans at different times, providing information on crack formation or the extent of wear or other damage that can occur. The dimensional evaluation provided can be used to assess suitability for further use and even provide predictions of further life expectancy.

The major limitations of the technique are the relatively poor resolution for large parts, components with thick walls, challenges with alloys such as copper, and the time and cost involved. In addition, some metals are highly absorbing for X-rays, making their CT ineffective except for very small parts. In these cases the use of smaller coupon samples are recommended for checking process optimization conditions [346] and witness specimens built alongside larger parts give a good indication of the quality of the build [357]. For larger parts, it is technically feasible to use higher-energy X-ray sources, but these are less widely available. For the above reasons, many in-process monitoring tools are being developed to improve the identification of flaws during the process, rather than post-process.

5. Conclusions

This review paper has demonstrated numerous successful examples of metal AM in aerospace applications. Various AM technologies are utilized for aerospace applications with L-PBF and DED as the most popular. DED is used for components with large build volumes and can be used to repair existing components in addition to building components. L-PBF is the most widely used for applications in aerospace with its capabilities to produce fully dense components at high resolution with complex geometries, with small to medium build volumes [200]. Most applications of metal AM in aerospace, demonstrated in Table 2 and Table 3, have shown advantages for cost and schedule reduction, some applications see mass reduction improvements and many part consolidations from previous designs. However, metal AM has the challenges of part certification, unique quality control requirements, poor high-volume production rates, limited materials in use, post-processing challenges, potential reduced fatigue properties, supply chain maturity issues, high cost of machines and expertise required to produce functional components.

Many open research questions remain, with opportunities for enhanced understanding and performance and further developments in the near future. The most important areas of current development are listed and discussed below:

- New alloys developed for AM and for aerospace applications
- In situ monitoring for digital twin and accurate flaw identification

- Build simulation for identification of risks
- In-space and non-terrestrial AM
- Wider usage of architected cellular structures (lattices)
- Usage of optimization techniques such as topology optimization (TO) and hybrid analytical thermal optimization (HAATO)
- Multi-functional components such as integrated electronics and sensors in AM processes

Significant future growth areas include the application of novel custom alloys, bimetallic and multimetallic processing and characterization, detailed process-structure–property understanding, databases for AM materials, process certification, design optimization, and process simulations. The application of TO and the use of lattice structures has potential for mass reduction, which is a requirement for aerospace. In both cases, the growing understanding of the design and successful fabrication of such structures leads to improvements in components with increasingly complex designs. TO has already seen some applications throughout aerospace with emphasis on lightweighting of components. Lattice structures have shown much potential for improvements in design for aerospace applications. With unique and precisely designed properties such as energy absorption characteristics, lightweighting and heat transfer characteristics, lattice structures are expected to be a popular topic of interest for research in aerospace applications in the near future. It is expected that these optimized geometries are also simultaneously optimized for build quality optimization, minimizing the need for support structures or overhanging regions, thereby enhancing the surface quality and minimizing the defect formation. Build simulation is expected to play an increasingly important role in optimizing the build quality by finding the optimal orientation and highlighting regions of potential thermal build-up, which can inform the design process. While the potential for TO and lattice structures could be used for mass reduction, there needs to be a significant understanding of mechanical and thermal load paths in addition to integrated load, which are not always defined with high certainty in aerospace. This is another area of research to ensure the techniques are applied appropriately and allow for fully safe and successful missions.

As highlighted here, the main advantages of metal AM in aerospace is cost and lead time reduction. Mass reduction is also a significant opportunity area with optimized design or use of multiple alloys, however these techniques need to be well understood and properties well defined. In addition, part consolidation is a major advantage in this industry. Part complexity capabilities inherent in metal AM allows for high complexity within components, including internal features such as channels and high surface area for heat transfer applications. AM has also been demonstrated in many large-scale applications, so scale is becoming far less of a limitation. These and other advantages of metal AM in aerospace hold great potential for wider adoption of this technology, which will further drive the remaining challenges to be overcome.

CRediT authorship contribution statement

Byron Blakey-Milner: Conceptualization, Writing - original draft, Writing - review & editing. **Paul Gradl:** Writing - review & editing, Resources. **Glen Snedden:** Writing - review & editing. **Michael Brooks:** Writing - review & editing. **Jean Pitot:** Writing - review & editing. **Elena Lopez:** Writing - review & editing. **Martin Leary:** Writing - review & editing. **Filippo Berto:** Writing - review & editing. **Anton Plessis:** Conceptualization, Methodology, Supervision, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Anton du Plessis acknowledges financial support from the Collaborative Program in Additive Manufacturing (CPAM). Martin Leary acknowledges the support from the facilities and technical staff of RMIT's Advanced Manufacturing Precinct. Paul Gradl acknowledges funding provided through NASA STMD RAMPT Project. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the National Aeronautics and Space Administration (NASA) or the United States Government. ASReG acknowledges the support of the Department of Science and Innovation (DSI).

References

[1] The Business Research Company, Aerospace Global Market Report 2021: COVID 19 Impact and Recovery to 2030, 2021. [Online]. Available: https://www.reportlinker.com/p06018925/Aerospace-Global-Market-Report-COVID-19-Impact-and-Recovery-to.html?utm_source=GNW.

[2] B.N. Bhat, (Ed.), Aerospace Materials and Applications, American Institute of Aeronautics and Astronautics, Inc., Reston, VA, 2018. doi: 10.2514/4.104893.

[3] R.R. Boyer, J.D. Cotton, M. Mohaghegh, R.E. Schafrik, Materials considerations for aerospace applications, MRS Bull. 40 (12) (2015) 1055–1066, https://doi.org/10.1557/mrs.2015.278.

[4] Market Research Future, Global Aerospace Additive Manufacturing Market Research Report – Forecast 2016-2021, 2019. [Online]. Available: https://www.marketresearchfuture.com/reports/aerospace-additive-manufacturing-market-1551.

[5] D. Herzog, V. Seyda, E. Wycisk, C. Emmelmann, Additive manufacturing of metals, Acta Mater. 117 (2016) 371–392, https://doi.org/10.1016/j.actamat.2016.07.019.

[6] A. Angrish, A critical analysis of additive manufacturing technologies for aerospace applications, in: 2014 IEEE Aerospace Conference, Mar. 2014, pp. 1–6. doi: 10.1109/AERO.2014.6836456.

[7] A.A. Shapiro, J.P. Borgonia, Q.N. Chen, R.P. Dillon, B. McEnerney, R. Polit-Casillas, L. Soloway, Additive manufacturing for aerospace flight applications, J. Spacecraft Rockets 53 (5) (2016) 952–959, https://doi.org/10.2514/1.A33544.

[8] J.C. Snyder, K.A. Thole, Effect of additive manufacturing process parameters on turbine cooling (2019) doi: 10.1115/GT2019-90862.

[9] F. Kerstens, A. Cervone, P. Gradl, End to end process evaluation for additively manufactured liquid rocket engine thrust chambers, Acta Astronaut. 182 (2021) 454–465, https://doi.org/10.1016/j.actaastro.2021.02.034.

[10] M.E. Orme, M. Gschweitl, M. Ferrari, R. Vernon, I.J. Madera, R. Yancey, F. Mouriaux, Additive manufacturing of lightweight, optimized, metallic components suitable for space flight, J. Spacecraft Rockets 54 (5) (2017) 1050–1059, https://doi.org/10.2514/1.A33749.

[11] General Electric - Additive, LEAP engine Fuel nozzle, https://www.ge.com/additive/stories/new-manufacturing-milestone-30000-additive-fuel-nozzles (accessed Feb. 02, 2021).

[12] Fraunhofer IWS, Annual report 2019/2020 Fraunhofer IWS, 2020. https://www.iws.fraunhofer.de/en/newsandmedia/mediacenter/annual_reports.html (accessed Mar. 16, 2021).

[13] S. Cellcore, Rocket Engine, https://www.etmm-online.com/3d-printing-a-rocket-engine-a-886960/ (accessed Feb. 02, 2021).

[14] I. Yadroitsev, I. Yadroitsava, A. du Plessis, E. MacDonald, Fundamentals of Laser Powder Bed Fusion of Metals, first ed. 2021. [Online]. Available: https://www.elsevier.com/books/fundamentals-of-laser-powder-bed-fusion-of-metals/yadroitsev/978-0-12-824090-8.

[15] M. Leary, D. Downing, B. Lozanovski, J. Harris, Design principles, in: I. Yadroitsev, I. Yadroitsava, A. du Plessis, E. MacDonald, (Eds.), Fundamentals of Laser Powder Bed Fusion of Metals, first ed., 2021, Accessed: Mar. 19, 2021. [Online]. Available: https://www.elsevier.com/books/fundamentals-of-laser-powder-bed-fusion-of-metals/yadroitsev/978-0-12-824090-8.

[16] M. Gebler, A.J.M. Schoot Uiterkamp, C. Visser, A global sustainability perspective on 3D printing technologies, Energy Policy 74 (C) (2014) 158–167, https://doi.org/10.1016/j.enpol.2014.08.033.

[17] B. Dutta, F.H. (Sam) Froes, The additive manufacturing (AM) of titanium alloys, in: Titanium Powder Metallurgy, Elsevier, 2015, pp. 447–468. doi: 10.1016/B978-0-12-800054-0.00024-1.

[18] A. Barz, T. Buer, H.-D. Haasis, A study on the effects of additive manufacturing on the structure of supply networks, IFAC-PapersOnLine 49 (2) (2016) 72–77, https://doi.org/10.1016/j.ifacol.2016.03.013.

[19] J. Allen, An Investigation into the Comparative Costs of Additive Manufacture vs. Machine from Solid for Aero Engine Parts, Cost Effective Manufacture via Net-Shape Processing, pp. 17-1-17–10, 2006, [Online]. Available: http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA521730.

[20] S.C. Joshi, A.A. Sheikh, 3D printing in aerospace and its long-term sustainability, Virt. Phys. Prototyp. 10 (4) (2015) 175–185, https://doi.org/10.1080/17452759.2015.1111519.

[21] T.A. Campbell, O.S. Ivanova, Additive manufacturing as a disruptive technology: implications of three-dimensional printing, Technol. Innov. 15 (1) (2013) 67–79, https://doi.org/10.3727/194982413x13608676060655.

[22] R. Russell, et al., Qualification and certification of metal additive manufactured hardware for aerospace applications, in: Additive Manufacturing for the Aerospace Industry, Elsevier, 2019, pp. 33–66. doi: 10.1016/B978-0-12-814062-8.00003-0.

[23] I. Gibson, D. Rosen, B. Stucker, Additive manufacturing technologies: 3D printing, rapid prototyping, and direct digital manufacturing, second edition, Springer New York, New York, NY, 2015, doi: 10.1007/978-1-4939-2113-3.

[24] L.E. Murr, Handbook of Materials Structures, Properties, Processing and Performance, Springer International Publishing, Cham, 2015. doi: 10.1007/978-3-319-01815-7.

[25] H. Bikas, P. Stavropoulos, G. Chryssolouris, Additive manufacturing methods and modelling approaches: a critical review, Int. J. Adv. Manuf. Technol. 83 (1–4) (2016) 389–405, https://doi.org/10.1007/s00170-015-7576-2.

[26] SAE International, AS9100 - Quality Systems - Aerospace - Model for Quality Assurance in Design, Development, Production, Installation and Servicing, 1999, https://www.sae.org/standards/content/as9100/.

[27] NASA, MSFC-SPEC-3717 - Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes, 2017. https://repository.msfc.nasa.gov/docs/multiprogram/MSFC-SPEC-3717.pdf.

[28] ISO/ASTM, Additive manufacturing — System performance and reliability (ISO/ASTM 52941-20), 2020. https://www.iso.org/standard/74948.html.

[29] ASTM, Guide for Additive manufacturing – Installation/Operation and Performance Qualification (IQ/OQ/PQ) of Laser-Beam Powder Bed Fusion Equipment for Production Manufacturing (ASTM F3434 - 20), 2020.

[30] ISO/ASTM, Additive manufacturing — Qualification principles (ISO/ASTM 52942-20), 2020. https://www.iso.org/standard/74949.html.

[31] NASA, Additive Manufacturing Requirements for Crewed Spaceflight Systems (NASA-STD-6030), [Online]. Available: https://standards.nasa.gov/nasa-technical-standards.

[32] J.J. Lewandowski, M. Seifi, Metal additive manufacturing: a review of mechanical properties, Annu. Rev. Mater. Res. 46 (1) (2016) 151–186, https://doi.org/10.1146/annurev-matsci-070115-032024.

[33] M. Seifi, A. Salem, J. Beuth, O. Harrysson, J.J. Lewandowski, Overview of materials qualification needs for metal additive manufacturing, JOM 68 (3) (2016) 747–764, https://doi.org/10.1007/s11837-015-1810-0.

[34] M. Seifi, M. Gorelik, J. Waller, N. Hrabe, N. Shamsaei, S. Daniewicz, J.J. Lewandowski, Progress towards metal additive manufacturing standardization to support qualification and certification, JOM 69 (3) (2017) 439–455, https://doi.org/10.1007/s11837-017-2265-2.

[35] P. Li, D.H. Warner, A. Fatemi, N. Phan, Critical assessment of the fatigue performance of additively manufactured Ti–6Al–4V and perspective for future research, Int. J. Fatigue 85 (2016) 130–143, https://doi.org/10.1016/j.ijfatigue.2015.12.003.

[36] A. Fatemi, R. Molaei, S. Sharifimehr, N. Phan, N. Shamsaei, Multiaxial fatigue behavior of wrought and additive manufactured Ti-6Al-4V including surface finish effect, Int. J. Fatigue 100 (2017) 347–366, https://doi.org/10.1016/j.ijfatigue.2017.03.044.

[37] A. Fatemi, R. Molaei, S. Sharifimehr, N. Shamsaei, N. Phan, Torsional fatigue behavior of wrought and additive manufactured Ti-6Al-4V by powder bed fusion including surface finish effect, Int. J. Fatigue 99 (2017) 187–201, https://doi.org/10.1016/j.ijfatigue.2017.03.002.

[38] I. Yadroitsev, P. Krakhmalev, I. Yadroitsava, A. du Plessis, Qualification of Ti6Al4V ELI alloy produced by laser powder bed fusion for biomedical applications, JOM 70 (3) (2018) 372–377, https://doi.org/10.1007/s11837-017-2655-5.

[39] ISO/ASTM, Additive Manufacturing - General Principles Terminology (ASTM52900), 2015. https://www.iso.org/standard/69669.html.

[40] T. DebRoy, H.L. Wei, J.S. Zuback, T. Mukherjee, J.W. Elmer, J.O. Milewski, A.M. Beese, A. Wilson-Heid, A. De, W. Zhang, Additive manufacturing of metallic components – Process, structure and properties, Prog. Mater Sci. 92 (2018) 112–224, https://doi.org/10.1016/j.pmatsci.2017.10.001.

[41] A. Uriondo, M. Esperon-Miguez, S. Perinpanayagam, The present and future of additive manufacturing in the aerospace sector: a review of important aspects, Proc. Inst. Mech. Eng., Part G: J. Aerospace Eng. 229 (11) (2015) 2132–2147, https://doi.org/10.1177/0954410014568797.

[42] C.Y. Yap et al., Review of selective laser melting: materials and applications, Appl. Phys. Rev. 2 (4) (2015) 041101, https://doi.org/10.1063/1.4935926.

[43] V. Bhavar, P. Kattire, V. Patil, S. Khot, K. Gujar, R. Singh, A review on powder bed fusion technology of metal additive manufacturing, in: 4th International conference and exhibition on Additive Manufacturing Technologies-AM-2014, 2014, pp. 1–2.

[44] I. Yadroitsev, I. Yadroitsava, A. du Plessis, Basics of laser powder bed fusion, in: Fundamentals of Laser Powder Bed Fusion of Metals, Elsevier, 2021, pp. 15–38. doi: 10.1016/B978-0-12-824090-8.00024-X.

[45] J. Parthasarathy, B. Starly, S. Raman, A. Christensen, Mechanical evaluation of porous titanium (Ti6Al4V) structures with electron beam melting (EBM), J. Mech. Behav. Biomed. Mater. 3 (3) (2010) 249–259, https://doi.org/10.1016/j.jmbbm.2009.10.006.

[46] J.C. Pereira, H. Borovkov, F. Zubiri, M.C. Guerra, J. Caminos, Optimization of thin walls with sharp corners in SS316L and IN718 alloys manufactured with laser metal deposition, J. Manuf. Mater. Process. 5 (1) (2021) 5, https://doi.org/10.3390/jmmp5010005.

[47] P.R. Gradl, C.S. Protz, T. Wammen, Additive manufacturing and hot-fire testing of liquid rocket channel wall nozzles using blown powder directed energy deposition inconel 625 and JBK-75 alloys, (2019) doi: 10.2514/6.2019-4362.

[48] J. Yu, M. Rombouts, G. Maes, F. Motmans, Material properties of Ti6Al4V parts produced by laser metal deposition, Phys. Proc. 39 (2012) 416–424, https://doi.org/10.1016/j.phpro.2012.10.056.

[49] S.M. Kelly, S.L. Kampe, Microstructural evolution in laser-deposited multilayer Ti-6Al-4V builds: Part II. Thermal modeling, Metall. Mater. Trans. A: Phys. Metall. Mater. Sci. 35 (6) (2004) 1869–1879, https://doi.org/10.1007/s11661-004-0095-7.

[50] S.M. Kelly, S.L. Kampe, Microstructural evolution in laser-deposited multilayer Ti-6Al-4V builds: Part 1. Microstructural characterization, Metall. Mater. Trans. A vol. 35 A, 6 (2004) 1861–1867, https://doi.org/10.1007/s11661-004-0094-8.

[51] A. Antonysamy, Microstructure, Texture and Mechanical Property Evolution during Additive Manufacturing of Ti6Al4V Alloy for Aerospace Applications, 2012.

[52] F. Wang, S. Williams, P. Colegrove, A.A. Antonysamy, Microstructure and mechanical properties of wire and arc additive manufactured Ti-6Al-4V, Metall. Mater. Trans. A 44 (2) (2013) 968–977, https://doi.org/10.1007/s11661-012-1444-6.

[53] P. Rambabu, N. Eswara Prasad, V. v. Kutumbarao, R.J.H. Wanhill, Aluminium Alloys for Aerospace Applications, 2017, pp. 29–52. doi: 10.1007/978-981-10-2134-3_2.

[54] A.G. Evans, J.W. Hutchinson, N.A. Fleck, M.F. Ashby, H.N.G. Wadley, The topological design of multifunctional cellular metals, Prog. Mater Sci. 46 (3–4) (2001) 309–327, https://doi.org/10.1016/S0079-6425(00)00016-5.

[55] N. Haghdadi, M. Laleh, M. Moyle, S. Primig, Additive manufacturing of steels: a review of achievements and challenges, J. Mater. Sci. 56 (1) (2021) 64–107, https://doi.org/10.1007/s10853-020-05109-0.

[56] A. Adeyemi, E.T. Akinlabi, R.M. Mahamood, Powder bed based laser additive manufacturing process of stainless steel: a review, Mater. Today:. Proc. 5 (9) (2018) 18510–18517, https://doi.org/10.1016/j.matpr.2018.06.193.

[57] X. Zhang, Y. Chen, J. Hu, Recent advances in the development of aerospace materials, Prog. Aerosp. Sci. 97 (2018) 22–34, https://doi.org/10.1016/j.paerosci.2018.01.001.

[58] M. Peters, J. Kumpfert, C.H. Ward, C. Leyens, Titanium alloys for aerospace applications, Adv. Eng. Mater. 5 (6) (2003) 419–427, https://doi.org/10.1002/adem.200310095.

[59] E. Uhlmann, R. Kersting, T.B. Klein, M.F. Cruz, A.V. Borille, Additive manufacturing of titanium alloy for aircraft components, Procedia CIRP 35 (2015) 55–60, https://doi.org/10.1016/j.procir.2015.08.061.

[60] J.C. Williams, R.R. Boyer, Opportunities and issues in the application of titanium alloys for aerospace components, Metals 10 (6) (2020) 705, https://doi.org/10.3390/met10060705.

[61] K. Minet, A. Saharan, A. Loesser, N. Raitanen, Superalloys, powders, process monitoring in additive manufacturing, in: Additive Manufacturing for the Aerospace Industry, Elsevier Inc., 2019, pp. 163–185. doi: 10.1016/B978-0-12-814062-8.00009-1.

[62] P.R. Gradl, et al., Additive manufacturing of liquid rocket engine combustion devices: a summary of process developments and hot-fire testing results, 2018. doi: 10.2514/6.2018-4625.

[63] M. Perrut, P. Caron, M. Thomas, A. Couret, High temperature materials for aerospace applications: Ni-based superalloys and γ-TiAl alloys, C.R. Phys. 19 (8) (2018) 657–671, https://doi.org/10.1016/j.crhy.2018.10.002.

[64] E. Akca, A. Gürsel, A review on superalloys and IN718 nickel-based INCONEL superalloy, Periodicals Eng. Nat. Sci. (PEN) 3 (1) (2015), https://doi.org/10.21533/pen.v3i1.43.

[65] J.A. Lee, Hydrogen embrittlement of nickel, cobalt and iron-based superalloys, in: Gaseous Hydrogen Embrittlement of Materials in Energy Technologies: The Problem, its Characterisation and Effects on Particular Alloy Classes, Elsevier Ltd., 2012, pp. 624–667. doi: 10.1533/9780857093899.3.624.

[66] P.R. Gradl, C.S. Protz, D.L. Ellis, S.E. Greene, Progress in additively manufactured copper-alloy GRCOP-84, GRCOP-42, and bimetallic combustion chambers for liquid rocket engines, in: Proceedings of the International Astronautical Congress, IAC, 2019, vol. 2019-Octob.

[67] P.R. Gradl, C. Protz, S.E. Greene, D. Ellis, B. Lerch, I. Locci, Development and hot-fire testing of additively manufactured copper combustion chambers for liquid rocket engine applications, 2017. doi: 10.2514/6.2017-4670.

[68] S. Moriya, T. Inoue, M. Sasaki, T. Nakamoto, T. Kimura, N. Nomura, K. Kikuchi, A. Kawasaki, T. Kato, I. Masuda, Feasibility study on additive manufacturing of liquid rocket combustion chamber, Trans. Japan Soc. Aeronaut. Space Sci., Aerospace Technol. Japan 16 (3) (2018) 261–266, https://doi.org/10.2322/tastj.16.261.

[69] H.C. de Groh, D.L. Ellis, W.S. Loewenthal, Comparison of GRCop-84 to other Cu alloys with high thermal conductivities, J. Mater. Eng. Perform. 17 (4) (2008) 594–606, https://doi.org/10.1007/s11665-007-9175-3.

[70] C. Zeng, H. Wen, B.C. Bernard, J.R. Raush, P.R. Gradl, M. Khonsari, S.M. Guo, Effect of temperature history on thermal properties of additively manufactured C-18150 alloy samples, Manuf. Lett. 28 (2021) 25–29, https://doi.org/10.1016/j.mfglet.2021.02.002.

[71] T.J. Horn, D. Gamzina, Additive manufacturing of copper and copper alloys, in: Additive Manufacturing Processes, ASM International, 2020, pp. 388–418. doi: 10.31399/asm.hb.v24.a0006579.

[72] J.W. Morris Jr, Making steel strong and cheap, Nat. Mater. 16 (8) (Aug. 2017) 787–789, https://doi.org/10.1038/nmat4949.

[73] W.M. Garrison, Ultrahigh-strength steels for aerospace applications, Jom 42 (5) (1990) 20–24, https://doi.org/10.1007/BF03220942.

[74] N.R. Philips, M. Carl, N.J. Cunningham, New opportunities in refractory alloys, Metall. Mater. Trans. A 51 (7) (2020) 3299–3310, https://doi.org/10.1007/s11661-020-05803-3.

[75] G.J. Schiller, Additive manufacturing for Aerospace, in: 2015 IEEE Aerospace Conference, 2015, pp. 1–8. doi: 10.1109/AERO.2015.7118958.

[76] J.O. Milewski, Additive manufacturing metal, the art of the possible, 2017, pp. 7–33. doi: 10.1007/978-3-319-58205-4_2.

[77] Folgarait Zitelli, di Schino, Laser powder bed fusion of stainless steel grades: a review, Metals 9 (7) (2019) 731, doi: 10.3390/met9070731.

[78] D. Manfredi, R. Bidulský, Laser powder bed fusion of aluminum alloys, Acta Metall. Slovaca 23 (3) (2017) 276, https://doi.org/10.12776/ams.v23i3.988.

[79] H. Eskandari Sabzi, Powder bed fusion additive layer manufacturing of titanium alloys, Mater. Sci. Technol. 35 (8) (2019) 875–890, https://doi.org/10.1080/02670836.2019.1602974.

[80] Z. Tian, C. Zhang, D. Wang, W. Liu, X. Fang, D. Wellmann, Y. Zhao, Y. Tian, A review on laser powder bed fusion of inconel 625 nickel-based alloy, Applied Sciences 10 (1) (Dec. 2019) 81, https://doi.org/10.3390/app10010081.

[81] P. Gradl, Principles of directed energy deposition for aerospace applications, 2021, doi: 10.13140/RG.2.2.10504.75527.

[82] A. Essop, NASA becomes first customer of HRL high strength aluminum 3d printing powder, 2019. https://3dprintingindustry.com/news/nasa-becomes-first-customer-of-hrl-high-strength-aluminium-3d-printing-powder-163530/ (accessed Mar. 16, 2021).

[83] M. Muhammad, P.D. Nezhadfar, S. Thompson, A. Saharan, N. Phan, N. Shamsaei, A comparative investigation on the microstructure and mechanical properties of additively manufactured aluminum alloys, Int. J. Fatigue 146 (2021) 106165, https://doi.org/10.1016/j.ijfatigue.2021.106165.

[84] N.T. Aboulkhair, M. Simonelli, L. Parry, I. Ashcroft, C. Tuck, R. Hague, 3D printing of aluminium alloys: additive manufacturing of aluminium alloys using selective laser melting, Prog. Mater. Sci. 106 (2019) 100578, https://doi.org/10.1016/j.pmatsci.2019.100578.

[85] S.C. Altıparmak, V.A. Yardley, Z. Shi, J. Lin, Challenges in additive manufacturing of high-strength aluminium alloys and current developments in hybrid additive manufacturing, Int. J. Lightweight Mater. Manuf. 4 (2) (2021) 246–261, https://doi.org/10.1016/j.ijlmm.2020.12.004.

[86] D. Waller, A. Polizzi, J. Iten, Feasibility study of additively manufactured Al-6061 RAM2 parts for aerospace applications, 2019. doi: 10.2514/6.2019-0409.

[87] C. Katsarelis, et al., Additive Manufacturing of NASA HR-1 Material for Liquid Rocket Engine Component Applications, JANNAF Dec, p. https://ntrs.nasa.gov/search.jsp?R=20200001007, 2019, [Online]. Available: https://ntrs.nasa.gov/search.jsp?R=20200001007.

[88] T.M. Pollock, A.J. Clarke, S.S. Babu, Design and tailoring of alloys for additive manufacturing, Metall. Mater. Trans. A 51 (12) (2020) 6000–6019, https://doi.org/10.1007/s11661-020-06009-3.

[89] Y.T. Tang, et al., The Effect of Heat Treatment on Tensile Yielding Response of the New Superalloy ABD-900AM for Additive Manufacturing (2020) 1055–1065. doi: 10.1007/978-3-030-51834-9_103.

[90] Y.T. Tang, C. Panwisawas, J.N. Ghoussoub, Y. Gong, J.W.G. Clark, André.A.N. Németh, D.G. McCartney, R.C. Reed, Alloys-by-design: Application to new superalloys for additive manufacturing, Acta Mater. 202 (2021) 417–436, https://doi.org/10.1016/j.actamat.2020.09.023.

[91] S. Ewald, F. Kies, S. Hermsen, M. Voshage, C. Haase, J.H. Schleifenbaum, Rapid alloy development of extremely high-alloyed metals using powder blends in laser powder bed fusion, Materials 12 (10) (2019) 1706, https://doi.org/10.3390/ma12101706.

[92] P.R. Gradl, S. Greene, T. Wammen, Bimetallic channel wall nozzle development and hot-fire testing using additively manufactured laser wire direct closeout technology, 2019. doi: 10.2514/6.2019-4361.

[93] P.R. Gradl, et al., Lightweight thrust chamber assemblies using multi-alloy additive manufacturing and composite overwrap, 2020. doi: 10.2514/6.2020-3787.

[94] C. Zhang, F. Chen, Z. Huang, M. Jia, G. Chen, Y. Ye, Y. Lin, W. Liu, B. Chen, Q. Shen, L. Zhang, E.J. Lavernia, Additive manufacturing of functionally graded materials: a review, Mater. Sci. Eng., A 764 (2019) 138209, https://doi.org/10.1016/j.msea.2019.138209.

[95] Y. Li, Z. Feng, L. Hao, L. Huang, C. Xin, Y. Wang, E. Bilotti, K. Essa, H. Zhang, Z. Li, F. Yan, T. Peijs, A review on functionally graded materials and structures via additive manufacturing: from multi-scale design to versatile functional properties, Adv. Mater. Technol. 5 (6) (2020) 1900981, https://doi.org/10.1002/admt.v5.610.1002/admt.201900981.

[96] A. Reichardt, A.A. Shapiro, R. Otis, R.P. Dillon, J.P. Borgonia, B.W. McEnerney, P. Hosemann, A.M. Beese, Advances in additive manufacturing of metal-based functionally graded materials, Int. Mater. Rev. 66 (1) (2021) 1–29, https://doi.org/10.1080/09506608.2019.1709354.

[97] J.C. Najmon, S. Raeisi, A. Tovar, Review of additive manufacturing technologies and applications in the aerospace industry, in: Additive Manufacturing for the Aerospace Industry, Elsevier, 2019, pp. 7–31. doi: 10.1016/B978-0-12-814062-8.00002-9.

[98] B. Westerweel, R.J.I. Basten, G.J. van Houtum, Traditional or additive manufacturing? Assessing component design options through lifecycle cost analysis, Eur. J. Oper. Res. 270 (2) (2018) 570–585, https://doi.org/10.1016/j.ejor.2018.04.015.

[99] S. Singamneni, Y. Lv, A. Hewitt, R. Chalk, W. Thomas, D. Jordison, Additive manufacturing for the aircraft industry: a review, J. Aeronaut. Aerospace Eng. 08 (01) (2019), https://doi.org/10.35248/2168-9792.19.8.215.

[100] A. du Plessis, S. Beretta, Killer notches: the effect of as-built surface roughness on fatigue failure in AlSi10Mg produced by laser powder bed fusion, Addit. Manuf. 35 (2020) 101424, https://doi.org/10.1016/j.addma.2020.101424.

[101] A. du Plessis, E. Macdonald, Hot isostatic pressing in metal additive manufacturing: X-ray tomography reveals details of pore closure, Addit. Manuf. 34 (2020) 101191, https://doi.org/10.1016/j.addma.2020.101191.

[102] N. Sanaei, A. Fatemi, Defect-based fatigue life prediction of L-PBF additive manufactured metals, Eng. Fract. Mech. 244 (2021) 107541, https://doi.org/10.1016/j.engfracmech.2021.107541.

[103] A. du Plessis, I. Yadroitsev, I. Yadroitsava, S.G. le Roux, X-ray microcomputed tomography in additive manufacturing: a review of the current technology and applications, 3D Print. Additive Manuf. 5 (3) (2018) 227–247, https://doi.org/10.1089/3dp.2018.0060.

[104] O. Sigmund, K. Maute, Topology optimization approaches: a comparative review, Struct. Multidis. Optim. 48 (6) (2013) 1031–1055, https://doi.org/10.1007/s00158-013-0978-6.

[105] M.P. Bendsøe, N. Kikuchi, Generating optimal topologies in structural design using a homogenization method, Comput. Methods Appl. Mech. Eng. 71 (2) (1988) 197–224, https://doi.org/10.1016/0045-7825(88)90086-2.

[106] F. Cucinotta, E. Guglielmino, G. Longo, G. Risitano, D. Santonocito, F. Sfravara, Topology optimization additive manufacturing-oriented for a biomedical application, in: Lecture Notes in Mechanical Engineering, 2019, pp. 184–193, https://doi.org/10.1007/978-3-030-12346-8_18.

[107] J. Liu et al., Current and future trends in topology optimization for additive manufacturing, Struct. Multidis. Optim. 57 (6) (2018) 2457–2483, https://doi.org/10.1007/s00158-018-1994-3.

[108] M. Benedetti, A. du Plessis, R.O. Ritchie, M. Dallago, S.M.J. Razavi, F. Berto, Architected cellular materials: a review on their mechanical properties towards fatigue-tolerant design and fabrication, Mater. Sci. Eng. R: Rep. 144 (2021) 100606, https://doi.org/10.1016/j.mser.2021.100606.

[109] A. Panesar, M. Abdi, D. Hickman, I. Ashcroft, Strategies for functionally graded lattice structures derived using topology optimisation for Additive Manufacturing, Addit. Manuf. 19 (2018) 81–94, https://doi.org/10.1016/j.addma.2017.11.008.

[110] H. Nakajima, Fabrication, properties and application of porous metals with directional pores, Prog. Mater. Sci. 52 (7) (2007) 1091–1173, https://doi.org/10.1016/j.pmatsci.2006.09.001.

[111] T. Maconachie et al., SLM lattice structures: properties, performance, applications and challenges, Mater. Des. 183 (2019) 108137, https://doi.org/10.1016/j.matdes.2019.108137.

[112] A. du Plessis, C. Broeckhoven, I. Yadroitsava, I. Yadroitsev, C.H. Hands, R. Kunju, D. Bhate, Beautiful and functional: a review of biomimetic design in additive manufacturing, Addit. Manuf. 27 (2019) 408–427, https://doi.org/10.1016/j.addma.2019.03.033.

[113] C. Yan, L. Hao, A. Hussein, P. Young, D. Raymont, Advanced lightweight 316L stainless steel cellular lattice structures fabricated via selective laser melting, Mater. Des. 55 (2014) 533–541, https://doi.org/10.1016/j.matdes.2013.10.027.

[114] C. Yan, L. Hao, A. Hussein, D. Raymont, Evaluations of cellular lattice structures manufactured using selective laser melting, Int. J. Mach. Tools Manuf 62 (2012) 32–38, https://doi.org/10.1016/j.ijmachtools.2012.06.002.

[115] J.-H. Zhu, W.-H. Zhang, L. Xia, Topology optimization in aircraft and aerospace structures design, Arch. Comput. Methods Eng. 23 (4) (2016) 595–622, https://doi.org/10.1007/s11831-015-9151-2.

[116] M. Tomlin, J. Meyer, Topology optimization of an additive layer manufactured (ALM) aerospace part, in: The 7th Altair CAE Technology Conference 2011, pp. 1–9, 2011.

[117] L. Meng, W. Zhang, D. Quan, G. Shi, L. Tang, Y. Hou, P. Breitkopf, J. Zhu, T. Gao, From topology optimization design to additive manufacturing: today's success and tomorrow's roadmap, Arch. Comput. Methods Eng. 27 (3) (2020) 805–830, https://doi.org/10.1007/s11831-019-09331-1.

[118] D. Jia, F. Li, Y. Zhang, 3D-printing process design of lattice compressor impeller based on residual stress and deformation, Sci. Rep. 10 (1) (2020) 600, https://doi.org/10.1038/s41598-019-57131-1.

[119] P. Rochus, J.-Y. Plesseria, M. van Elsen, J.-P. Kruth, R. Carrus, T. Dormal, New applications of rapid prototyping and rapid manufacturing (RP/RM) technologies for space instrumentation, Acta Astronaut. 61 (1–6) (2007) 352–359, https://doi.org/10.1016/j.actaastro.2007.01.004.

[120] EOS GmbH, Certified for Universal Success: Additive Manufacturing of Satellite Components. 2018. [Online]. Available: https://cdn.eos.info/b63671baf552082c/88339183a70a/CS_M_Aerospace_RUAG_Citim_en_WEB.pdf.

[121] EOS, Future Ariane propulsion module: Simplified by additive manufacturing, 2018. https://www.eos.info/01_parts-and-applications/case_studies_

applications_parts/_case_studies_pdf/en_cases/cs_m_aerospace_arianegroup_en.pdf.

[122] NASA, NASA Tests Limits of 3-D Printing with Powerful Rocket Engine Check, 2013. https://www.nasa.gov/exploration/systems/sls/3d-printed-rocket-injector.html (accessed Mar. 16, 2021).

[123] NASA, Hot-Fire Tests Show 3-D Printed Rocket Parts Rival Traditionally Manufactured Parts, 2013. https://www.nasa.gov/exploration/systems/sls/3dprinting.html (accessed Mar. 15, 2021).

[124] S. Kim, S.K. Moon, A part consolidation design method for additive manufacturing based on product disassembly complexity, Appl. Sci. 10 (3) (2020) 1100, https://doi.org/10.3390/app10031100.

[125] T.D. Ngo, A. Kashani, G. Imbalzano, K.T.Q. Nguyen, D. Hui, Additive manufacturing (3D printing): A review of materials, methods, applications and challenges, Compos. B Eng. 143 (2018) 172–196, https://doi.org/10.1016/j.compositesb.2018.02.012.

[126] ManufacturingTalkRadio, Pratt & Whitney uses 3D printing for Aero Engine Parts, 2019. https://optics.org/news/6/4/7.

[127] P. Gradl, O. Mireles, N. Andrews, Intro to additive manufacturing for propulsion systems, in: AIAA Joint Propulsion Conference, 2018, p. 83, [Online]. Available: https://ntrs.nasa.gov/api/citations/20180006357/downloads/20180006357.pdf.

[128] J. Loy, P. Tatham, Redesigning production systems, Environ. Footprints Eco-Des. Prod. Process. (2016) 145–168, https://doi.org/10.1007/978-981-10-0549-7_7.

[129] General Electric - Additive, GE9X Engine Additive Parts, https://www.ge.com/additive/sites/default/files/2020-08/GE9X Additive parts.pdf (accessed Feb. 02, 2021).

[130] D. Saltzman, et al., Design and evaluation of an additively manufactured aircraft heat exchanger, vol. 138. Elsevier Ltd, 2018, pp. 254–263. doi: 10.1016/j.applthermaleng.2018.04.032.

[131] M. Bici, S. Brischetto, F. Campana, C.G. Ferro, C. Seclì, S. Varetti, P. Maggiore, A. Mazza, Development of a multifunctional panel for aerospace use through SLM additive manufacturing, Procedia CIRP 67 (2018) 215–220, https://doi.org/10.1016/j.procir.2017.12.202.

[132] S. Donath, 3D printing a rocket engine, 2019. https://www.etmm-online.com/3d-printing-a-rocket-engine-a-886960/.

[133] P.R. Gradl, C.S. Protz, Technology advancements for channel wall nozzle manufacturing in liquid rocket engines, Acta Astronaut. 174 (2020) 148–158, https://doi.org/10.1016/j.actaastro.2020.04.067.

[134] P.R. Gradl, C.S. Protz, K. Cooper, D. Ellis, L.J. Evans, C. Garcia, GRCop-42 development and hot-fire testing using additive manufacturing powder bed fusion for channel-cooled combustion chambers, 2019. doi: 10.2514/6.2019-4228.

[135] S. Woolley, Hot Stuff: To Build More Affordable Rocket Engines, NASA Researchers Are Using The Latest 3D Printers — And 1 Ancient Metal, 2019. https://www.ge.com/news/reports/hot-stuff-to-build-more-affordable-rocket-engines-nasa-researchers-are-using-the-latest-3d-printers-and-1-ancient-metal (accessed Mar. 16, 2021).

[136] Team NASA, NASA Advances New Alloys and Scale of Metal Additive Manufacturing, 2021. https://3dprint.com/278670/nasa-advances-new-alloys-and-scale-of-metal-additive-manufacturing/ (accessed Mar. 16, 2021).

[137] NASA, 3D Printed Rocket Engine Parts Survive 23 Hot-Fire Tests, 2020. https://www.nasa.gov/centers/marshall/news/releases/2020/3d-printed-rocket-engine-parts-survive-23-hot-fire-tests.html (accessed Mar. 16, 2021).

[138] R. Liu, Z. Wang, T. Sparks, F. Liou, J. Newkirk, Aerospace applications of laser additive manufacturing, in: Laser Additive Manufacturing: Materials, Design, Technologies, and Applications, Elsevier, 2017, pp. 351–371. doi: 10.1016/B978-0-08-100433-3.00013-0.

[139] E. RUAG Altair, Sentinel Antenna Bracket, https://www.eos.info/01_parts-and-applications/case_studies_applications_parts/_case_studies_pdf/en_cases/cs_m_aerospace_ruag_en.pdf (accessed Feb. 02, 2021).

[140] Altair, Generative Design and Topology Optimization, 2019. [Online]. Available: https://web.altair.com/generative-design-report?product__c=Inspire&msdcampaignid=CMP-06217-C9P7Y&detailed_lead_source=AdWords_Generative_Design_ad&campaign_source=AdWords&utm_campaign=Generative+Design&utm_term=%2Bgenerative %2Bdesign&utm_medium=ppc&utm.

[141] Optomec, LENS® Component Repair Solution, 2016. https://optomec.com/wp-content/uploads/2014/04/Optomec_LENS_Blisk_Repair_Datasheet.pdf.

[142] P.R. Gradl, C.S. Protz, K. Zagorski, V. Doshi, H. McCallum, Additive manufacturing and hot-fire testing of bimetallic GRCop-84 and C-18150 channel-cooled combustion chambers using powder bed fusion and inconel 625 hybrid directed energy deposition, 2019. doi: 10.2514/6.2019-4390.

[143] M. Leary, Design for additive manufacturing, 2019, doi: 10.1016/C2017-0-04238-6.

[144] J.-H. Zhu, Y. Li, W.-H. Zhang, J. Hou, Shape preserving design with structural topology optimization, Struct. Multidiscip. Optim. 53 (4) (2016) 893–906, https://doi.org/10.1007/s00158-015-1364-3.

[145] L.J. Kumar, C.G. Krishnadas Nair, Current trends of additive manufacturing in the aerospace industry, in: Advances in 3D Printing & Additive Manufacturing Technologies, Springer Singapore, Singapore, 2017, pp. 39–54. doi: 10.1007/978-981-10-0812-2_4.

[146] M.E. Orme, M. Gschweitl, M. Ferrari, I. Madera, F. Mouriaux, Designing for additive manufacturing: lightweighting through topology optimization enables lunar spacecraft, J. Mech. Des., Trans. ASME 139 (10) (2017), https://doi.org/10.1115/1.4037304.

[147] N. Titanium, Norsk Titanium to Deliver the World's First FAA-Approved, 3D-Printed, Structural Titanium Components to Boeing | Additive Manufacturing (AM), [Online]. Available: http://additivemanufacturing.com/2017/04/10/norsk-titanium-to-deliver-the-worlds-first-faa-approved-3d-printed-structural-titanium-components-to-boeing/.

[148] Marie Caujolle, First titanium 3D-printed part installed into serial production aircraft, 2017. https://www.airbus.com/newsroom/press-releases/en/2017/09/first-titanium-3d-printed-part-installed-into-serial-production-.html (accessed Feb. 02, 2021).

[149] D.A. Pisano, J.L. Bromberg, NASA and the Space Industry 105 (5) (2000) doi: 10.2307/2652132.

[150] P. Kit, Jupiter Orbit Insertion - Press Kit, 2016. [Online]. Available: https://www.jpl.nasa.gov/news/press_kits/juno/.

[151] S.M. Yusuf, S. Cutler, N. Gao, S. Mohd Yusuf, S. Cutler, N. Gao, Review: the impact of metal additive manufacturing on the aerospace industry, Metals 9 (12) (2019) 1286, https://doi.org/10.3390/met9121286.

[152] L. Valdevit, A.J. Jacobsen, J.R. Greer, W.B. Carter, Protocols for the optimal design of multi-functional cellular structures: from hypersonics to micro-architected materials, J. Am. Ceramic Soc. 94 (2011) s15–s34, https://doi.org/10.1111/j.1551-2916.2011.04599.x.

[153] Y. Wang, L. Zhang, S. Daynes, H. Zhang, S. Feih, M.Y. Wang, Design of graded lattice structure with optimized mesostructures for additive manufacturing, Mater. Des. 142 (2018) 114–123, https://doi.org/10.1016/j.matdes.2018.01.011.

[154] A. Hussein, L. Hao, C. Yan, R. Everson, P. Young, Advanced lattice support structures for metal additive manufacturing, J. Mater. Process. Technol. 213 (7) (2013) 1019–1026, https://doi.org/10.1016/j.jmatprotec.2013.01.020.

[155] nTopology, Air Force optimizes cubesat using Architected Materials. https://ntopology.com/case-studies/air-force-optimizes-cubesat-using-architected-materials/ (accessed Feb. 15, 2021).

[156] L. Chougrani, J.-P. Pernot, P. Véron, S. Abed, Parts internal structure definition using non-uniform patterned lattice optimization for mass reduction in additive manufacturing, Eng. Comput. 35 (1) (2019) 277–289, https://doi.org/10.1007/s00366-018-0598-2.

[157] Thales Alenia Space, Diphasic heat spreader, 2017. https://www.metal-am.com/large-scale-metal-lattice-structure-complex-satellite-part/ (accessed Mar. 22, 2021).

[158] D. Nagy, D. Zhao, D. Benjamin, Nature-based hybrid computational geometry system for optimizing component structure, in: Humanizing Digital Reality, Springer Singapore, Singapore, 2018, pp. 167–176. doi: 10.1007/978-981-10-6611-5_15.

[159] Airbus Group, Pioneering bionic 3D printing - Learning from nature, 2016. https://www.airbus.com/newsroom/news/en/2016/03/Pioneering-bionic-3D-printing.html.

[160] B. Danon, How this light-weight airplane seat can save airlines $200,000,000 (and dramatically reduce carbon emissions), 2017. https://adsknews.autodesk.com/stories/how-this-light-weight-airplane-seat-can-save-airlines-200000000-and-dramatically-reduce-carbon-emissions.

[161] F. Froes, Combining additive manufacturing with conventional casting and reduced density materials to greatly reduce the weight of airplane components such as passenger seat frames, in: Additive Manufacturing for the Aerospace Industry, Elsevier, 2019, pp. 419–425. doi: 10.1016/B978-0-12-814062-8.00021-2.

[162] W. Tao, M.C. Leu, Design of lattice structure for additive manufacturing, in: 2016 International Symposium on Flexible Automation (ISFA), 2016, pp. 325–332. doi: 10.1109/ISFA.2016.7790182.

[163] T. Allison, A. Rimple, R. Pelton, J. Moore, J. Wilkes, K. Wygant, Manufacturing and testing experience with direct metal laser sintering for closed centrifugal compressor impellers, 2014. doi: https://doi.org/10.21423/R1F64W.

[164] C. Noon, Taking Wing: Boeing's 777X, Powered By GE's Record-Breaking Engines, Soars Above Seattle, 2020. [Online]. Available: https://www.ge.com/news/reports/taking-wing-boeings-777x-powered-by-ges-record-breaking-engines-soars-above-seattle.

[165] S. Gautam Chhibber, S.T. Jahrmarcht, Stack Up the Layers WP, 2020. [Online]. Available: https://assets.new.siemens.com/siemens/assets/api/uuid:a4659ee4-06f3-4089-91cb-399854611dbb/version:1588178306/wp-march2020-stackupthelayers-article.pdf.

[166] D. Godfrey, Additive Manufacturing (AM) and the Honeywell Global Initiative, in: International Society of Air Breathing Engines Conference, Phoenix, AZ., 2015, [Online]. Available: https://drc.libraries.uc.edu/bitstream/handle/2374.UC/745770/ISABE2015_CS%26A_Donald Godfrey_227_MANUSCRIPT_20193.pdf?sequence=2.

[167] General Electric, New manufacturing milestone: 30,000 additive fuel nozzles, GE Additive, 2018. https://www.ge.com/additive/stories/new-manufacturing-milestone-30000-additive-fuel-nozzles%0Ahttps://www.ge.com/additive/blog/new-manufacturing-milestone-30000-additive-fuel-nozzles.

[168] C. Hauser, Case study: laser powder metal deposition manufacturing of complex real parts, Materials Joining and Engineering Technologies, 2014. https://docplayer.net/48458850-Case-study-laser-powder-metal-deposition-manufacturing-of-complex-real-parts.html.

[169] W.E. Frazier, Metal additive manufacturing: a review, J. Mater. Eng. Perf. 23 (6) (2014) 1917–1928, https://doi.org/10.1007/s11665-014-0958-z.

[170] F. Walachowicz, I. Bernsdorf, U. Papenfuss, C. Zeller, A. Graichen, V. Navrotsky, N. Rajvanshi, C. Kiener, Comparative energy, resource and recycling lifecycle analysis of the industrial repair process of gas turbine

burners using conventional machining and additive manufacturing, J. Ind. Ecol. 21 (S1) (2017) S203–S215, https://doi.org/10.1111/jiec.2017.21.issue-S110.1111/jiec.12637.

[171] Optomec, LENS® Component Repair Solution, 2016. https://optomec.com/wp-content/uploads/2014/04/Optomec_LENS_Blisk_Repair_Datasheet.pdf (accessed Feb. 02, 2021).

[172] F. Froes, R. Boyer, Additive manufacturing for the aerospace industry, Additive Manuf. Aerospace Ind. (2019) 1–482, https://doi.org/10.1201/9780429466236-10.

[173] L. Xue, Y. Li, J. Chen, S. Wang, laser consolidation: a novel additive manufacturing process for making net-shape functional metallic components for gas turbine applications, in: Proceedings of the ASME Turbo Expo, vol. 6, 2015. doi: 10.1115/GT2015-43971.

[174] NASA, NASA Rocket Fuel Pump Tests Pave Way for Methane-Fueled Mars Lander, 2016. https://www.nasa.gov/centers/marshall/news/news/releases/2016/nasa-rocket-fuel-pump-tests-pave-way-for-methane-fueled-mars-lander.html (accessed Mar. 16, 2021).

[175] NASA, Successful NASA Rocket Fuel Pump Tests Pave Way for 3-D Printed Demonstrator Engine, 2015. https://www.nasa.gov/centers/marshall/news/news/releases/2015/successful-nasa-rocket-fuel-pump-tests-pave-way-for-3-d-printed-demonstrator-engine.html (accessed Mar. 16, 2021).

[176] P. Gradl, et al., Additive manufacturing overview : propulsion applications, design for and lessons learned, 2018, no. December 2017. [Online]. Available: https://core.ac.uk/download/pdf/154738243.pdf.

[177] B. West, E. Robertson, R. Osborne, M. Calvert, Additive manufacturing for affordable rocket engines, 2016, [Online]. Available: http://hdl.handle.net/2060/20160012051.

[178] D. O'Neal, Evaluation of Additively Manufactured Demonstration Hardware for a Turbopump Application, 2014. [Online]. Available: https://ntrs.nasa.gov/api/citations/20140016517/downloads/20140016517.pdf.

[179] D. Jafari, W.W. Wits, The utilization of selective laser melting technology on heat transfer devices for thermal energy conversion applications: a review, Renewable Sustainable Energy Rev. 91 (2018) 420–442, https://doi.org/10.1016/j.rser.2018.03.109.

[180] P.R. Gradl, Rapid fabrication techniques for liquid rocket channel wall nozzles, 2016. doi: 10.2514/6.2016-4771.

[181] Z. Gobetz, A. Rowen, C. Dickman, K. Meinert, R. Martukanitz, Utilization of additive manufacturing for aerospace heat exchangers, 2016, [Online]. Available: https://apps.dtic.mil/sti/citations/AD1010878.

[182] NASA, NASA's Perseverance Rover Bringing 3D-Printed Metal Parts to Mars, 2020. http://www.nasa.gov/feature/jpl/nasas-perseverance-rover-bringing-3d-printed-metal-parts-to-mars (accessed Feb. 19, 2021).

[183] H.P. de Bock, Exploration of a hybrid analytical thermal topology optimization method for an additively manufactured heat sink, in: 2018 17th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm), May, 2018, pp. 761–767, https://doi.org/10.1109/ITHERM.2018.8419585.

[184] Conflux Technologies, Conflux sectioned F1 heat exchanger. https://www.eos.info/01_parts-and-applications/case_studies_applications_parts/_case_studies_pdf/en_cases/cs_m_industry_conflux_en.pdf%0A (accessed Feb. 02, 2021).

[185] nTopology, Cobra Aero uses multiphysics simulation to optimize UAV engine for thermal mitigation. https://ntopology.com/case-studies/cobra-aero/ (accessed Feb. 16, 2021).

[186] Hieta, High and Low tempurature heat exchangers. https://www.hieta.biz/wp-content/uploads/2018/09/HiETA-Brochure.pdf (accessed Feb. 02, 2021).

[187] A. Orlova, R. Nogueira, P. Chimenti, The present and future of the space sector: a business ecosystem approach, Space Policy 52 (2020) 101374, https://doi.org/10.1016/j.spacepol.2020.101374.

[188] R. Pyle, Space 2.0: How Private Spaceflight, a Resurgent NASA, and International Partners are Creating a New Space Age. 2019. [Online]. Available: https://books.google.com/books?hl=en&lr=&id=IxRbDwAAQBAJ&oi=fnd&pg=PT295&dq=cosmic+dust+nasa&ots=MfLHyB6N1y&sig=DuM9nZMGtN1w6uUSgUWCF7OgEWE.

[189] K. Whealan George, The economic impacts of the commercial space industry, Space Policy 47 (2019) 181–186, https://doi.org/10.1016/j.spacepol.2018.12.003.

[190] J.E. Catchpole, The International Space Station. Praxis, New York, NY, 2008. doi: 10.1007/978-0-387-78145-7.

[191] C. Marchesan, Linkdin Post. https://www.linkedin.com/feed/update/urn:li:activity:6742612928245198848/ (accessed Dec. 10, 2020).

[192] C. Suborbitals, Coaxial Swirl Injectors. https://www.3dprintingmedia.network/copenhagen-suborbitals-3d-prints-coaxial-swirl-injector-by-metal-binder-jetting/ (accessed Feb. 02, 2021).

[193] M. K. Ilja Müller, I. Petkov, S. Bletsch, K. Huybrechts, P. van Cauwenbergh, 3D-PRINTED COAXIAL INJECTOR FOR A LOX/KEROSENE ROCKET ENGINEle.

[194] NASA, Rocket Injector. https://www.designworldonline.com/building-a-3d-printed-rocket-engine/ (accessed Feb. 02, 2021).

[195] NASA, RS-25 Pogo z-baffle. https://www.nasa.gov/exploration/systems/sls/j2x/3d_print.html (accessed Feb. 02, 2021).

[196] Aerojet Rocketdyne, AR1 Preburner. https://3dprintingindustry.com/news/aerojet-rocketdyne-successfully-tests-3d-printed-ar1-engine-bid-replace-current-rd-180-112732/ (accessed Feb. 02, 2021).

[197] Aerojet Rocketdyne, Thrust Chamber. https://www.i3dmfg.com/aerojet-rocketdyne-tests-3d-printed-thrust-chamber-success/ (accessed Feb. 02, 2021).

[198] E. Ariane Group, Rocket Combustion Chamber. https://3dprintingindustry.com/news/arianegroup-successfully-tests-fully-3d-printed-combustion-chamber-for-esa-rocket-engine-172357/ (accessed Feb. 02, 2021).

[199] L. Sorrentino, M. Marchetti, C. Bellini, A. Delfini, M. Albano, Design and manufacturing of an isogrid structure in composite material: numerical and experimental results, Compos. Struct. 143 (2016) 189–201, https://doi.org/10.1016/j.compstruct.2016.02.043.

[200] Lockheed Martin, Satalite Fuel Tank. https://news.lockheedmartin.com/2018-07-11-Giant-Satellite-Fuel-Tank-Sets-New-Record-for-3-D-Printed-Space-Parts#assets_115 (accessed Feb. 02, 2021).

[201] Relativity Space, Terran 1 Fuel Tank. https://spectrum.ieee.org/aerospace/space-flight/the-worlds-largest-3d-metal-printer-is-churning-out-rockets (accessed Feb. 02, 2021).

[202] SpaceX, SuperDraco Engine Chamber. https://www.designnews.com/design-hardware-software/spacex-reveals-3d-printed-rocket-engine-parts (accessed Feb. 02, 2021).

[203] S. Clark, Astronauts fly with SpaceX in landmark launch for commercial spaceflight. [Online]. Available: https://spaceflightnow.com/2020/11/16/astronauts-ride-spacex-crew-capsule-in-landmark-launch-for-commercial-spaceflight/.

[204] SpaceX, SuperDraco Test Fire Mosaic, 2015. https://www.flickr.com/photos/spacex/22925132396/in/photolist-rzAxfp-AVPiao/ (accessed Mar. 16, 2021). https://creativecommons.org/licenses/by/2.0/.

[205] SpaceX, SuperDracos, 2014. https://www.flickr.com/photos/spacex/16789102495/in/photolist-rzAxfp-AVPiao/ (accessed Mar. 16, 2021). https://creativecommons.org/licenses/by/2.0/.

[206] RocketLab, Rutherford Engine. https://amfg.ai/2019/08/28/application-spotlight-3d-printed-rockets-and-the-future-of-spacecraft-manufacturing/ (accessed Feb. 02, 2021).

[207] Relativity Space, Aeon Engine. https://spectrum.ieee.org/aerospace/space-flight/the-worlds-largest-3d-metal-printer-is-churning-out-rockets (accessed Feb. 02, 2021).

[208] L. EOS, E-2 Rocket Engine. https://launcherspace.com/engine-2 (accessed Feb. 02, 2021).

[209] Team NASA, NASA Advances New Alloys and Scale of Metal Additive Manufacturing, 2021. https://3dprint.com/278670/nasa-advances-new-alloys-and-scale-of-metal-additive-manufacturing/amp/ (accessed Feb. 21, 2021).

[210] P. Gradl, Principles of Directed Energy Deposition for Aerospace Applications, 2021. doi: https://doi.org/10.13140.

[211] W. Bryan, Future Rocket Engines May Include Large-Scale 3D Printing, 2020. https://www.nasa.gov/centers/marshall/news/releases/2020/future-rocket-engines-may-include-large-scale-3d-printing.html (accessed Mar. 16, 2021).

[212] Team NASA, NASA Advances New Alloys and Scale of Metal Additive Manufacturing, 2021. https://3dprint.com/278670/nasa-advances-new-alloys-and-scale-of-metal-additive-manufacturing/ (accessed Feb. 21, 2021).

[213] J. Hahn, Hyperganic uses AI to design 3D-printed rocket engine, 2020. https://www.dezeen.com/2020/03/30/hyperganic-ai-rocket-engine-3d-printed/ (accessed Feb. 02, 2021).

[214] Airborne Engineering, 3D printing technology provides another breakthrough at Westcott, 2019. https://www.westcottvp.com/news-and-insights/news/3d-printing-technology-provides-another-breakthrough-at-westcott (accessed Mar. 26, 2021).

[215] Airbus, Reflector Bracket. https://www.eos.info/01_parts-and-applications/case_studies_applications_parts/_case_studies_pdf/en_cases/cs_m_aerospace_airbus_en.pdf (accessed Feb. 02, 2021).

[216] Airbus, A350 Cabin Bracket Connector. https://www.makepartsfast.com/additive-manufacturing-enables-bionic-aircraft-designs/ (accessed Feb. 02, 2021).

[217] Airbus, A350 XWB Pylon Bracket. https://www.airbus.com/newsroom/press-releases/en/2017/09/first-titanium-3d-printed-part-installed-into-serial-production-.html (accessed Feb. 02, 2021).

[218] A. 3D Systems, RF Filter. https://www.3dsystems.com/customer-stories/first-air-worthy-metal-printed-rf-filter-ready-take (accessed Feb. 02, 2021).

[219] A. EOS, Aircraft Door Locking Shaft. https://www.eos.info/en/3d-printing-examples-applications/aerospace-3d-printing/airbus-case-study (accessed Feb. 02, 2021).

[220] Autodesk, Bionic Partition Project, 2016. https://www.archdaily.com/780661/the-livings-parametric-3d-printed-airplane-partition-is-designed-to-mimic-bone-structure (accessed Feb. 02, 2021).

[221] S. Amaero Engineering, Aero-Engine. https://sief.org.au/wp-content/uploads/2019/02/RP04-153AeroFinalReportSummary.pdf (accessed Feb. 02, 2021).

[222] E. Ariane Group, Ariane 6 Injector head. https://www.eos.info/01_parts-and-applications/case_studies_applications_parts/_case_studies_pdf/en_cases/cs_m_aerospace_arianegroup_en.pdf (accessed Feb. 02, 2021).

[223] Autodesk, Lattice Aircraft Seat. https://adsknews.autodesk.com/stories/how-this-light-weight-airplane-seat-can-save-airlines-200000000-and-dramatically-reduce-carbon-emissions (accessed Feb. 02, 2021).

[224] Betatype Ltd, Rocket Nozzle - Betatype, 2020. https://www.betaty.pe/case-studies/rocket-nozzle/ (accessed Feb. 02, 2021).

[225] Blue Origin, BE-7 Engine. https://www.amchronicle.com/news/blue-origin-3d-printed-be-7-engine-confirms-capability-to-land-on-moon/ (accessed Feb. 02, 2021).

[226] Blue Origin, Jeff Bezos gives a geeky boost to Blue Origin's BE-4 rocket engine boost pump, 2017. https://www.geekwire.com/2017/jeff-bezos-blue-origin-be4-ox-boost-pump/ (accessed Mar. 17, 2021).

[227] D. 3D systems, Liquid Rocket Engine Injector. https://www.small-launcher.eu/wp-content/uploads/Müller-3d-printed-coaxial-injector-for-a-LOX-kerosene-rocket-engine-SP2018_176-Sevilla-2018.pdf (accessed Feb. 02, 2021).

[228] E. Airbus, Borescope Bosses. https://www.eos.info/01_parts-and-applications/case_studies_applications_parts/_case_studies_pdf/en_cases/cs_m_aerospace_mtuaeroengines_en.pdf (accessed Feb. 02, 2021).

[229] E. Airbus, Hydraulic spoiler manifold. https://www.eos.info/01_parts-and-applications/case_studies_applications_parts/_case_studies_pdf/en_cases/cs_m_aerospace_liebherr_en.pdf (accessed Feb. 02, 2021).

[230] E. Vectoflow, Flow Meusurement Probe. https://www.eos.info/01_parts-and-applications/case_studies_applications_parts/_case_studies_pdf/en_cases/cs_m_aerospace_vectoflow_en.pdf (accessed Feb. 02, 2021).

[231] S., A. EOS, Vertical tail plane bracket. https://www.eos.info/01_parts-and-applications/case_studies_applications_parts/_case_studies_pdf/en_cases/cs_m_aerospace_sogeti_en.pdf (accessed Feb. 02, 2021).

[232] F. 3D Systems, GE Aircraft Bracket. https://www.3dsystems.com/learning-center/case-studies/topology-optimization-and-dmp-combine-meet-ge-aircraft-engine-bracket (accessed Feb. 02, 2021).

[233] General Electric - Additive, Sump Cover. https://www.ge.com/additive/us-air-force (accessed Feb. 02, 2021).

[234] General Electric - Additive, NACA inlet. https://www.ge.com/additive/sites/default/files/2020-06/GE_Addworks_Brochure_US_EN_Digital.pdf (accessed Feb. 02, 2021).

[235] GKN Aerospace and ArianeGroup, GKN Aerospace Wins ArianeGroup Contract for Ground-breaking Additively Manufactured Rocket Engine Turbines, 2018.

[236] GKN Aerospace, Tubine exhaust casting H sectors, 2020. https://www.gknaerospace.com/en/our-technology/2020/gkn-aerospace-ansys-and-additive-industries-have-collaborated-to-demonstrate-their-shared-capabilities-in-the-production-of-a-large-aero-engine-component/ (accessed Jun. 10, 2021).

[237] GKN Aerospace, GKN Aerospace: The development of Additive Manufacturing at a global Tier 1 aerospace supplier, 2016. https://www.metal-am.com/articles/gkn-aerospace-3d-printing-at-a-tier-1-aerospace-supplier/ (accessed Jun. 10, 2021).

[238] GKN Aerospace, GKN Aerospace engine systems journey to introduce additive manufacturing, 2017. https://www.gknaerospace.com/en/our-technology/2017/gkn-aerospace-engine-systems-journey-to-introduce-additive-manufacturing/ (accessed Jun. 10, 2021).

[239] GKN Aerospace, GKN Aerospace has successful first flight of additive manufactured optical ice detection probe, 2017. https://www.gknaerospace.com/en/newsroom/news-releases/2017/gkn-aerospace-has-successful-first-flight-of-additive-manufactured-optical-ice-detection-probe/ (accessed Jun. 10, 2021).

[240] L.S. Oerlikon, Propulsion system Impeller. http://lenaspace.com/2017/06/16/lena-space-developing-turbopumps/ (accessed Feb. 02, 2021).

[241] L.-A. Airbus, Landing Gear Sensor Bracket. https://amfg.ai/2020/01/23/applications-spotlight-3d-printed-brackets/ (accessed Feb. 02, 2021).

[242] NASA, Rocket Combustion Chamber. https://3dprint.com/59881/nasa-3d-prints-copper-rocket/ (accessed Feb. 02, 2021).

[243] NASA, Rocket Engine. https://3dprint.com/111799/nasa-3d-printed-rocket-engine/ (accessed Feb. 02, 2021).

[244] NASA, SLS B2 Turbopump. https://www.nasa.gov/centers/marshall/news/news/releases/2015/successful-nasa-rocket-fuel-pump-tests-pave-way-for-3-d-printed-demonstrator-engine.html (accessed Feb. 02, 2021).

[245] NASA, Pogo Accumulator Assembly. https://3dprint.com/205157/nasa-tests-rs-25-engines/ (accessed Feb. 02, 2021).

[246] NASA, Maintenance Port Cover. https://www.nasa.gov/exploration/systems/sls/j2x/3d_print.html (accessed Feb. 02, 2021).

[247] Oerlikon, Turbine Blade. https://www.oerlikon.com/stories/2018/08/03/whats-being-added-to-additive-manufacturing/ (accessed Feb. 02, 2021).

[248] Oerlikon, Double Nozzle. https://www.metal-am.com/articles/oerlikon-a-leading-developer-of-3d-printed-components-and-materials/ (accessed Feb. 02, 2021).

[249] Orbex, Rocket Engine. https://www.aero-mag.com/orbex-single-piece-rocket-engine-3d-printing-slm-800/ (accessed Feb. 02, 2021).

[250] Orbital ATK, Orbital ATK Successfully Tests Hypersonic Engine Combustor Produced Through Additive Manufacturing, 2016. http://www.parabolicarc.com/2016/01/19/orbital-atk-successfully-tests-hypersonic-engine-combustor-produced-additive-manufacturing/ (accessed Mar. 17, 2021).

[251] Parabilis Space Technologies, Multi-Material Nozzle. https://parabilis-space.com/december-8-2017-parabilis-demonstrates-multi-material-printing-technology/ (accessed Feb. 02, 2021).

[252] P.S. Technologies, RCS Thruster. https://parabilis-space.com/october-30-2017-parabilis-test-fires-innovative-3d-printed-thruster/ (accessed Feb. 02, 2021).

[253] E. RUAG Altair, Star Tracker Bracket. https://cdn2.hubspot.net/hubfs/47251/Altair_Generative_Design_Report.pdf (accessed Feb. 02, 2021).

[254] E. RUAG Altair, LEROS Engine support bracket. https://cdn2.hubspot.net/hubfs/47251/Altair_Generative_Design_Report.pdf (accessed Feb. 02, 2021).

[255] Siemens, High Pressure Hydraulic Manifold. https://www.siemens-energy.com/global/en/news/key-topics/additive-manufacturing.html#Download (accessed Feb. 02, 2021).

[256] SpaceX, Main Oxidiser Valve Body. https://www.designnews.com/design-hardware-software/spacex-reveals-3d-printed-rocket-engine-parts (accessed Feb. 02, 2021).

[257] SpaceX, Raptor Engine Components. https://spaceflight101.com/spx/spacex-raptor/ (accessed Feb. 02, 2021).

[258] S.A. Boeing, Acess Door Latch. https://www.additivemanufacturing.media/articles/what-is-the-role-for-additive-manufacturing-in-aircraft-structural-components (accessed Feb. 02, 2021).

[259] T.A.S. 3D Systems, Antenna Bracket. https://www.3dsystems.com/learning-center/case-studies/tipping-point (accessed Feb. 02, 2021).

[260] The Welding Institute, Helicopter combustion chamber. https://docplayer.net/48458850-Case-study-laser-powder-metal-deposition-manufacturing-of-complex-real-parts.html (accessed Feb. 02, 2021).

[261] ULA, Vulcan Bellows Feedline Housing. https://www.ge.com/additive/sites/default/files/2019-05/GE Additive Print Services - Large Format Prints - ULA Case Study.pdf (accessed Feb. 02, 2021).

[262] NASA and Virgin Orbit, NASA and Virgin Orbit 3D Print, Test Rocket Combustion Chamber, 2019. https://www.nasa.gov/centers/marshall/news/news/releases/2019/nasa-and-virgin-orbit-3d-print-test-rocket-combustion-chamber.html (accessed Mar. 17, 2021).

[263] M. Godec et al., Hybrid additive manufacturing of Inconel 718 for future space applications, Mater. Charact. 172 (2021), https://doi.org/10.1016/j.matchar.2020.110842.

[264] Z. Zhan, H. Li, A novel approach based on the elastoplastic fatigue damage and machine learning models for life prediction of aerospace alloy parts fabricated by additive manufacturing 145 (2021) doi: 10.1016/j.ijfatigue.2020.106089.

[265] P. van den Berg, B. Jyoti, R. Hermsen, Investigation of thermal behaviour of additively manufactured green bi-propellant thrusters in cubesat applications using transient thermal modelling, 2021.

[266] I. Waugh, E. Moore, A. Greig, J. Macfarlane, Additive manufacture of rocket engine combustion chambers from CuCrZr (C-18150) using the DMLS process, 2021.

[267] I. Waugh, Moore, A. Greig, J. Macfarlane, and W. D. Cleland, Additive manufacture of rocket engine combustion chambers using the ABD R -900AM nickel Superalloy, 2021.

[268] G. D'Emilia, A. di Ilio, A. Gaspari, E. Natale, A.G. Stamopoulos, Uncertainty assessment for measurement and simulation in selective laser melting: a case study of an aerospace part, Acta IMEKO 9 (4) (2020) 96–105, https://doi.org/10.21014/acta_imeko.v9i4.720.

[269] C. Dordlofva, P. Törlind, Qualification challenges with additive manufacturing in space applications, in: Solid Freeform Fabrication 2017: Proceedings of the 28th Annual International Solid Freeform Fabrication Symposium - An Additive Manufacturing Conference, 2017, 2020,, pp. 2699–2712.

[270] E. Fereiduni, A. Ghasemi, M. Elbestawi, Selective laser melting of aluminum and titanium matrix composites: recent progress and potential applications in the aerospace industry, Aerospace 7 (6) (2020), https://doi.org/10.3390/AEROSPACE7060077.

[271] L. Gao, S. Yu, R. Yu, T. He, Y. Shi, Study on Arc additive manufacturing process and properties of 5356 aluminum alloy rocket booster module transition end frame, Jixie Gongcheng Xuebao/J. Mech. Eng. 56 (8) (2020) 28–36, https://doi.org/10.3901/JME.2020.08.028.

[272] D. Gu, H. Zhang, H. Chen, H. Zhang, L. Xi, Laser additive manufacturing of high-performance metallic aerospace components, Zhongguo Jiguang/Chinese J. Lasers 47 (5) (2020), https://doi.org/10.3788/CJL202047.0500002.

[273] A. Hehr et al., Hot isostatic pressing of ultrasonic additive manufacturing liquid cold plate heat exchangers, J. Spacecraft Rockets (2020) 1–5, https://doi.org/10.2514/1.a34888.

[274] L.L. Jing, Y.H. Li, K.W. Cheng, F. Wang, J.W. Shi, Application of selective laser melting technology based on titanium alloy in aerospace products, IOP Conf. Ser.: Mater. Sci. Eng. 740 (1) (2020), https://doi.org/10.1088/1757-899X/740/1/012056.

[275] S. Kuntanapreeda, D. Hess, Opening access to space by maximizing utilization of 3D printing in launch vehicle design and production, Appl. Sci. Eng. Prog. 14 (2) (2020) 1–3, https://doi.org/10.14416/J.ASEP.2020.12.002.

[276] F. Liu, W. Jingchao, T. Zhi, L. Bin, G. Yue, D. Z. Zhang, An aerospace integrated component application based on selective laser melting: Design, fabrication and FE simulation, in: Solid Freeform Fabrication 2018: Proceedings of the 29th Annual International Solid Freeform Fabrication Symposium - An Additive Manufacturing Conference, SFF 2018, pp. 488–499, 2020.

[277] P. Manil, et al., Structural optimization, additive manufacturing and vibration testing of titanium alloy supports based on the space detector SVOM-MXT, 2021, p. 119. doi: 10.1117/12.2562351.

[278] M.O. Oyesola, K. Mpofu, N.R. Mathe, I.A. Daniyan, Hybrid-additive manufacturing cost model: a sustainable through-life engineering support for maintenance repair overhaul in the aerospace, Procedia Manuf. 49 (2020) 199–205, https://doi.org/10.1016/j.promfg.2020.07.019.

[279] G. Shi, C. Guan, D. Quan, D. Wu, L. Tang, T. Gao, An aerospace bracket designed by thermo-elastic topology optimization and manufactured by additive manufacturing, Chin. J. Aeronaut. 33 (4) (2020) 1252–1259, https://doi.org/10.1016/j.cja.2019.09.006.

[280] R. Stolt, F. Elgh, Introducing design for selective laser melting in aerospace industry, J. Comput. Des. Eng. 7 (4) (2020) 489–497, https://doi.org/10.1093/jcde/qwaa042.

[281] R. Willner, S. Lender, A. Ihl, C. Wilsnack, S. Gruber, A. Brandão, L. Pambaguian, M. Riede, E. López, F. Brueckner, C. Leyens, Potential and challenges of additive manufacturing for topology optimized spacecraft structures, J. Laser Appl. 32 (3) (2020) 032012, https://doi.org/10.2351/7.0000111.

[282] O. Mireles, O. Rodriguez, Y. Gao, N. Philips, Additive manufacture of refractory alloy C103 for propulsion applications, 2020. doi: 10.2514/6.2020-3500.

[283] M. Abi-Fadel, et al., Leveraging additive manufacturing to enable deep space crewed missions, in: Proceedings of the International Astronautical Congress, IAC, vol. 2019-Octob, 2019.

[284] B. Barroqueiro, A. Andrade-Campos, R.A.F. Valente, V. Neto, Metal additive manufacturing cycle in aerospace industry: a comprehensive review, J. Manuf. Mater. Process. 3 (3) (2019), https://doi.org/10.3390/jmmp3030052.

[285] F. Belfi, F. Iorizzo, C. Galbiati, F. Lepore, Space structures with embedded flat plate pulsating heat pipe built by additive manufacturing technology: development, test and performance analysis, J. Heat Transfer 141 (9) (2019), https://doi.org/10.1115/1.4042082.

[286] L. Berrocal, R. Fernández, S. González, A. Periñán, S. Tudela, J. Vilanova, L. Rubio, J.M. Martín Márquez, J. Guerrero, F. Lasagni, Topology optimization and additive manufacturing for aerospace components, Prog. Additive Manuf. 4 (2) (2019) 83–95, https://doi.org/10.1007/s40964-018-0061-3.

[287] N. Chekir, J.J. Sixsmith, R. Tollett, M. Brochu, Laser wire deposition of a large Ti-6Al-4V space component the methodology for creating a functional Ti-6Al-4V satellite part using LWD additive manufacturing is detailed, Weld. J. 98 (6) (2019) 172S–180S, https://doi.org/10.29391/2019.98.014.

[288] A. Diaz, Surface texture characterization and optimization of metal additive manufacturing-produced components for aerospace applications, Additive Manuf. Aerospace Ind. (2019) 341–374, https://doi.org/10.1016/B978-0-12-814062-8.00018-2.

[289] F. Facchini, A. de Chirico, G. Mummolo, Comparative cost evaluation of material removal process and additive manufacturing in aerospace industry, Springer Proc. Math. Stat. 280 (2019) 47–59, https://doi.org/10.1007/978-3-030-14969-7_5.

[290] F. Froes, R. Boyer, B. Dutta, Introduction to aerospace materials requirements and the role of additive manufacturing, Additive Manuf. Aerospace Ind. (2019) 1–6, https://doi.org/10.1016/B978-0-12-814062-8.00001-7.

[291] C. Fuchs, D. Baier, D. Elitzer, R. Kleinwort, A. Bachmann, M.F. Zäh, Additive manufacturing for structural components in aerospace engineering, ZWF Zeitschrift fuer Wirtschaftlichen Fabrikbetrieb 114 (7–8) (2019) 431–434, https://doi.org/10.3139/104.112124.

[292] M. Gas, A. Rene-Corail, S. Eyrignoux, G. Iker, S. Sudre, Improving competitiveness of additive manufacturing aerospace serial parts, SAE Technical Papers, vol. 2019-Septe, no. September. 2019. doi: 10.4271/2019-01-1900.

[293] N. Gloria et al., Performance of a small-orifice rocket injector utilizing additive manufacturing, in: AIAA Propulsion and Energy Forum and Exposition, 2019. 2019. doi: 10.2514/6.2019-4231.

[294] A. Hehr, J. Wenning, M. Norfolk, J. Sheridan, J.A. Newman, M. Domack, Selective reinforcement of aerospace structures using ultrasonic additive manufacturing, J. Mater. Eng. Perform. 28 (2) (2019) 633–640, https://doi.org/10.1007/s11665-018-3614-1.

[295] E. Hilpert, J. Hartung, H. von Lukowicz, T. Herffurth, N. Heidler, Design, additive manufacturing, processing, and characterization of metal mirror made of aluminum silicon alloy for space applications, Opt. Eng. 58 (09) (2019) 1, https://doi.org/10.1117/1.oe.58.9.092613.

[296] M. Kalender, S. E. Kilic, S. Ersoy, Y. Bozkurt, S. Salman, Additive manufacturing and 3D printer technology in aerospace industry, in: Proceedings of 9th International Conference on Recent Advances in Space Technologies, RAST 2019. pp. 689–695, 2019. doi: 10.1109/RAST.2019.8767881.

[297] M. Kamal, G. Rizza, Design for metal additive manufacturing for aerospace applications, Additive Manuf. Aerospace Ind. (2019) 67–86, https://doi.org/10.1016/B978-0-12-814062-8.00005-4.

[298] P. Kohl, M. Kilian, A. Schinagl-Weis, C. Hartwanger, Additive manufacturing developments for satellite antenna applications from C- to Ka-band, in: GeMiC 2019 - 2019 German Microwave Conference. pp. 222–225, 2019. doi: 10.23919/GEMIC.2019.8698174.

[299] T. Kozmel, J. Grabowski, C. Kantner, J. Sebastian, B. Nez, J. Fetty, Additive manufacturing of ferrium® c64® for aerospace gear applications, in: The Vertical Flight Society - Forum 75: The Future of Vertical Flight - Proceedings of the 75th Annual Forum and Technology Display, 2019.

[300] S.B. Liu et al., A summary of research on 3D printing technology of titanium alloys for aerospace field, Zhuzao/Foundry 68 (9) (2019) 965–970.

[301] B.S. Mekki, J. Langer, S. Lynch, Genetic algorithm based topology optimization of heat exchanger fins used in aerospace applications, in: ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE), Nov. 2019, vol. 8. doi: 10.1115/IMECE2019-10617.

[302] T.F. Murphy, C.T. Schade, Measurement of powder characteristics and quality for additive manufacturing in aerospace alloys, Additive Manuf. Aerospace Ind. (2019) 99–142, https://doi.org/10.1016/B978-0-12-814062-8.00007-8.

[303] X.D. Niu, 3D printing in China's aerospace industries, in: 59th Israel Annual Conference on Aerospace Sciences, IACAS 2019, pp. 667–674, 2019.

[304] M.M.J. Opgenoord, K.E. Willcox, Design for additive manufacturing: cellular structures in early-stage aerospace design, Struct. Multidiscip. Optim. 60 (2) (2019) 411–428, https://doi.org/10.1007/s00158-019-02305-8.

[305] M. Oyesola, K. Mpofu, N. Mathe, A techno-economic analytical approach of laser-based additive manufacturing processes for aerospace application, Procedia Manuf. 35 (2019) 155–163, https://doi.org/10.1016/j.promfg.2019.05.019.

[306] N. Patel, S. Standbridge, M. van den Berghe, V. Devalaraju, Design and additive manufacturing considerations for liquid rocket engine development, AIAA Propulsion and Energy Forum and Exposition, 2019. 2019. doi: 10.2514/6.2019-4392.

[307] R. Piticescu et al., Powder-bed additive manufacturing for aerospace application: techniques, metallic and metal/ceramic composite materials and trends, Manuf. Rev. 6 (2019), https://doi.org/10.1051/mfreview/2019003.

[308] A. Riou, Metal powders for additive manufacturing in aerospace & land turbines. Trends and challenges, Metallurgia Italiana 111 (6) (2019) 56–61.

[309] E. Sacco, S.K. Moon, Additive manufacturing for space: status and promises, Int. J. Adv. Manuf. Technol. 105 (10) (2019) 4123–4146, https://doi.org/10.1007/s00170-019-03786-z.

[310] T.E. Shelton, C.R. Hartsfield, G.R. Cobb, C.A. Sheffield, Additive manufacturing: Designing to withstand space launch, in: AIAA Scitech 2019 Forum. 2019. doi: 10.2514/6.2019-0314.

[311] N. Tepylo, X. Huang, P.C. Patnaik, Laser-based additive manufacturing technologies for aerospace applications, Adv. Eng. Mater. 21 (11) (2019), https://doi.org/10.1002/adem.201900617.

[312] Vetrivel, P. Varun Teja, R. Sivaprakash, V. Vinay Krishnan, Vasanth, Potential and scope of additive manufacturing in aerospace industry with reference to India, Int. J. Innov. Technol. Explor. Eng. 8 (6 Special Issue 4) (2019) 1085–1089. doi: 10.35940/ijitee.F1225.0486S419.

[313] P.A. Vityaz, M.L. Kheifetz, S.A. Chizhik, Synergetic technologies of direct layer deposition in aerospace additive manufacturing, Additive Manuf. Aerospace Ind. (2019) 427–447, https://doi.org/10.1016/B978-0-12-814062-8.00022-4.

[314] J.C. Withers, Fusion and/or solid state additive manufacturing for aerospace applications, Additive Manuf. Aerospace Ind. (2019) 187–211, https://doi.org/10.1016/B978-0-12-814062-8.00010-8.

[315] G. YongXin, Z. Lihua, L. Zhijia, G. Yimin, M. Lingxi, Optimization design of star tracker bracket of small satellite for 3D printing, in: 2019 5th International Conference on Control, Automation and Robotics, ICCAR 2019. pp. 808–811, 2019. doi: 10.1109/ICCAR.2019.8813432.

[316] X. Zhang, E. Liang, Metal additive manufacturing in aircraft: current application, opportunities and challenges, IOP Conf. Ser.: Mater. Sci. Eng. 493 (1) (2019), https://doi.org/10.1088/1757-899X/493/1/012032.

[317] G. Allevi, M. Cibeca, R. Fioretti, R. Marsili, R. Montanini, G. Rossi, Non-contact measurement techniques for qualification of aerospace brackets made by additive manufacturing technologies, J. Phys.: Conf. Ser. 1110 (1) (2018), https://doi.org/10.1088/1742-6596/1110/1/012002.

[318] Y. Cailloce, P. Hourlay, F. Lebrun, B. Palacin, Additive manufacturing of Ku band horn antennas for telecommunications space applications, IET Conference Publications, vol. 2018, no. CP741, 2018. doi: 10.1049/cp.2018.0602.

[319] S. Eberle, et al., Additive manufacturing of an AlSi40 mirror coated with electroless nickel for cryogenic space applications (2019) 40. doi: 10.1117/12.2535960.

[320] J. Fessl, H. Shen, N. Patel, T. W. Chen, S. Ghirnikar, M. van den Berghe, Liquid rocket engine design for additive manufacturing, in: Proceedings of the International Astronautical Congress, IAC, vol. 2018-Octob, 2018.

[321] K.V. Fetisov, P.V. Maksimov, Topology optimization and laser additive manufacturing in design process of efficiency lightweight aerospace parts, J. Phys.: Conf. Ser. 1015 (5) (2018), https://doi.org/10.1088/1742-6596/1015/5/052006.

[322] P. Gaudenzi, S. Atek, V. Cardini, M. Eugeni, G. Graterol Nisi, L. Lampani, M. Pasquali, L. Pollice, Revisiting the configuration of small satellites structures in the framework of 3D Additive Manufacturing, Acta Astronaut. 146 (2018) 249–258, https://doi.org/10.1016/j.actaastro.2018.01.036.

[323] P.R. Gradl, W. Brandsmeier, S.E. Greene, Channel wall nozzle manufacturing and hot-fire testing using a laser wire direct closeout technique for liquid rocket engines, (2018). doi: 10.2514/6.2018-4860.

[324] T. Hettesheimer, S. Hirzel, H.B. Roß, Energy savings through additive manufacturing: an analysis of selective laser sintering for automotive and aircraft components, Energ. Effi. 11 (5) (2018) 1227–1245, https://doi.org/10.1007/s12053-018-9620-1.

[325] P. Maksimov, O. Smetannlkov, A. Dubrovskaya, K. Dongauzer, L. Bushuev, Numeric simulation of aircraft engine parts additive manufacturing process, MATEC Web Conf. 224 (2018), https://doi.org/10.1051/matecconf/201822401065.

[326] M. Oyesola, N. Mathe, K. Mpofu, S. Fatoba, Sustainability of Additive Manufacturing for the South African aerospace industry: a business model for laser technology production, commercialization and market prospects, Procedia CIRP 72 (2018) 1530–1535, https://doi.org/10.1016/j.procir.2018.03.072.

[327] R. Stolt, T. Heikkinen, F. Elgh, Integrating additive manufacturing in the design of aerospace components, Adv. Transdis. Eng. 7 (2018) 145–154, https://doi.org/10.3233/978-1-61499-898-3-145.

[328] K. Vishnu Prashant Reddy, I. Meera Mirzana, A. Koti Reddy, Application of Additive Manufacturing technology to an Aerospace component for better

trade-off's, Mater. Today:. Proc. 5 (2) (2018) 3895–3902, https://doi.org/10.1016/j.matpr.2017.11.644.

[329] D. Vogel, L. Geismayr, M. Langer, P. Leslabay, G. Schlick, Combining additive manufacturing and biomimetics for the optimization of satellite structures, in: Proceedings of the International Astronautical Congress, IAC, vol. 2018-Octob, 2018.

[330] A.M. Cismilianu et al., End-to-end process of hollow spacecraft structures with high frequency and low mass obtained with in-house structural optimization tool and additive manufacturing, INCAS Bull. 9 (3) (2017) 13–20, https://doi.org/10.13111/2066-8201.2017.9.3.2.

[331] R. Clinton, NASA additive manufacturing initiatives: In space manufacturing and rocket engines, in: Proceedings of the International Astronautical Congress, IAC, vol. 12, 2017, pp. 8226–8246.

[332] M.F. Cruz, A.V. Borille, Decision methods application to compare conventional manufacturing process with metal additive manufacturing process in the aerospace industry, J. Braz. Soc. Mech. Sci. Eng. 39 (1) (2017) 177–193, https://doi.org/10.1007/s40430-016-0532-8.

[333] D.B. Froes F.H., Boyer R., Additive manufacturing for aerospace applications-part I, Advanced Materials and Processes, 2017, [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85026852703&partnerID=40&md5=6dedfc6ba21e7823cfee6191ba0591b5%0A.

[334] F.H. Froes, R. Boyer, B. Dutta, Additive manufacturing for aerospace applications-part II, Adv. Mater. Processes 175 (6) (2017) 18–22.

[335] S.S. Gill, H. Arora, Jidesh, V. Sheth, On the development of Antenna feed array for space applications by additive manufacturing technique, Addit. Manuf. 17 (2017) 39–46, https://doi.org/10.1016/j.addma.2017.06.010.

[336] N. Judalet, A. Kazakçi, E. le Gouguec, A. Balvay, Performance monitoring & control for an additive manufacturing factory - A case study in the aerospace industry, 21st International Conference on Engineering Design, ICED 2017, vol. 5, no. DS87-5, 2017, pp. 249–258, [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85029815782&partnerID=40&md5=bf943f31ccb7f7f666cbc5a96328b3d9.

[337] K. Kasim, A. Muley, M. Stoia, F. Ladeinde, Advanced heat transfer devices for aerospace applications, in: ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE), vol. 8, 2017. doi: 10.1115/IMECE2017-72382.

[338] A. Lindwall, C. Dordlofva, A. Öhrwall Rönnbäck, Additive manufacturing & the product development process: insights from the space industry, in: Proceedings of the International Conference on Engineering Design, ICED, vol. 5, no. DS87-5, 2017, pp. 345–354.

[339] C.E. Munteanu, A.M. Cismilianu, A.I. Chira, D. Baran, Structural optimization of space components adapted for 3d printing, in: Annals of DAAAM and Proceedings of the International DAAAM Symposium, 2017, pp. 821–825, https://doi.org/10.2507/28th.daaam.proceedings.115.

[340] A. Nagasaki, et al., Additive manufacturing development for rocket engine in Japan, in: Proceedings of the International Astronautical Congress, IAC, vol. 13, 2017, pp. 8713–8719.

[341] D. Obilanade, J. Kingston, Spacecraft designers' guide to using additive manufacturing processes for large metallic spacecraft structures, in: Proceedings of the International Astronautical Congress, IAC, vol. 13, 2017, pp. 8280–8304.

[342] R. Pacurar, A. Pacurar, N. Bâlc, Research on the mechanical behaviour of an airplane component made by selective laser melting technology, MATEC Web Conf. 94 (2017), https://doi.org/10.1051/matecconf/20179403012.

[343] M. Yakout, A. Cadamuro, M.A. Elbestawi, S.C. Veldhuis, The selection of process parameters in additive manufacturing for aerospace alloys, Int. J. Adv. Manuf. Technol. 92 (5–8) (2017) 2081–2098, https://doi.org/10.1007/s00170-017-0280-7.

[344] A. Sola, A. Nouri, Microstructural porosity in additive manufacturing: the formation and detection of pores in metal parts fabricated by powder bed fusion, J. Adv. Manuf. Process. 1 (3) (2019), https://doi.org/10.1002/amp2.10021.

[345] N. Sanaei, A. Fatemi, N. Phan, Defect characteristics and analysis of their variability in metal L-PBF additive manufacturing, Mater. Des. 182 (2019) 108091, https://doi.org/10.1016/j.matdes.2019.108091.

[346] A. du Plessis, Effects of process parameters on porosity in laser powder bed fusion revealed by X-ray tomography, Addit. Manuf. 30 (2019) 100871, https://doi.org/10.1016/j.addma.2019.100871.

[347] S.A. Khairallah, A.T. Anderson, A. Rubenchik, W.E. King, Laser powder-bed fusion additive manufacturing: Physics of complex melt flow and formation mechanisms of pores, spatter, and denudation zones, Acta Mater. 108 (Apr. 2016) 36–45, https://doi.org/10.1016/j.actamat.2016.02.014.

[348] Y.Y. Sun, et al., Fatigue performance of additively manufactured Ti-6Al-4V: surface condition vs. Internal defects, JOM 72 (3) (2020) 1022–1030 doi: 10.1007/s11837-020-04025-7.

[349] N. Sanaei, A. Fatemi, Defects in additive manufactured metals and their effect on fatigue performance: a state-of-the-art review, Prog. Mater Sci. 117 (2021) 100724, https://doi.org/10.1016/j.pmatsci.2020.100724.

[350] A. du Plessis, I. Yadroitsava, I. Yadroitsev, Effects of defects on mechanical properties in metal additive manufacturing: a review focusing on X-ray tomography insights, Mater. Des. 187 (2020) 108385, https://doi.org/10.1016/j.matdes.2019.108385.

[351] N.E. Uzan, R. Shneck, O. Yeheskel, N. Frage, Fatigue of AlSi10Mg specimens fabricated by additive manufacturing selective laser melting (AM-SLM), Mater. Sci. Eng., A 704 (2017) 229–237, https://doi.org/10.1016/j.msea.2017.08.027.

[352] H. Masuo, Y. Tanaka, S. Morokoshi, H. Yagura, T. Uchida, Y. Yamamoto, Y. Murakami, Influence of defects, surface roughness and HIP on the fatigue strength of Ti-6Al-4V manufactured by additive manufacturing, Int. J. Fatigue 117 (2018) 163–179, https://doi.org/10.1016/j.ijfatigue.2018.07.020.

[353] W.E. King et al., Laser powder bed fusion additive manufacturing of metals; physics, computational, and materials challenges, Appl. Phys. Rev. 2 (4) (2015) 041304, https://doi.org/10.1063/1.4937809.

[354] H.L. Wei, T. Mukherjee, W. Zhang, J.S. Zuback, G.L. Knapp, A. De, T. DebRoy, Mechanistic models for additive manufacturing of metallic components, Prog. Mater Sci. 116 (2021) 100703, https://doi.org/10.1016/j.pmatsci.2020.100703.

[355] C. Meier, R.W. Penny, Y. Zou, J.S. Gibbs, A.J. Hart, Thermophysical phenomena in metal additive manufacturing by selective laser melting: fundamentals, modeling, simulation, and experimentation, Ann. Rev. Heat Transfer 20 (1) (2017) 241–316, https://doi.org/10.1615/AnnualRevHeatTransfer.v2010.1615/AnnualRevHeatTransfer.2018019042.

[356] A. du Plessis, E. MacDonald, J. M. Waller, F. Berto, Non-destructive testing of parts produced by laser powder bed fusion, in: Fundamentals of Laser Powder Bed Fusion of Metals, Elsevier, 2021, pp. 277–300. doi: 10.1016/B978-0-12-824090-8.00016-0.

[357] A. du Plessis, et al., X-ray computed tomography inspection in metal additive manufacturing: the role of witness specimens, in: Structural Integrity of Additive Manufactured Materials & Parts, ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, 2020, pp. 139–156. doi: 10.1520/STP163120190109.