



Additive manufacturing for space: status and promises

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Abstract

Additive manufacturing (AM) or 3D printing is a manufacturing technique where successive layers of material are layered to produce parts. The design freedom afforded by AM is ideal for the space industry, where part production is low volume and highly customized. The objective of this paper is to review research in the area of additive manufacturing for space (AMFS) in all areas, from propulsion to electronics to printing of habitats, and to identify the gaps and directions in the research. In this paper, we investigate the AMFS research by splitting it into two domains: space and ground-based. Space-based AMFS has been performed on the International Space Station using polymers, and we also discuss the future of in space AM, a subject closely related to more general in space manufacturing. The ground-based research is split into three categories based on the printing material: metal, polymer, and others. The last category includes regolith, cement, and ceramic. This paper explores AMFS by bringing together as much research information as possible using a combination of papers, presentations, and news articles. We expect that the paper will allow the reader to gain an understanding of the current status of AMFS research and will contribute to the field as a reference and research guidelines.

Keywords 3D printing · Additive manufacturing · AM certification · Satellite · Space · Spacecraft

1 Introduction

There are various techniques used to manufacture objects such as casting, coating, molding, forming, machining, and joining. Most of these processes involve subtractive manufacturing, the process of removing material in order to manufacture a final object. Additive manufacturing (AM), or 3D printing (3DP), does the opposite: successive layers of material are added one on top of the other until the object is complete [1].

In the 1980s, an early form of stereolithography (SLA) [2] for producing plastic prototypes was developed to help visualization of parts during development. From these beginnings came many other techniques and machines that can be used to manufacture both functional parts and prototypes, for example, fused deposition modeling (FDM) [3], selective laser melting (SLM) [4], selective laser sintering (SLS) [5], digital light processing (DLP) [6], and

rapid freeze prototyping (RFP) [7]. Although all these forms of 3DP work using the same basic concept, the key differences are in the printing process and the materials used.

3DP's main strength is removing a lot of the limitations present with previous manufacturing techniques and allowing unparalleled design freedom. This greatly reduces the time and cost of development, making AM an integral part of future manufacturing systems. 3DP is especially relevant in the production of complex and customized structures that used to be hard if not impossible to make [8, 9].

A sector that is poised to greatly benefit from AM is the space industry. Almost everything in space is custom made so it is ideal for this manufacturing technology. Space entities have begun using AM in a variety of applications broadly for two reasons. Firstly, mass savings from 40 to 90% [10] are possible and mass is directly related to cost (since more massive spacecraft require more fuel and thrust). Secondly, AM can manufacture complex parts much faster than traditional manufacturing, reducing fabrication times from 1 year to only 4 months [11]. Agencies like National Aeronautics and Space Administration (NASA) and European Space Agency (ESA) have been conducting research into how to use AM in a variety of space-related applications, from using it to print CubeSat propulsion systems [12], to printing ceramics [13], to using laser engineered

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net shaping (LENS) [14] with lunar and Martian regolith [15], to potentially printing an entire spacecraft in orbit [16]. Regolith is the term used to describe the lunar soil [17] but can be used to also for the Martian soil.

Mass use of AM in the space industry has not occurred yet though. This is mainly because of the difficulty in modeling the manufacturing process and predicting the properties of printed parts. This leads to a lack of standardization and therefore limited use in the space industry.

Efforts have been made in recent years to characterize and model the properties of parts made with AM. This has proven to be difficult since there is an inherent variability in the nature of 3DP that makes modeling complicated. The variability comes from many sources, but despite this, progress has been made in characterizing AM materials and efforts are being made to model and predict the material properties [1].

The goal of the current study is to provide an overview of the state of AM research that is aimed directly at use in the space sector, referred to additive manufacturing for space (AMFS) research. This allows the discussion to be specifically about the accomplishments and gaps in AM research whose end goal is use in some aspect of space-related applications, from launchers to habitat building on extraterrestrial planets. Trends and knowledge gaps will be identified and discussed in an effort to highlight the areas where more research is needed so that products with higher accuracy, better quality, and desired properties can be produced for use in space.

It must be noted that although an attempt has been made to make this paper as comprehensive as possible, it does not cover all AMFS due to the sparsity of details when it comes to research in this specific area. For example, some references are presentations given by NASA personnel at occasions where no proceedings were printed; therefore, these sources lack details that research papers would have. NASA has published these presentations and other sources on their server (<https://ntrs.nasa.gov/>) and the classification numbers have been provided.

There is also the fact that governmental agencies like NASA and ESA are at times not able to release sensitive information to the public so cannot go into much detail. Private companies such as Space-X, Boeing, Thales Alenia Space (TAS), and Airbus usually release even less details, most research news coming in the form of press releases and finished products whose details are protected by intellectual copyrights. Finally, there are relatively few research institutions such as universities that specialize in AMFS, most of the research is in general AM. Should the reader wish, more specific review papers can be found on processes [14, 18], materials [19, 20], simulation and modeling [1, 21], and cost models [22, 23].

There is currently only one way to print in space and this has been used to test AM in microgravity to great success but due to the difficulties in performing space-based research, most research is still ground-based. It should be noted that there are instances when authors discuss both space and aerospace AM research. These have been included in this paper since they are typically from agencies like NASA.

This paper is organized as follows: first an introduction will be given on the importance of mass savings for the space industry in Section 2. Then, Section 3 is a discussion of the usage of new technologies in the space sector. Next, the paper is split into two broad sections, Section 4 covers AMFS research performed in space and the future of in orbit manufacturing. Section 5 then discusses the research done on the ground divided by material used during printing: metal, polymer, and others. Lastly, the research gaps are highlighted in Section 6 and the conclusion can be found in Section 8.

2 The importance of mass reductions for spacecraft

A variety of materials are used in spacecraft, including [24]:

- Ceramic matrix composites
- Various types of carbon composites
- Kapton
- Teflon
- Aluminum alloys
- Glass
- Stainless steel
- Inconel alloys
- Various types of plastics

Some of these are used only in small amounts, such as gold and silver, and therefore do not add much weight. Materials such as plastics by their nature do not weigh very much so they also do not add much weight. Aluminum, steel, and inconel on the other hand add a lot of weight because large parts are built out these materials, such as the structure and nozzles.

Spacecrafts, so far, have been built using traditional methods, but this section briefly describes the basics of orbits and thrusters in an effort to emphasize one, if not the main, way that 3DP can substantially help to reduce costs: mass savings for spacecraft. AM has other advantages, as will be discussed later, but this is one of the main ones and helps to emphasize the design freedom that is possible with this manufacturing technology. Orbits are going to be approximated as circles for the purposes of this work.

A spacecraft in a circular orbit has speed v and is traveling in a direction orthogonal to the force of gravity.

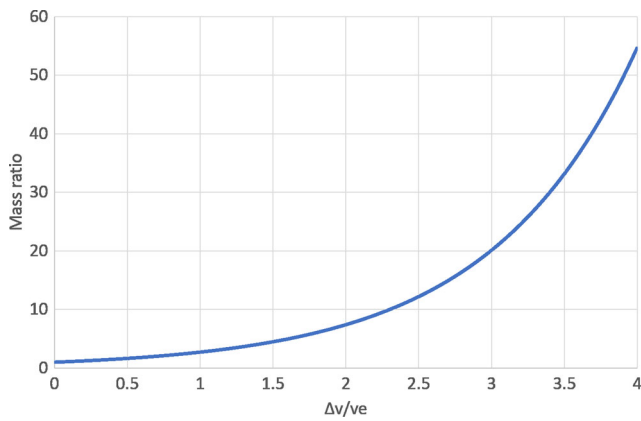


Fig. 1 Final velocities as a function of launch vehicle mass ratios calculated using Eq. 3

The velocity of the spacecraft is as follows:

$$v = \sqrt{\frac{GM}{r}} \tag{1}$$

where $G = 6.67 \times 10^{-11} \text{ m}^3\text{kg}^{-1}\text{s}^{-2}$ is the universal gravitational constant, M is the mass of the planet being orbited, and r is the radius of the circle. Equation 1 tells us the speed (or orbital velocity) that the satellite needs to have in order to maintain a stable orbit.

In order to get a spacecraft into orbit from the surface of the Earth or change its orbit in space, fuel must be expended to change the spacecraft’s velocity to the value calculated in Eq. 1. This change in velocity is referred to as the spacecraft’s Δv . The equation that governs the basic operation of a spacecraft is called the Tsiolkovsky equation or the ideal rocket equation as follows:

$$\Delta v = v_e \ln\left(\frac{m_0}{m_f}\right) \tag{2}$$

It relates Δv to the exhaust velocity v_e of the spacecraft’s thruster (the velocity at which the fuel is being ejected), the initial mass m_0 (which includes the spacecraft and the fuel before the burn), and the final mass m_f (which is smaller because fuel has been used up during the burn).

Equation 2 is simplified and does not consider factors like changing thrust and atmospheric drag but like the assumption of circular orbits it is sufficient for this report. It can be rewritten as follows:

$$\frac{m_0}{m_f} = \exp\left(\frac{\Delta v}{v_e}\right) \tag{3}$$

where $\frac{m_0}{m_f}$ is called the mass ratio. This second form allows the plotting of the graph shown in Fig. 1. From this plot, it becomes apparent that the greater the mass ratio, the greater the change in velocity. If the mass of the spacecraft is as small as possible, the mass ratio increases, and therefore the Δv budget increases for a given amount of fuel.

Lower mass at launch also reduces the cost significantly as can be seen in Table 1. This will be discussed in more detail in the next section.

3 Usage of new technologies in the space sector

There are many ways in which the space industry can benefit from AM, summarized by the National Research Council (NRC) in the following points [16, 25]:

- The creation of new materials and parts that may one day be made in microgravity only and may only function there, i.e. they would be truly space-based.
- Given the previous point, there would be a shift in the logistic and planning of space missions since in space construction would be a reality.
- Lastly, given the previous two points, there is the possibility that AM could change the space market by allowing construction of spacecraft directly in space.

Implementation of these ideas would have the potential to lower costs and manufacture times enormously but there is a problem: new technologies are typically implemented very slowly in the space industry for two main reasons. Firstly, a long approval process means that many years may pass until a mission’s actual implementation. For example, the Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer (OSIRIS-REx) mission was approved in 2011 and launched by NASA in 2016 [26]. Considering the high rate of development of new technologies, especially in a fertile field such as AM, the time gap from the approval to launch of the mission means that it is difficult to implement any new technologies or developments on the OSIRIS-REx spacecraft made in the interim.

The second reason is that space missions are very expensive. The rough costs of launching to low Earth orbit (LEO) using SpaceX’s Falcon Heavy (FH) and NASA’s

Table 1 Cost to launch to LEO using the Space Launch System and FH [27]

Launch vehicle	Mass to LEO	Cost to launch to LEO	Cost per metric tons (MT)	Cost per kg
Space launch system	70	USD 600M	USD 8.57M	USD 8,570
FH	53	USD 158M	USD 2.97M	USD 2,970

Space Launch System are shown in Table 1, highlighting how launching a heavier spacecraft will cost more than a lighter one.

Table 1 does not include the costs associated with the development, construction, testing, and certification of the payload before the launch, which [28] estimates can be in the order of 290 million USD for a satellite that can track hurricanes. Other types of satellites will cost different amounts depending on their intended mission. Once the spacecraft is in orbit, it needs constant monitoring which means further expenses in the order of millions of USD per year for communication satellites [28].

Given the high costs and slow development times, the space industry relies mainly on tried and tested methods and parts. Many of the main players in the industry such as NASA, ESA, Boeing, Airbus, TAS, and Lockheed Martin are reluctant to use new technologies due to the potential monetary and sometimes human cost that might be incurred.

But, the potential mass and time savings offered by AM are huge so there is a strong push to research these new manufacturing technologies. For example, efforts have been made to use 3DP to reduce the mass, complexity, part count, and welds of parts [8, 10, 25, 29]. 3DP is now being considered of paramount importance for human exploration of space and the space sector in general [10, 30, 31].

4 In space AM

When discussing 3DP as applied to the space sector, as mentioned before not all research is done on the Earth, some has been done in space on the International Space Station (ISS). 3DP done in orbit will be referred to as in space additive manufacturing (ISAM) and is different from the concept of in space manufacturing (ISM), which is broader and includes also traditional forms of manufacturing. This

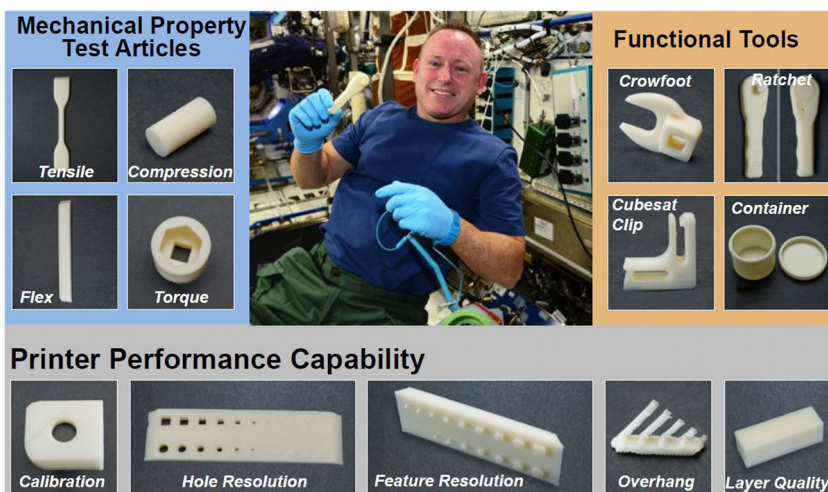
section discusses what research has been done in this domain and the plans for ISM since the two are strongly connected. Most of the ISAM research has been performed as part of NASA's in space manufacturing initiative [32].

The first time that 3DP was performed in orbit was during the 3D printing in zero-G experiment (3DPrint) [33, 34], during which an FDM printer small enough to fit into the Microgravity Science Glovebox (MSG) on the ISS was developed and built by California-based Made In Space (MIS). It was launched in September 2014 and used to perform experiments to verify whether the parts manufactured in space were as good as their counterparts manufactured on the ground.

Before sending the printer to the ISS, a testing campaign was performed on zero-g flights [36]. Once the printer was in space, calibration was performed by printing several test objects and coupons using acrylonitrile butadiene styrene (ABS) (a selection of which is shown in Fig. 2) and then sent back to Earth in April 2015 to NASA's Marshall Space Flight Center (MSFC). Their properties were investigated and compared to a set of identical objects printed using the flight printer prior to launch. Tests included the following [35, 37–39]:

- Visual and photographic inspection - To identify any anomalies, de-lamination, damage, curling, warping, and any differences between the flight and ground samples.
- Mass and density calculation - This is to ensure that the microgravity environment did not cause any unwanted expansion of the material as it was extruded.
- Structured light scanning - The scans are used to build a computer-aided design (CAD) model of the objects for accurate comparison to the original computer models and for better volume calculation.
- X-ray and computer tomography (CT) scanning - Investigation of the internal structures to determine any defects.

Fig. 2 Some of the objects printed on the ISS [35]



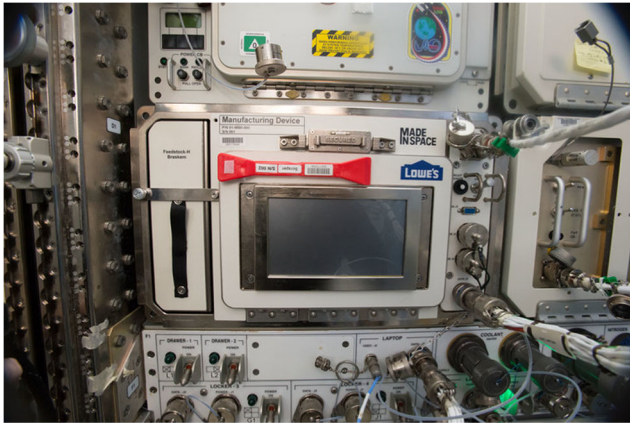


Fig. 3 The AMF mounted in an EXPRESS Rack Mid-Deck Locker in the ISS (image credit: NASA)

- Destructive mechanical testing - Done following ASTM standards for tensile [40], flexural [41], and compression [42] testing, the results of which can be seen in Table 3.
- Optical and scanning electron microscopy - Used to examine in detail the inter-laminar regions and any defects identified during the initial inspection.

3DPrint was the first printer launched into space and since 2016 there is a new one, the additive manufacturing facility (AMF) [43] (shown in Fig. 3). The AMF is another small FDM printer whose specifications are listed in Table 2.

MIS applied the lessons learned from 3DPrint to develop an improved printer with an expanded selection of materials. As with its predecessor, tensile, compression, and flexural tests were performed on samples fabricated using the AMF following ASTM guidelines [41, 42, 44]. The filament used for this round of testing was the same ABS as that used in 3DPrint. Table 3 shows the test results of the AMF and 3DPrint both in flight and on the ground.

As expected, the samples manufactured with the AMF were better than those fabricated using the 3DPrint printer. Comparing the flight AMF samples to the ground ones shows that microgravity seems to produce parts with better tensile but worse compressive and flexural properties. MIS also analyzed the phase distribution of the printed material using the AMF's ground test unit and found that there

were no significant differences between samples fabricated in microgravity and those printed in normal gravity [34]. Further testing is to be performed to explore the effects of re-heating and weld line interface interactions.

An example of how AM can benefit space travel is the multipurpose precision maintenance tool (MPMT), as shown in Fig. 4. By compacting several tools into one, it demonstrates how 3DP allows astronauts to create ad-hoc tools for any situation [45]. This was the winning design of the “Future Engineers Space Tool Challenge,” and it is designed to provide several functions in one tool, such as tightening bolts and stripping wires.

4.1 The future of ISAM

The ultimate goal of ISM is to manufacture and assemble large structures in orbit. The advantage of ISM is obvious, reducing the cost of missions greatly by only requiring the launch of raw materials and components. New spacecraft designs can be developed because there will be no need to launch them [46].

The ability to re-use unwanted parts to produce new objects is especially important in manned exploration but also for ISAM. To this end, Tethers Unlimited Inc. has delivered a “combination 3-D printer and plastic recycler” to NASA for testing on the ISS called Refabricator [47]. By using a system called Positrusion, which does not involve grinding and therefore production of dangerous dust, the Refabricator recycles old parts into new filament that can be printed, closing the loop [48]. Positrusion has already been demonstrated with Ultem and ABS and it produces higher quality filament than would normally be obtained by existing systems [49].

Tethers Unlimited along with Interlog Corp. and Techshot are also trying to develop a prototype system called FabLab, which can print and recycle multiple materials including plastic and metal [50]. Once the prototypes are delivered, NASA will decide which partner to continue the investigation with.

There is also an effort to print electronics in space, another crucial component for ISM. 3D-printed ultra-capacitors have already been developed, tested, and patented

Table 2 AMF system specifications [43]

Attribute	Value
Print volume	14 × 10 × 10 cm, 1400 cm ³
Material	ABS, green polyethylene (PE), polycarbonate (PC)
Resolution	0.1 - 0.44 mm
Height resolution	≥ 75 microns
Maximum wall thickness	1 mm

Table 3 Results from tests on samples prepared in orbit (0 g) and on the ground (1 g) [34, 38]

Environment	0 g		1 g		Test type	
	Printer	AMF	3DPrint	AMF		3DPrint
Ultimate strength (MPa)		38.0	27.9	37.8	23.9	Tensile
Elastic modulus (GPa)		3.1	1.7	2.2	1.5	Tensile
Ultimate strength (MPa)		51.1	38.5	52.9	51.4	Compressive
Elastic modulus (GPa)		1.7	1.1	1.5	1.7	Compressive
Ultimate strength (MPa)		58.9	45.1	62.3	35.9	Flexural
Elastic modulus (GPa)		1.9	1.7	2.1	1.4	Flexural

[32] and the next step is printing an radio frequency identification (RFID) antenna. A future target is to perform an ISS demonstration with this technology.

There are a lot of challenges to implementing full ISM. These include the ability to move large structures during construction, robotic dexterity in fabricating complex parts, and being limited to materials that can resist the space environment. A big issue is also the large up-front cost and great risk for ISM that sees agencies and companies prefer the ground-based fabrication approach because it is currently safer and cheaper [46], as mentioned in Section 3.

A proposed solution for ISM of large structures is shown in Fig. 5. Tethers Unlimited, Inc. (TUI) was developing a suite of technologies called SpiderFab [51] that would build large structures in space. It uses a combination of 3DP and on-orbit robot assembly to create structures such as antenna reflectors, solar concentrators, solar sails, and manned habitats. Currently, two systems are being developed [52]:

- Trusselator: a machine able to assemble large trusses through a combination of AM and robotic assembly
- OrbWeaver: used to “manufacture large, high-precision antenna reflectors on-orbit and then robotically integrate them with a phased-array RF system”

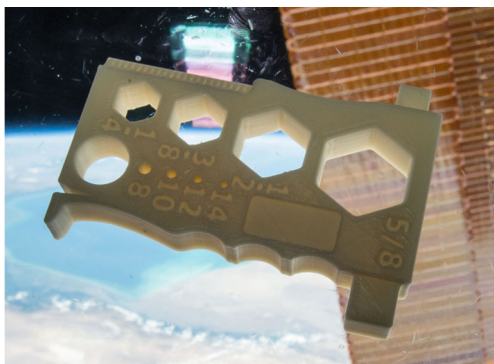


Fig. 4 The MPMT, created by a university student as part of the “Future Engineers Space Tool Challenge,” printed on the ISS [45]

There are other projects that are developing similar technologies for ISM. Dragonfly is a system for providing in-space reconfiguration and installation of large RF reflectors by Space Systems Loral [32]. Made in Space is developing Archinaut, similar to SpiderFab it is a “free-flying space manufacturing and assembly capability that enables advanced spacecraft and structures to be produced in the space environment” [53]. Orbital ATK are developing Commercial Infrastructure for Robotic Assembly and Services (CIRAS), a set of in space hardware assembly technologies [54].

McGuire et al. [46] also proposed an architecture for a spacecraft that is able to perform 3DP in orbit of large structures as shown in Fig. 6. Unlike SpiderFab, they proposed to use FDM and print polymers due to the fact that most metals required heat treating to achieve their full properties, which was difficult in space. Polymers also have the advantage of requiring lower printing temperatures so the printer’s nozzle can be heated by a solar concentrator, thus reducing the amount of power required by the spacecraft. To ensure a consistent source of light, the spacecraft would likely be in a sun-synchronous orbit, which also helps to reduce the amount of temperature fluctuations and simplifies the thermal systems. Since the spacecraft would be autonomous, a quality control system

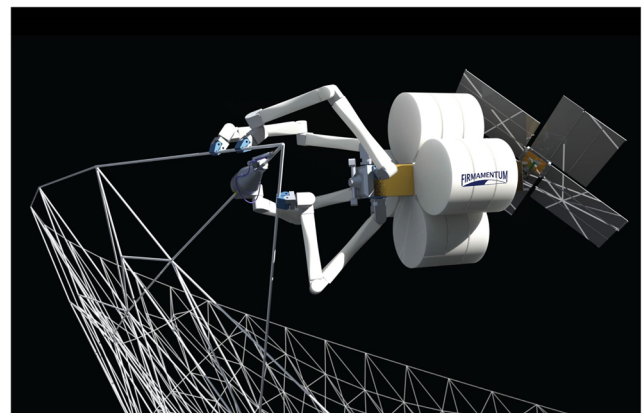


Fig. 5 A concept art of SpiderFab Bot creating a truss in orbit [51]

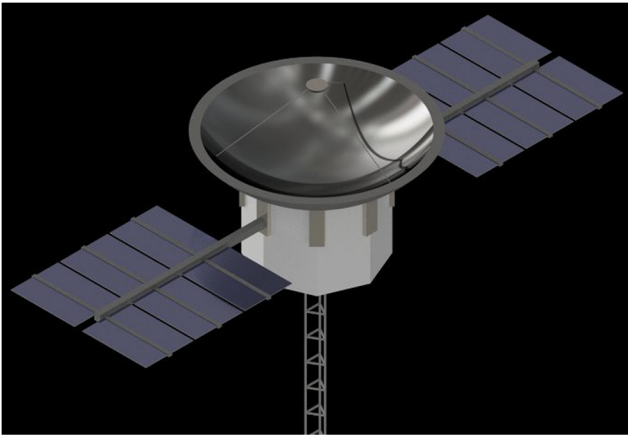


Fig. 6 System architecture for in space 3DP spacecraft [46]

would be necessary to ensure that the printed parts meet requirements through a monitoring system.

5 Ground-based AMFS

The ground-based facilities present all over the world that perform AMFS research have already developed many techniques that allow the printing of an increasingly wide range of materials [55] and of increasing complexity. AM is now considered a valid manufacturing technique for aerospace parts [14], not just to be used for prototyping.

AMFS research can be broadly divided into three categories based on the material used for printing: metal, polymer, and others. AMFS can also be divided loosely into

research for manned and unmanned missions so this paper will classify research into these six categories. Since a lot of the developments can be used in either, an attempt has been made to classify research under “manned” only if it is specifically targeted for this use.

Although most AMFS research can be applied to all spacecraft, some is particularly aimed at certain types of satellites. Therefore, a brief description of satellite classification and what is special about CubeSats follows.

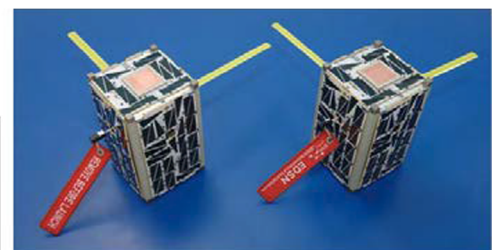
5.1 Satellite classifications

Satellites come in many shapes and sizes but they are generally classified based on mass as follows [56]:

- Large: > 1000 kg
- Medium: 500–1000 kg
- Mini: 100–500 kg
- Micro: 10–100 kg
- Nano: 1–10 kg
- Pico: 0.1–1 kg
- Femto: < 100 g

CubeSats are a particular type of nano-satellites that come in units of $10 \times 10 \times 10$ cm (1U) and can be configured into spacecraft of up to 12U in size, shown in Fig. 7. CubeSats are widely used by institutions such as universities [57] and even elementary schools [58] because they are very cheap to make and launch (as little as 100,000 USD [59]). They are mostly built with commercial off-the-shelf components and are launched in tandem with other CubeSats in the fairings of bigger satellites, thus sharing the cost of launch.

Fig. 7 Examples of different configurations of CubeSats [12]. Left, 1U “Phonesat”; top right, 1.5U “EDSN Spacecraft”; bottom right, 6U “EcAMSat”



5.2 Metal AMFS research

5.2.1 Manned missions

Since AM can produce very particular geometries, printed components for the ISS's urine processor assembly and the oxygen system [25] have been investigated. In [60], the oxygen system study, a comparison was made between wrought Inconel 718 and SLM printed In718 with post-heat treatment to determine the differences in material flammability, a major concern on the ISS. The long-term goal of the study is to evaluate how different print parameters and post-processing affect the flammability of materials to be used in oxygen systems. Printed In718 with heat treatment and hot isostatic pressing (HIP) was found to burn more than both printed In718 with only heat treatment and wrought In718.

5.2.2 Unmanned missions

Most AMFS research with metals is focused on propulsion systems using powder bed fusion (PBF) techniques, especially SLM, since these are reliable and among the most well understood.

Werkheiser [32] and Clinton [61] mentioned that NASA has an ongoing project whose objective is to develop a rocket engine prototype using AM. The challenge here is to prototype the engine in 2.5 years by using AM to reduce part count, cost, and fabrication times, more details can be found in Table 4. The developed engine prototype will then be used as a basis for creating a new engine which will receive certification to use on missions.

Carter et al. [62] presents a summary of the findings of NASA's Glenn Research Center (GRC) with regards to metal AM, which helps to give an overview of the activities in this agency. Various fields were investigated and the findings presented in the paper.

Hot fire testing of sub-scale combustion chamber with full-scale RL-10 features was performed [11]. The injector was made of AM Ni alloy and the thrust chamber out

of AM copper alloy. Nineteen tests were performed in total with four different engine configurations. This study lead to the verification of functional requirements for the AM parts which in turn allowed the implementation of AM components into the RL10. This work also identified ways that AM's design freedom could be used to improve performance and reduce cost.

Another study mentioned by Carter et al. [62] is the creation of a material database for Ti-6Al-4V printed with electron beam melting (EBM) [63, 64]. Following printing the material underwent HIP to close porosities and to achieve the desired micro-structure. The chemistry and micro-structure changes from powder to after heat treatment were observed and high-cycle fatigue (HCF) and tensile testing were performed as well as CT analysis. EBM Ti-6Al-4V was found to posses mechanical properties comparable or superior to Ti-6Al-4V produced by conventional means [65]. The work lead to the aforementioned creation of a complete database for Ti-6Al-4V where characteristics such as microstructure, mechanical properties, fatigue crack growth, fracture toughness, and thermal properties were observed from cryogenic to elevated temperatures.

GRCop-84 is a high-temperature copper alloy developed by GRC for rocket engine main combustion chamber liners and has excellent mechanical and thermal properties [66]. Printing using laser beam melting (LBM) [67] has been found to produce parts whose properties are better than those made with traditional means [62, 68].

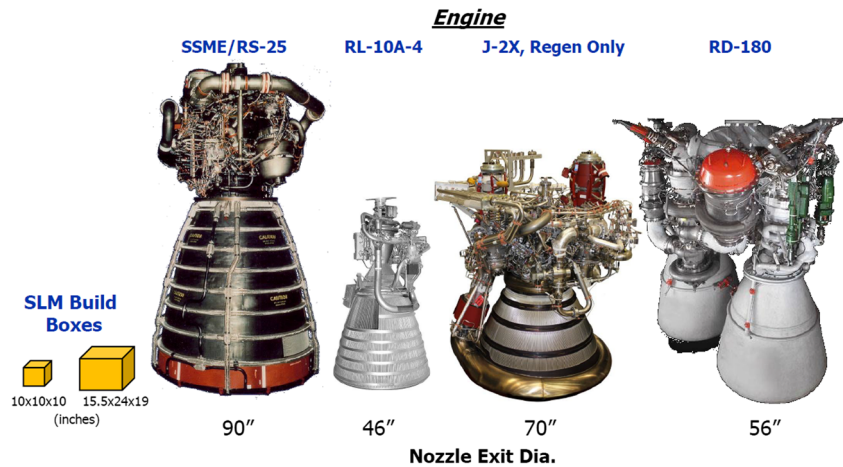
GRCop-84 is also being used in the low-cost upper stage-class propulsion (LCUSP) effort, which is aimed at using 3DP to reduce the cost and time taken to manufacture rocket engines [69]. Using SLM, GRCop-84 was used to print a combustion chamber liner then Inconel 625 was used with electron-beam freeform fabrication (EBF³) [70] to manufacture a structural jacket on the inside of the liner [64]. This was done in an effort to develop features for rocket engines that were previously difficult and to design a process that allows the rapid manufacture of reliable advanced engine parts.

Table 4 Developing a prototype rocket engine with AM versus conventional manufacturing [32]

	State of the art for typical engine developments	Prototype AM engine
Design, development, test, and evaluation (DDTE) time	7–10 years	2–4 years
Hardware lead times	3–6 years	6 months
Testing	Late in the DDTE cycle	Early in the DDTE cycle
Cost	Engine, 20–50 million USD	Prototype, 3–5 million USD
Applicability	Design specific to mission and often proprietary	Provide relevant data to multiple cusotmers and flexible test bed can accommodate changes in hardware or design concepts

Fig. 8 Comparison of SLM build volumes to rocket engines [72]. Dimensions in SI starting from the left are

25.4 × 25.4 × 25.4 cm (16387.064 cm³),
39.37 × 60.96 × 48.26 cm (115823.768 cm³), 228.6 cm, 116.84 cm, 177.8 cm, and 142.24 cm



A multi-agency team has investigated Ni-based superalloys using multi-beam EBM [64, 71]. The objective is to expand the capabilities of AM with these materials and to develop new alloys that specifically use AM's capabilities.

NASA has been investigating large scale metal AM using techniques such as LENS, EBF³, laser freeform manufacturing technology (LFMT), and various forms of direct energy deposition (DED) [72]. This is because 3D printers are currently quite limited in size, especially metal ones. As shown in Fig. 8, bigger print volumes are required in order to be able to fabricate parts for rockets.

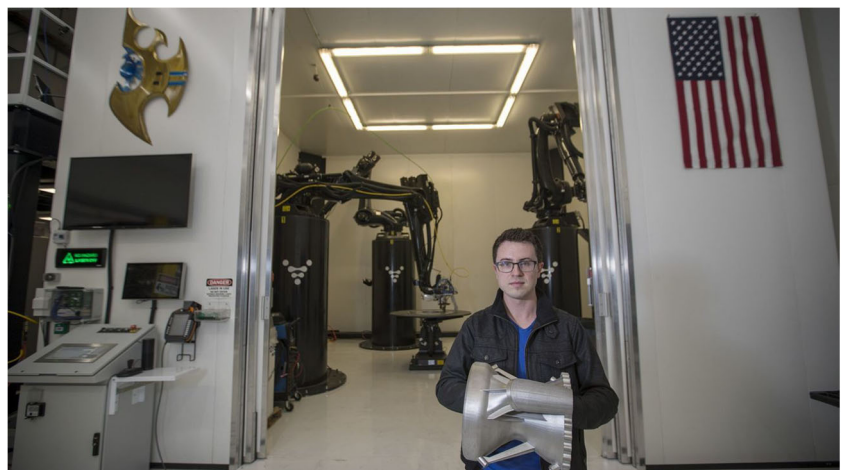
There is some non-governmental research in this field. For example, relativity space is a privately funded orbital launch company that will deploy and resupply satellite constellations with their own launchers manufactured using Stargate, a proprietary, automated, large-scale metal 3D printing system developed by its founders. The Stargate system, shown in Fig. 9, uses robotic arms to perform laser sintered metal printing of rockets [73]. Relativity

plans to simplify and reduce the cost of building launchers by reducing the part count and development time. The company's first launch vehicle, called Terran 1, is slated to have its inaugural launch in 2020 with a capacity of 1,250 kg to LEO [74].

Goddard Space Flight Center (GSFC) has been conducting research into spacecraft instruments, components, electronics, sensors, and coatings using techniques such as direct metal laser sintering (DMLS) [14] and atomic layer deposition (ALD) [76] and making use of printers such as the Aerosol Jet [25]. GRC (with Aerojet Rocketdyne) and MSFC have 3D-printed and tested several injectors [25].

Mireles et al. [77] discusses the potential to use AM for nuclear thermal propulsion (NTP). This is a form of propulsion whose mass ratio (defined in Eq. 3) is very small because it is extremely efficient. Similar to normal thermal rockets, NTP works by heating a gas-like liquid hydrogen (LH₂) and expelling it to create thrust. Unlike in conventional rockets, the LH₂ is heated using a nuclear

Fig. 9 Tim Ellis, co-founder of relativity, holding a printed nozzle in front of the Stargate printing system [75]



reactor as shown in Fig. 10. Like for more traditional propulsion, the advantage of AM for NTP is the ability to easily fabricate a number of complex parts.

The additive manufacturing aiming towards zero waste and efficient production of high-tech metal parts (AMAZE) project (cordis.europa.eu/project/rcn/105484_en.html) was a European effort to improve several key areas of metal AM for the aerospace, space, energy, and automotive sectors. It was the largest metal AM research project in Europe and the objectives included increasing print volume and productivity, cost reduction compared to traditional processes, improve dimensional accuracy, and reducing scrap rates [79]. The printing technologies studied were laser and electron PBF and powder and wire DED.

The AMAZE project led to many developments including the following [79–81]:

- Wire and powder feedstock specifications and test protocols to aid in development of a robust supply chain
- Software for rapid and reliable design of 3D-printed parts
- Build strategies and processes which enabled build times to be reduced by a factor of 10
- Novel materials including aluminum alloys and composites which better utilize the AM process
- New finishing procedures and flexible fixtures
- In-process monitoring methods to capture key process variables during printing
- Improved process models

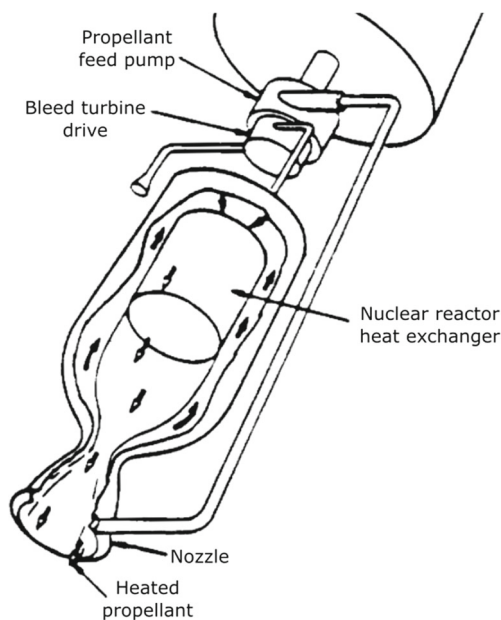


Fig. 10 Schematic of a NTP rocket [78]. Fuel is pumped into the combustion chamber where a nuclear reactor provides the heat for combustion. This is much more efficient than traditional rockets due to the far greater amount of thermal energy provided by the nuclear reactor

- A new benchmarking process, further discussed in Section 6
- Many demonstration parts which have reduced cost, part count, weight, and improved performance

The cited references are only those that directly pertain to AMFS, if the reader wishes they may refer to the AMAZE website for further reading.

Non-governmental agencies (NGO) are also using metal AM to develop propulsion systems. For example, the aforementioned relative space that is trying to print launchers with reduced part counts. SpaceX have successfully developed and launched a 3D-printed main oxidizer valve (MOV) in a Falcon 9 rocket [82]. Airbus Defence and Space have used AM to print brackets for their Eurostar E3000 telecommunications satellites [83], shown in Fig. 11. Other examples include Lockheed Martin using AM to also print brackets for NASA's JUNO spacecraft in 2011 and Thales Alenia Space launching a total of 79 3D-printed parts spread across various missions: Telkom 3S, SGDC, and KOREASAT-8 [80].

In Deepak et al. [8], the authors designed and tested a novel liquid bi-propellant rocket engine by the Students for the Exploration and Development of Space at the University of California San Diego (SEDS UC) student association. The combustion chamber and injector plate were printed with In718 using DMLS. The group designed the engine from scratch and took full advantage of the ability to change the design at any point due to AM's ease of manufacturing. They also designed a regenerative cooling system that was embedded in the chamber walls and has optimized channel cross-sections. The group continues its work to this day and in 2018 has printed a liquid oxygen and kerosene engine again using In718 with DMLS [85].

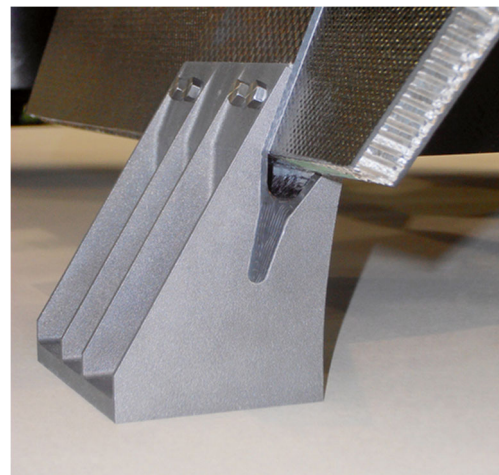


Fig. 11 Titanium brackets manufactured using an EOSINT M 280 for use on Eurostar E3000 satellites [84]

5.3 Polymer AMFS research

5.3.1 Manned missions

Wong et al. [31] carried out an investigation into the quality of ABS surgical tools printed with FDM for long-duration space missions. Like with the MPMT, the idea is that by using AM, astronauts would be able to print ad-hoc instruments for any emergency rather than having to bring pre-made ones all the way from Earth. Thirteen surgeons were asked to perform simulated prepping, draping, incision, and suturing using 3DP forceps, hemostats, and clamps, and they agreed that the instruments would perform adequately. Although ABS was not an ideal material, the usefulness of AM for long-duration manned missions is greatly highlighted by this study.

5.3.2 Unmanned missions

Catina et al. [86] used FDM with ABS to print various configurations of injector plates to test if an acceptable flow would be possible. They found that all the injectors worked and produced acceptable flow rates and also observed that computational fluid dynamics (CFD) and stress simulations diverged significantly from the experimental data. This is due to the lack of software that is able to accurately represent materials produced with AM and will be further discussed in Section 6. Finally, they mentioned how easy and fast it was to design, fabricate, and test the injectors, the entire process taking only 2 days.

Marshall et al. [12] discusses how AM could aid designers of CubeSats by allowing embedded wiring, electronics, and propulsion systems. The team investigated this last possibility by incorporating a commercial Busek micro pulsed plasma thruster (PPT) into a structure printed with FDM. A μ PPT operates by causing ablation and sublimation of the fuel (usually a solid) which is then expelled by an electric field. In this study, the objective was first to determine whether the dielectric strength of printed PC would be appropriate to use with the μ PPTs. Results showed that the material could withstand the voltage without breaking down so they embedded the μ PPT into a printed panel and fired it. The material again performed well as there were no signs of degradation from the firing apart from some coloring on the casing due to arching.

NASA has also undertaken a study in polylactic acid (PLA) reinforced with metal [87]. They tested and compared simple PLA and PLA mixed with bronze, copper, iron, and stainless steel. Tensile, wear, fracture, and microscopy testing was performed at different layer heights. The metal-filled filaments were found to have higher densities than pure PLA, which was to be expected given the metal contents. Tensile testing showed that increased

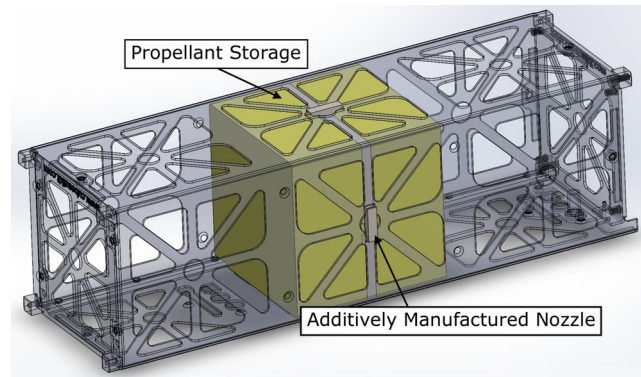


Fig. 12 Artist's impression of the thruster in a 3U CubeSat [88]

concentrations of metals lowered the strength of the printed material but increased the stiffness and porosity while Poisson's ratio stayed about constant. Kuentz et al. [87] concluded that the metal powder mixed into the PLA acted as a weak interface, and therefore lowered the strength and toughness of the printed material.

Gagne et al. [88] outlined the development of a micro-thruster fabricated with AM for use on nano-satellites as either primary propulsion or for attitude control, shown in Fig. 12. The main considerations in designing the thruster was that it should be easy to fabricate and respect the launch rules for CubeSats [89], thus only “green” propellants were considered. Printed with FormLabs' Clear V2 resin using SLA, the thruster was a liquid mono-propellant engine that brought hydrogen peroxide (the mono-propellant)

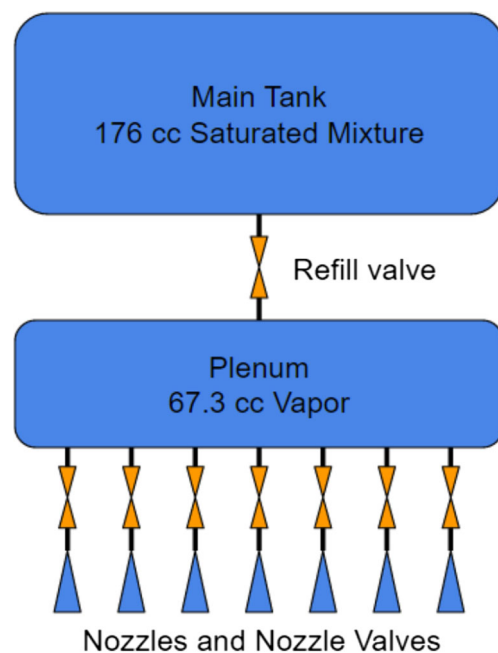


Fig. 13 Diagram showing the tanks, pipes, nozzles, and valves for the thruster [90]

into contact with different catalysts (hexanol, 2-propanol, ethanol, methanol, n-Hexane, and water as a baseline non-reactive solvent), resulting in an exothermic decomposition whose products were expelled through a converging-diverging nozzle. The thruster was designed so that there would be no need for a catalyst bed, which is where AM's design flexibility comes into play. Nozzle size was also a factor that was investigated. Using a theoretical expected performance calculation that considered relative specific impulse, chemical storage energy density, and solute concentration they found that 15% ferric chloride in 2-propanol gave the best theoretical performance.

Another CubeSat thruster design is presented in Stevenson et al. [90]. This is a cold gas thruster (CGT) for attitude control of an interplanetary 6U CubeSat. Manufactured once again using SLA with Accura Bluestone, the printed portion of the thruster includes the main propellant tank and plenum, seven nozzles, and the propellant feed pipes, a schematic of which can be found in Fig. 13. Solenoid valves were installed where necessary to direct the flow of fuel, which was R-236fa, also known as 1,1,1,3,3,3-Hexafluoropropane. Testing in a thermal vacuum chamber showed that the thruster generated 50–60 mN of thrust with $I_{sp} = 31.7$ s and total impulse of 62.2 Ns [90].

Like with metal printing, private companies also have an interest in investigating the potential of polymers. For example, StratasyS had partnered with NASA/NASA/Jet Propulsion Laboratory (JPL) to print 30 polymer antenna array supports to be used directly in space on the FormoSat-7/COSMIC-2 constellation [91].

Polymer materials also have the potential to produce CubeSat structures. As part of a project called BRICSAT, Slejko et al. [92] is an investigation into the feasibility

of using polyetheretherketone (PEEK) HP3, WINDFORM XT, and DuraForm PA for printing modular, non-metallic CubeSat buses. They performed mechanical testing of the three materials and concluded that PEEK was the most suitable given its mechanical properties and the fact that it has already been approved for use in space by NASA [32]. The modular nature of the bus was achieved by printing and combining several elements (bars, panels, etc.) to produce the size needed. A prototype 1U structure was printed using SLS and is being tested to ascertain its mechanical properties.

5.4 Other AMFS research

5.4.1 Manned missions

As humanity expands into space, in situ resource utilization (ISRU) will become increasingly important. The ability to build habitats for astronauts on the Moon or Mars using locally sourced materials means cheaper and simpler missions and the ability to build large structures. In partnership with the US Army Corps of Engineers, NASA was developing a system to automatically build structures called automated additive construction system (ACES)-3 for terrestrial applications (using Portland cement), as shown in Fig. 14, and additive construction with mobile emplacement (ACME) for extraterrestrial ones (using lunar or Martian regolith) [93].

In [94–96], the authors discussed using ACES-3 and 2 with contour crafting [97] to fabricate habitats using “waterless” and normal concretes with minimally processed lunar (JSC-1A) and Martian (JSC Mars-1A) regolith simulants as aggregates. The objective was to characterize

Fig. 14 Overview of ACES-3 [94]

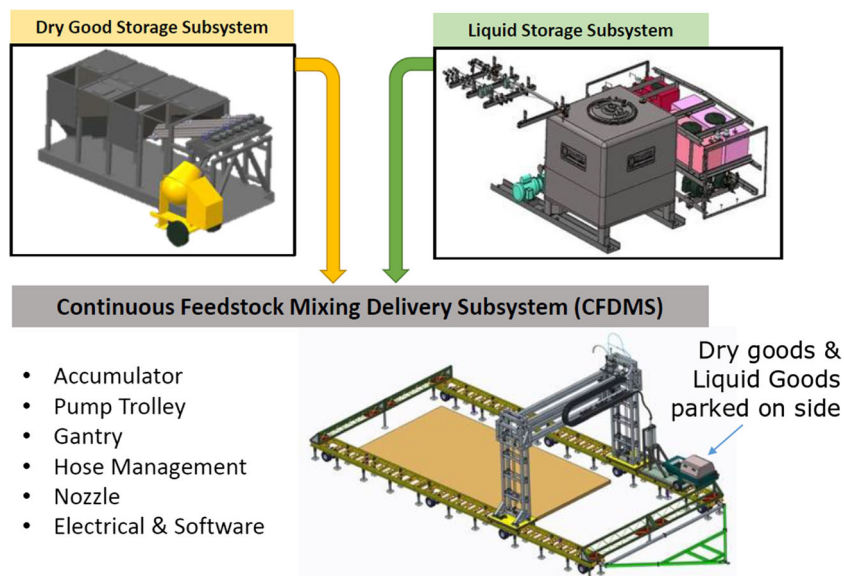


Table 5 Constituents of the samples investigated in the ACME study [98]

Sample	Simulant	Cement	Additives
1	JSC Mars-1A	Portland	Stucco mix
2	JSC Mars-1A	Portland	Stucco mix, Navitas 33
3	JSC Mars-1A	Sorel	Boric acid
4	JSC-1A	Portland	Stucco mix

the mechanical properties of the deposited materials, investigate various types of binders, and how the ACES coped with the various concrete mixtures.

Three types of cement were under investigation in [96]: Portland, Sorel, and sulfur. Werkheiser et al. [96] went into detail about how the constituents for each types of cement could be obtained on the Moon and Mars.

In [94, 95, 98], four samples were fabricated and tested using only Portland and Sorel, three using casting and one using additive construction. The constituents of each sample are shown in Table 5. Testing included impact by a 2-mm sphere traveling at 7 km/s to simulate the potential damage caused by micrometeorites, compression, and visual inspection. Results showed that sample 3 was not as resistant as the others to micrometeorites and they noticed that the lunar regolith cement had shallower penetration depth than the ones with Martian regolith [94, 98].

An alternative to ACES is presented in Meurisse et al. [99]. The objective is to fabricate a “brick-sized model building block of a lunar base outer shell made from model material” using only concentrated sunlight. This is an interesting solution given the extremely thin atmosphere on the Moon and subsequent strength of solar illumination.

The printer is in essence an SLS but instead of using a laser beam it uses a focused beam of solar light, the set-up is shown in Fig. 15. The powder dispenser first deposits a layer of regolith on the testbed while the wall is in place to prevent unwanted sintering. The wall is then removed and the testbed moves under the beam where sintering occurs. The process repeats until the part is fabricated.

Results from 23 printed samples produced an average compressive strength of 2.48765 ± 0.71097 MPa and an average Young’s modulus of 0.20601 ± 0.1519 GPa. The samples also possessed large porosities and the surface finish was very rough. Given that there are still many limitations, this is a promising AM technique since it is

being developed to be completely self-sufficient and does not require powder sieving, making it ideal for ISRU.

Cesaretti et al. [100] describes the outcomes of another ESA feasibility study into using ISRU to build habitats by using D-shaping [101] and Sorel cement. In the course of the study both a habitat design, shown in Fig. 16, and novel simulant of lunar regolith (called DNA, based on natural volcanic material) were developed. The plan was to use the D-shape system to print only the outer wall of the habitat to offer protection from micro-meteoroids and radiation while artificial atmosphere was provided by an inner inflatable module. Demonstration building blocks were printed, one weighing 14.4 kg and another 1.3 tons, to test the mechanical properties of the lattice and the printer’s accuracy, both of which were found to be satisfactory.

ISRU can also be used to manufacture parts and objects from locally sourced material. In Ball et al. [15], the lunar regolith simulant JSC-1AC was printed using LENS after sieving to reduce the particle size to 50–150 μm . Dense cylindrical parts were then fabricated, tested, and their mechanical properties found to be satisfactory.

This kind of work was later expanded. Goulas et al. [102] used SLM to study how scanning speed, hatch spacing, laser power, beam diameter, and layer thickness affected the microstructure, surface roughness, and mechanical properties of various types of lunar regolith samples manufactured via AM. They also added a discussion about the possible effects of the lunar environment on printing and noted that PBF processes would suffer due to the reduced gravity.

Jakus et al. [103] instead used FDM to print inks made by combining sieved JSC MARS-1A and JSC-1A regoliths mixed with elastomeric binders and a solvent mixture. This resulted in mechanically elastic composites whose creation is largely independent of regolith composition except for particle size due to nozzle restrictions. These materials can

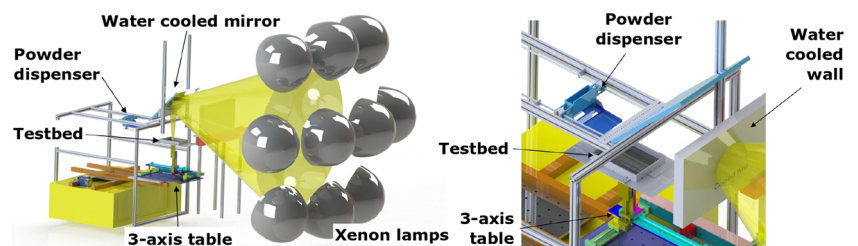
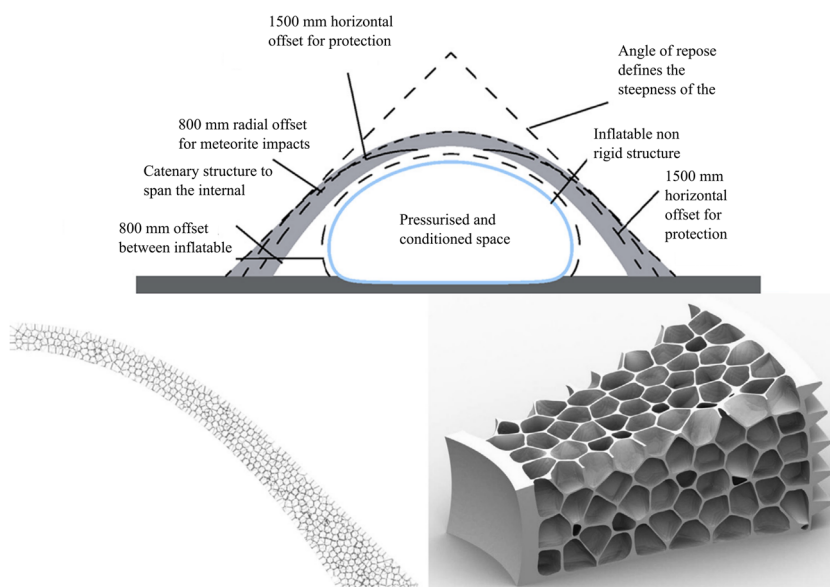
Fig. 15 Solar powered 3D printer with xenon lamps for testing [99]

Fig. 16 Outpost structure (top) and wall profile (bottom left) with detail (bottom right) [100]



potentially address the difficulty in producing plastic-like materials on the Moon and Mars using ISRU.

Lietaert et al. used direct metal printing (DMP), a form of PBF, to produce “M-type asteroid material” using an iron meteorite [104]. This preliminary study was aimed at investigating the feasibility of printing metallic structures using ISRU during asteroid mining.

5.4.2 Unmanned missions

There are projects such as “3D Printing the Complete CubeSat” whose goal is to advance 3DP for CubeSat applications [105]. Since CubeSats are so small, space inside is at a premium and 3DP’s design flexibility would allow for great mass and volume savings. As previously discussed, 3DP frames with channels for wiring would free up a lot of internal space that is usually wasted. As Kief [105] mentions, AM allows the development of new structure designs where several subsystems like power, propulsion, and communications are incorporated directly into the structure.

The presentations in [11, 13] discuss using AM to print ceramics and ceramic-based composites. Ease of fabrication and possibility to tailor material composition and properties are the justifications for using 3DP. Laminated object manufacturing (LOM) [106] and binder jet printing (BJP) [107] are considered to be viable techniques for manufacturing ceramic parts with fiber reinforcements. Halbig et al. [13] mentioned that the AM technologies can only be selectively applied to parts but this may change in the future. Testing for these manufacturing techniques was conducted on gas turbine components using both ceramics and polymers [11, 108].

6 Research in AMFS: gaps and directions

As highlighted throughout the paper, there are several advantages to using AM in the fabrication of parts for the space sector. Table 4 is a particularly clear example of how much time, material, and money can be saved by using 3DP.

There are many factors that determine characteristics and therefore behavior of printed parts, their interaction and effects still not understood. For example, SLM can have as many as 130 different factors [109]. AM also has an inherent variability that comes from random factors like powder distribution, the flow of melt pools, or the alignment of build platforms. These further increase the difficulty in predicting the features of printed parts.

Even components produced in the same print may have large feature variations [110], this is inherent in the printing process and cannot be avoided. Ghidini [10] concluded by talking about the challenges that need to be overcome to use 3DP for space in a presentation about AM activities at ESA. These included the following:

- The need to change the approach to design in order to take full advantage of the capabilities of AM, in other words more research into design for additive manufacturing (DFAM).
- The need to ensure reproducibility, accuracy, and reliability.
- The need to develop new standards and verification methodologies for 3D-printed parts since classical standards do not apply, also mentioned by [9].

Werkheiser [25] made similar points by stating that there are still many challenges to terrestrial AM that remain unresolved, which would be magnified when AM is transposed

to a microgravity and/or vacuum environment. Therefore, ISAM would require a support infrastructure which, like AM itself, would be hard to implement in the space environment. They discuss the fact that that “supply chain logistics, integrated processes, minimal human interaction, and quality control” are not easy in space.

To establish AM as a valid form of manufacturing, the first step is standardization. This is difficult because of AM’s variability, but also because material and technology qualification requirements are particularly stringent in the space sector [69].

There are, however, three basic questions that can be asked of any material technology in order to be consider it valid for mass use, no matter the application [111]:

- Has the material technology been developed and standardized? In other words, the material must be made in a way that is consistent and approved for the application.
- Has the materials technology been fully characterized? For example, Frazier [14] suggests that enough statistically relevant data should be generated to be consistent

with the standards set by entities such as the National Technical Information Service (NTIS) [112], i.e., a population has to exceed the wanted value with at least 99% of its members and a 95% confidence level.

- Has the materials technology been demonstrated? Here, a subcomponent made of the material must be made and tested in a relevant environment, preferably its operational environment. If the subcomponent is not able to operate as intended, then the technology cannot be considered demonstrated.

Frazier [14] suggests three reasons why it is difficult to develop a method for the qualification of AM for critical applications:

- Since there are many ways to 3D print materials and new ones are being constantly developed (for example, RFP [113]), it can be difficult to stay on top of the latest developments, making the standardization process difficult, a point that is also raised by [114, 115].
- Ideally, the development of AM should therefore be halted until standards have been put into place. This

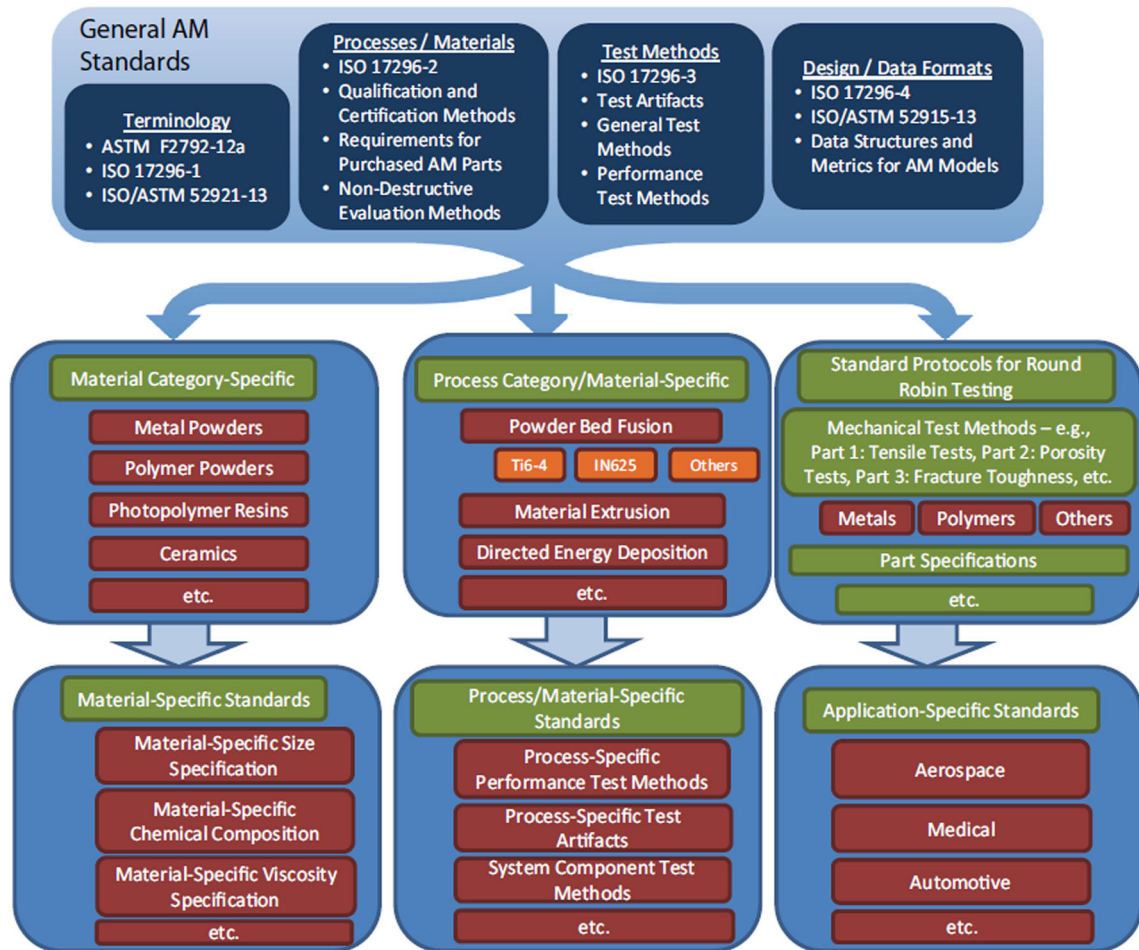


Fig. 17 Structure of ISO and ASTM standards for AM [16]

is of course impossible, but through the ASTM-F42 committee, there are now standards in place for terminology [116, 117], evaluation of mechanical properties of 3D-printed metals [118], data reporting [119], and specifications for PBF of plastic materials [120] (more details can be found in Seifi et al. [121]).

- Lastly, a lot of time is needed to generate the amount of data needed to fully characterize AM processes and how process variables have effect on the properties of the parts produced. In order to understand AM thoroughly, a much large data set is required [69].

As mentioned, there are efforts to achieve standardization of AM parts by the ASTM and ISO, the general structure of which can be seen in Fig. 17. ASTM-F3122 [118] provides guidelines on how to evaluate the mechanical properties of materials made using AM and references several existing standards. Some examples are ASTM A370-16 [122], ASTM B565-04(2015) [123], ASTM E132-04(2010) [124], ASTM E290-14 [125], and several others.

As discussed in the literature [32, 64, 71], the problem is that all these standards do not consider that AM produces materials whose properties are different from their traditionally manufactured counterparts due to the influences of parameters that are not clearly understood. This is especially true for standards such as ASTM E290-14 [125]. Aguilar et al. [126] tested and analyzed the performance of ULTEM 9085 and reported that “the geometry and size of the sample, as well as the size of gaps [...] have a large effect on deflection behavior of a given sample” in their analysis for NASA. They recommended that a sample be fabricated per batch of parts and subject it to the highest stresses undergone by the parts. The coupon would need to break within a given safety factor and in a way that corresponds to simulations in order to consider the batch to be valid.

Bean et al. [127] discussed the applicability of existing standards to polymer parts produced by AM. Out of 45 ASTM and ISO standards reviewed, they concluded that none could be applied to AM in their current state. With modifications or additional considerations, only 27 could be used with AM. Like many others, they concluded that there was need for better understanding of the effects of the printing process and the microstructure on the properties of the final part(s).

For example [128], compared with FDM printed Ultem 9085 coupons to injection molded ones and found that the tensile strength and modulus of the former were about 87% and 64% of the latter. These values changed depending on the printing orientation, since that could drop the tensile strength of the FDM coupon to 75% of the strength of the injection molded sample.

Through the work done during the AMAZE project, new standards are being developed for benchmarking printers and print processes involving a suite of test objects to assess “geometrical accuracy, surface finish, resolution, density,

microstructure, and productivity.” This benchmark is being developed by the ASTM-F42/ ISO-TC committees [79].

Creating a consistent method for standardizing AM parts is a challenge and is one of the main concerns. If 3D-printed parts were used in oxygen recycling systems on manned space missions [60], it is important to know what settings need to be used to ensure that the part will function correctly since if the part were to release metal particles into the air, it could be dangerous for the astronauts.

Werkheiser [32, 35] mentions several requirements for AM and one of them is developing and institutionalizing a “Verification and Certification Process [...] that ensures that the part designs meet all functional and ISS interface/safety requirements.” This is especially crucial in medical applications, for example, Wong [129] discusses the need for validation and certification of sterilization and recycling systems for 3D-printed surgical tools.

Misra et al. [11] makes two interesting points in their conclusions: the need to model the relationship between the printing process, the microstructure, and the final product’s properties; and the need to certify AM components for use by NASA. The first point is also raised by Carter [64] as well as others: the need for predictive models, new alloys, and multi-material, multi-functional structures for space applications.

Mireles et al. [77] mentioned the variability of the AM process as a disadvantage and state that flight certification and qualification of 3D-printed parts would add an extra 30% cost compared to traditional manufacturing. They also discuss that there are no printing parameters for materials that could be used for NTP like ZrC and AlBeMet 162.

The lack of printing parameters for various materials is related to a point discussed by Clinton et al. [39], where they discuss the need for a database of parts that have been approved for use in space. In order to achieve this, the printing parameters, effects of microgravity on materials, and part design all need to be investigated. This kind of work is under-way [62, 64], but in a limited fashion due to the time and cost that testing takes and the fact that parts need to be tested also in flight but access to this environment is very limited.

Several authors [32, 130, 131] discussed methodologies for flight certification of AM parts for NASA. This involves creating a document that outlines the standards for AM certification that can be used by the entire agency. They identified several key topics that need to be addressed in order to develop a reliable system including qualification of metallurgical processes, part process control, and vendor control.

NASA’s additive manufacturing structural integrity initiative (AMSII) project aims to establish a qualification method for SLM parts for spaceflight applications. MSFC has so far developed two documents: engineering and

quality standard for additively manufactured spaceflight hardware (MSFC-STD-3716) [132] and specification for

control and qualification of laser powder bed fusion metallurgical processes (MSFC-STD-3717) [133]. MSFC-

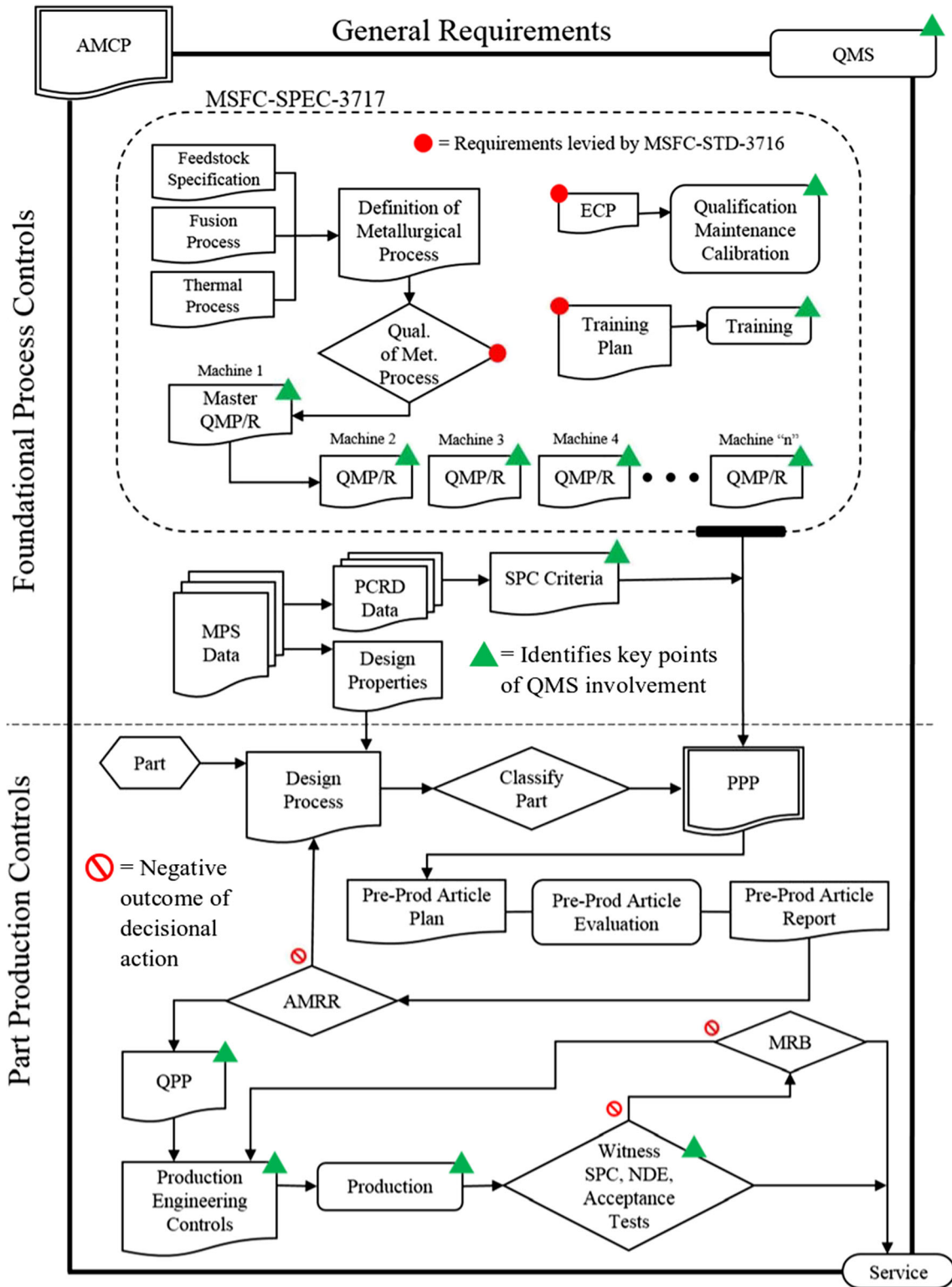


Fig. 18 General requirements for MSFC-STD-3716 [132]



Fig. 19 Cranfield University's WAAM 3D printer being used to print a double-sided, 6-m long aluminum spar [139]

STD-3717 provides the overall requirements for control and qualification of the process while MS-FC-STD-3716 provides requirements for aspects such as the follows [134]:

- Design process
- Part classification, pre-production, and production
- Manufacturing
- Qualification
- Acceptance

Together, MSFC-STD-3717 and MSFC-STD-3716 provide a framework for standardization of laser PBF of metals as shown in Fig. 18.

Along with the work done by the AMAZE project, MSFC-STD-3716 and MSFC-STD-3716 are a step forward and currently the closest thing to a full standard for the qualification of AM parts for use in spaceflight (even though MSFC-STD-3716 and MSFC-STD-3717 are still under review [134]). The limitation of MS-FC-STD-3716 and MS-FC-STD-3716 is though obvious; they only apply to laser PBF. There may be an opportunity to tailor these documents to other forms of AM, but it remains to be seen. Even given MSFC-STD-3716 and MSFC-STD-3717, Wells [115] and Morgan [134] recognized that more understanding is needed of the relationship between printing factors and properties of the final parts.

7 New technologies and challenges

There are new printing techniques being developed for other sectors that could be used for AMFS. An example

is Wire+Arc AM (WAAM), shown in Fig. 19, a printing technology that uses off-the-shelf components to print metal [135]. It involves using a six-axis robot, a power source, and a metal inert gas (MIG) torch to manufacture parts out of steel, aluminum, or any welding wire. The advantage of this technology is that it is relatively cheap to assemble, it has an open architecture (so the user can employ any brand of power source and manipulator), and since steel and aluminum can get away with reduced gas shielding, the part size is really only limited by the reach of the manipulator [136].

Titanium instead requires an inert atmosphere for successful printing; therefore, producing large monolithic titanium components has remained a challenge. Companies such as UK-based GKN Aerospace and the US Energy Department's Oak Ridge National Laboratory (ORNL) are collaborating to increase the quality and print volume of laser metal deposition with wire (LMD-w) [137]. The objective of the project is to build a prototype machine that will use titanium to fabricate medium to large size, complex aircraft components [138].

An example of a technology that is still in early stages of development but has the potential to be used in AMFS is direct 3D metal printing using droplet generators [140]. This technique is similar to polymer ink jet printers but would need to be adapted to handle the high temperatures required for metals. The potential for large-scale printing using this technology is very appealing to the aerospace industry since Murr [140] states that systems with build volumes greater than 10 m³ are possible.

New printing technologies are not limited to only metals. An example of a different printing technology that could one day be used in the space sector is organ printing. Although still in early stages, in 1 day of astronauts exploring Mars might be able to print replacement teeth and relatively simple organs like bones [141]. This would be very useful for medical emergencies and is a line of research parallel to that of Wong et al. [31].

Although this paper is mainly focused AMFS, it is important to recognize that there are still a lot of challenges that are faced not only by the space sector but by the aerospace industry in general. These include the following:

- Creating large parts that then require novel methods to relieve internal stresses caused by fabrication [142].

Table 6 Summary of space-based AMFS literature classified by printing environment

Environment	Section	Details
ISS	4	3DPrint AMF
In space	4.1	Material recycling Construction of large structures using metal and polymer

Table 7 Summary of ground-based AMFS literature classified based on material and use in manned or unmanned missions

Printing material	Section	Details
Metal	5.2	
Manned missions	5.2.1	ISS urine processing assembly and oxygen system
Unmanned missions	5.2.2	Propulsion systems using PBF Creation of material database for EBM Ti-6Al-4V GRCop-84 printing Multi-beam EBM and large scale metal AM Using AM to print electronics and components for NTP Developments of the AMAZE project NGOs using metal AM to develop propulsion systems and parts with reduced mass
Polymer	5.3	
Manned missions	5.3.1	Printed surgical tools
Unmanned missions	5.3.2	Injector plate simulation and testing Embedded μ PPT for satellites Testing of PLA reinforced with metals Development of a 3DP micro-thruster for nano-satellites using SLA that burns “green” propellant Development of a CGT for nano-satellites again using SLA Antenna arrays for FormoSat-7/COSMIC-2 constellation Modular CubeSat structures using PEEK
Other	5.4	
Manned missions	5.4.1	Habitat construction using ISRU Solar-powered SLS using ISRU Development and printing of habitat design using D-shaping and Sorel cement Using LENS, SLM, and FDM with ISRU to create parts and objects
Unmanned missions	5.4.2	Using 3DP to create CubeSat structures with integrated components Printing of ceramics and ceramic-based composites using LOM and BJP

- As shown in Table 4, AM can greatly reduce costs but scaling production up will require a drop in the cost of materials and machines that can produce parts which meet aerospace qualification standards [143].
- Related to the point above is the fact that there are still relatively few materials available for AM [144] and they cost a lot compared to traditional materials [145], something that is being remedied [146] but still needs work.
- Finally, there is the constant problem of the inconsistency in mechanical and material properties of parts produced via AM and the fact that they have still not been properly characterized [147].

These challenges are being addressed by private companies, entities such as NASA and ESA and projects like AMAZE. This has led to the development of standards such as MSFC-STD-3716 and MSFC-STD-3716. But, it will still take some years before AM is truly ready for use in the manufacturing world.

General standards have been developed but with limited scope, which will need to be addressed in order to allow the full potential of AM to be unlocked. Once this gap has been

addressed, AM will become one of the main manufacturing methods for the space sector.

8 Conclusions

The objective of this work was to provide an overview of AMFS research and the gaps therein. Tables 6 and 7 summarize the research covered in this paper. Table 6 classifies research based on printing environment, while Table 7 classifies research based on material and whether the use is for manned or unmanned missions.

AM has the potential to usher in a new era of space exploration due to its ease of use and fast manufacturing times. In just a few short decades, it has grown from prototyping tool to full manufacturing method for functional parts. The space sector’s reliance on custom made, low production volume parts is ideal for AM.

As covered in this paper, AMFS research is taking place in a large variety of areas such as propulsion, buses, electronics, and habitats. The bulk of the research is concentrated on metals, with polymers coming in second and various others in third.

AM in space is limited to the FDM on the ISS. This had been used to characterize materials printed in space and for printing small objects such as the MPMT. In the future, the a closed loop system will be created where printed parts will be recycled into new filament. There are also several plans for a large-scale ISAM using metal and plastic, but for now, they are still at an early stage of development.

Generally, the trend of ground-based AM is that metal 3DP is being used in large spacecraft and launchers while polymers are applied to smaller spacecraft like CubeSats. In particular, a large effort is ongoing to integrate metal 3DP, specifically PBF and laser-based methods, into the production of launchers for the aforementioned mass and complexity reductions. Research into using other materials is mainly concentrated into developing ISRU AM to help with the manufacturing of habitats in future missions to the Moon and Mars.

AM's use in the space sector is still relatively moderate. AM has a high degree of variability compared to conventional manufacturing, leading to limited understanding of the process factors and how they affect the properties of printed parts. This, along with a rapid development of new printing technologies and establishment of new vendors and manufacturers, has resulted in a lack of established models and standards for AMFS. There are many research gaps in many areas of AMFS, but the main one is the need for specifications related to all aspects of AM, from design to post-processing.

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References

- Bikas H, Stavropoulos P, Chryssoulouris G (2016) *Int J Adv Manuf Technol*, 83
- Kodama H (1981) *Rev Sci Instrum* 52(11):1770
- Mohamed OA, Masood SH, Bhowmik JL (2015) *Adv Manuf* 3(1):42. <https://doi.org/10.1007/s40436-014-0097-7>
- Khorasani A, Gibson I, Goldberg M, Littlefair G (2017) *Rapid Prototyp J* 23(2):295. <https://doi.org/10.1108/RPJ-02-2016-0022>
- Sing SL, Yeong WY, Wiria FE, Tay BY, Zhao Z, Zhao L, Tian Z, Yang S (2017) *Rapid Prototyp J* 23(3):611. <https://doi.org/10.1108/RPJ-11-2015-0178>
- Wang X, Jiang M, Zhou Z, Gou J, Hui D (2017) *Compos Part B: Eng* 110:442. <https://doi.org/10.1016/j.compositesb.2016.11.034> <http://www.sciencedirect.com/science/article/pii/S1359836816321230>
- Bang Pham C, Fai Leong K, Chiun Lim T, Sin Chian K (2008) *Rapid Prototyp J* 14(4):246
- Atyam DM, Nguyen NH (2015) In: 51st AIAA/SAE/ASEE joint propulsion conference, p 4051
- Koelbl MB (2015) Technology development and trends: liquid rocket propulsion. <https://ntrs.nasa.gov>. Presented at 51st AIAA/SAE/ASEE Joint Propulsion Conference (AIAA Propulsion and Energy), Orlando, FL, USA. NASA Report/Patent Number: M15-4789
- Ghidini T (2013) An overview of current AM activities at the European Space Agency. <http://www.3d-printing-additive-manufacturing.com/media/downloads/52-d1-12-20-c-tommaso-ghidini-esa.pdf>. Presented at the 3D printing & additive manufacturing - Industrial Applications Global Summit 2013. London, UK
- Misra AK, Grady JE, Carter R (2015) Additive manufacturing of aerospace propulsion components. <https://ntrs.nasa.gov>. Presented at Additive Manufacturing for Small Manufacturers, Pittsburgh, PA, USA. NASA Report/Patent Number: GRC-E-DAA-TN27123
- Marshall WM, Zemba M, Shemelya C, Wicker R, Espalin D, MacDonald E, Keif C, Kwas A (2015) AIAA/SAE/ASEE Joint Propulsion Conference (NASA)
- Halbig MC, Singh M (2015) Additive manufacturing of SiC-based ceramics and ceramic matrix composites. <https://ntrs.nasa.gov>. Presented at 11th International Conference on Ceramic Materials and Components for Energy and Environmental Applications in Vancouver, BC, Canada. NASA Report/Patent Number: GRC-E-DAA-TN24157
- Frazier WE (2014) *J Mater Eng Perform* 23(6):1917. <https://doi.org/10.1007/s11665-014-0958-z>
- Ball VK, Roberson LB, O'Connor GW, Trigwell S, Bose S, Bandyopadhyay A (2012) *Rapid Prototyp J* 18(6):451
- Council NR (2014) 3D printing in space. The National Academies Press, Washington, DC. <https://www.nap.edu/catalog/18871/3d-printing-in-space> <https://doi.org/10.17226/18871>
- Merrill GP (1897) A treatise on rocks rock-weathering and soils. Macmillan. <https://doi.org/10.5962/bhl.title.66971>
- Pan Z, Ding D, Wu B, Cuiuri D, Li H, Norrish J (2018). In: Chen S, Zhang Y, Feng Z (eds) *Transactions on intelligent welding manufacturing*. Springer Singapore, Singapore, pp 3–24
- Kok Y, Tan XP, Wang P, Nai MLS, Loh NH, Liu E, Tor SB (2018) *Mater Des* 139:565. <https://doi.org/10.1016/j.matdes.2017.11.021> <http://www.sciencedirect.com/science/article/pii/S0264127517310493>
- Parandoush P, Lin D (2017) *Compos Struct* 182:36. <https://doi.org/10.1016/j.compstruct.2017.08.088> <http://www.sciencedirect.com/science/article/pii/S0263822316329063>
- Schoinochoritis B, Chantzis D, Salonitis K (2017) *Proc Inst Mech Eng Part B: J Eng Manuf* 231(1):96. <https://doi.org/10.1177/0954405414567522>
- Costabile G, Fera M, Fruggiero F, Lambiase A, Pham D (2017) *Int J Ind Eng Comput* 8(2):263. <https://doi.org/10.5267/j.ijiec.2016.9.001>
- Busachi A, Erkoyuncu J, Colegrove P, Martina F, Watts C, Drake R (2017) *CIRP J Manuf Sci Technol* 19:117. <https://doi.org/10.1016/j.cirpj.2017.07.001> <http://www.sciencedirect.com/science/article/pii/S1755581717300299>
- Dennison JR (2015) An overview of the dynamic interplay between the space environment and spacecraft materials. https://digitalcommons.usu.edu/mp_presentations/114/. Laboratory of Spacecraft Environment Interaction Engineering
- Werkheiser N (2014) Overview of nasa initiatives in 3D printing and additive manufacturing. <https://ntrs.nasa.gov>. Presented at 2014 DoD Maintenance Symposium, Birmingham, AL, USA. NASA Report/Patent Number: M15-4252
- Brown DC (2011) NASA to launch new science mission to asteroid in 2016. <https://www.nasa.gov/topics/solarsystem/features/osiris-rex.html>. Accessed 2015-11-23
- Skran DL (2015) Battle of the Collossi: SLS vs Falcon Heavy. <http://www.thespacereview.com/article/2737/1>. Accessed 2016-03-16

28. GlobalCom Satellite Phones (2015) The cost of building and launching a satellite. <https://www.globalcomsatphone.com/hughesnet/satellite/costs.html>. Accessed 2016-06-15
29. Imken TK, Stevenson TH, Lightsey EG (2015) *J Small Satellites* 4(2):371
30. Molitch-Hou M (2016) 3D printing has its place in Martian settlements, according to NASA. <https://3dprintingindustry.com/news/3d-printing-in-martian-settlements-nasa-66718/>. Accessed 2017-09-01
31. Wong JY, Pfahnl AC (2014) *Aviat Space Environ Med* 85(7):758. <https://doi.org/10.3357/ASEM.3898.2014>
32. Werkheiser N (2017) NASA additive manufacturing overview. <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170001551.pdf>. Presented at military additive manufacturing summit 2017, Tampa, FL, USA. NASA Report/Patent Number: MSFC-E-DAA-TN38811
33. Made In Space (2018) 3D printing in zero gravity experiment. <http://madeinspace.us/projects/3dp/>. Accessed 2016-05-10
34. Thomas D, Snyder MP, Napoli M, Joyce ER, Shestople P, Letcher T (2017) In: AIAA SPACE and astronautics forum and exposition, p 5278
35. Werkheiser N (2015) In-space manufacturing: pioneering a sustainable path to Mars. <https://ntrs.nasa.gov>. Presented at NASA Marshall Space Flight Center; Huntsville, AL, United States. NASA Report/Patent Number: M15-4866
36. Snyder M, Dunn J, Gonzalez E (2013) In: AIAA SPACE 2013 conference and exposition, p 5439
37. Bean QA, Cooper KG, Edmunson JE, Johnston MM, Werkheiser MJ (2015) International Space Station (ISS) 3D printer performance and material characterization methodology. <https://ntrs.nasa.gov>. Presented at 62nd JANNAF Propulsion Meeting, Nashville, TN, USA. NASA Report/Patent Number: M15-4563
38. Prater TJ, Bean QA, Beshears RD, Rolin TD, Werkheiser NJ, Ordonez E, Ryan RM, Ledbetter III (2016) Summary report on phase I results from the 3D printing in zero g technology demonstration mission, volume i. Tech. rep., NASA Marshall Space Flight Center
39. Clinton RG, Morgan K (2015) Additive manufacturing at NASA marshall space flight center: In-space and for-space initiatives. <https://ntrs.nasa.gov>. Presented at the additive manufacturing for defense and government symposium in Huntsville, AL, USA. NASA Report/Patent Number: M16-5001
40. ASTM International (2014) ASTM D638-14 standard test method for tensile properties of plastics
41. ASTM International (2015) ASTM D790 - 15e2 standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials
42. ASTM International (2015) ASTM D695 - 15 standard test method for compressive properties of rigid plastics
43. Made In Space (2018) Additive manufacturing facility. <http://madeinspace.us/projects/amf/>. Accessed 2018-05-31
44. ASTM International (2014) ASTM D638 - 14 standard test methods for tensile properties of plastics
45. Rainey K (2016) Building the future: space station crew 3-d prints first student-designed tool in space. https://www.nasa.gov/mission_pages/station/research/news/multipurpose_precision_maintenance_tool. Accessed 2016-08-01
46. McGuire T, Hirsch M, Parsons M, Leake S, Straub J (2016) In: *Sensors and systems for space applications IX*, vol 9838. International Society for Optics and Photonics, p 98380V
47. Boyle A (2018) Tethers unlimited delivers 3-D printer and recycler combo to NASA for space station. <https://www.geekwire.com>. Accessed 2018-10-21
48. SBIR, NASA (2014) Positrusion filament recycling system for ISS. <https://www.sbir.gov/sbirsearch/detail/888089>. Accessed 2017-08-17
49. T.U. Inc. (2015) Positrusion filament Recycler, superior quality filament for 3D printers. Brochure. http://www.tethers.com/SpecSheets/Brochure_Positrusion_20150127.pdf
50. Boyle A (2017) Tethers unlimited wins NASA grant to work on future FabLab for 3-D printing in space. www.geekwire.com
51. Hoyt RP, Cushing JI, Slostad JT, Jimmerson G, Moser T, Kirkos G, Jaster ML, Voronka NR (2013) In: AIAA Space 2013 conference and exposition, p 5509
52. Tethers Unlimited (2014) Spiderfab. <http://www.tethers.com/SpiderFab.html>. Accessed 2018-03-06
53. Patane S, Joyce ER, Snyder MP, Shestople P (2017) In: AIAA SPACE and astronautics forum and exposition, p 5227
54. Clinton RG (2018) Additive manufacturing for human space exploration. <https://ntrs.nasa.gov/search.jsp>. Presented at the Additive Manufacturing for Aerospace and Space conference, Munich, Germany. NASA Report/Patent Number: MSFC-E-DAA-TN52182
55. Kruth J, Leu M, Nakagawa T (1998) *{CIRP} Ann - Manuf Technol* 47(2):525. [https://doi.org/10.1016/S0007-8506\(07\)63240-5](https://doi.org/10.1016/S0007-8506(07)63240-5). <http://www.sciencedirect.com>
56. Konecny G (2004) In: XXth ISPRS Congress, commission, vol 4, pp 12–23
57. SaRC (2016) Satellite Research Centre (SaRC) factsheet. <http://www.sarc.eee.ntu.edu.sg/Research/Projects/Documents/SaRC>
58. Mahoney E (2016) First cubesat built by an elementary school deployed into space. <https://www.nasa.gov/>. Accessed 2016-12-03
59. amsat-uk (2013) Ossi-1 amateur radio cubesat launched. <https://amsat-uk.org/2013/04/19/ossi-1-amateur-radio-cubesat-launched/>. Accessed 2018-02-26
60. Tylka J (2016) Evaluation of additively manufactured metals for use on oxygen systems. <https://ntrs.nasa.gov>. Presented at Additive Manufacturing for Propulsion Applications, Huntsville, AL, USA. NASA Report/Patent Number: JSC-CN-37294
61. Clinton RG (2017) Overview of additive manufacturing initiatives at NASA marshall space flight center - in space and rocket engines. <https://ntrs.nasa.gov/>. Presented at the Additive Manufacturing for Aerospace, Defence & Space Conference, London, UK. NASA Report/Patent Number: MSFC-E-DAA-TN38745
62. Carter R, Draper S, Locci I, Lerch B, Ellis D, Senick P, Meyer M, Free J, Cooper K, Jones Z (2015) 66th International Astronautical Congress
63. Hinojos A, Mireles J, Reichardt A, Frigola P, Hosemann P, Murr LE, Wicker RB (2016) *Mater Des* 94:17. <https://doi.org/10.1016/j.matdes.2016.01.041> <http://www.sciencedirect.com/science/article/pii/S0264127516300405>
64. Carter RW (2015) GRC metal additive manufacturing. <https://ntrs.nasa.gov>. Presented in Cleveland, OH, USA. NASA Report/Patent Number: GRC-E-DAA-TN25102
65. Susan D, Brad L, Richard R, Richard M, Ivan L, Anita G (2016) Materials characterization of electron beam melted $Ti - 6Al - 4V$. Wiley-Blackwell, chap 242, pp 1433–1440. <https://doi.org/10.1002/9781119296126.ch242> <https://onlinelibrary.wiley.com/doi/abs/10.1002/9781119296126.ch242>
66. Ellis DL (2005) Grcop-84: a high-temperature copper alloy for high-heat-flux applications. Tech. rep., NASA Glenn Research Center. NASA Report/Patent Number: NASA/TM-2005-213566, E-15011
67. Greitemeier D, Palm F, Syassen F, Melz T (2017) *Int J Fatigue* 94:211. <https://doi.org/10.1016/j.ijfatigue.2016.05.001> <http://www.sciencedirect.com/science/article/pii/S0142112316300871>. Fatigue and Fracture Behavior of Additive Manufactured Parts

68. Minneci R, Rawn C, Bunn J, Floyd J, Jones Z (2017) Preliminary residual stress mapping of GRCop-84 fabricated by SLM. <https://ntrs.nasa.gov>. Presented at 2017 Joint Nanoscience and Neutron Scattering User Meeting, Oak Ridge, TN, USA. NASA Report/Patent Number: M17-6172
69. Vickers J (2015) Low cost upper stage-class propulsion (Icusp). techreport, NASA. <https://ntrs.nasa.gov>
70. Ding D, Pan Z, Cuiuri D, Li H (2015) Int J Adv Manuf Technol 81(1):465. <https://doi.org/10.1007/s00170-015-7077-3>
71. Sudbrack CK, Kirka MM, Dehoff RR, Carter RW, Semiatin SL, Gabb TP (2016) NASA/ORNL/AFRL project work on EBM LSHR: additive manufacturing of high-temperature gamma-prime strengthened ni-based superalloys. Tech. rep., NASA Glenn Research Center. <https://doi.org/10.2172/1362246>, <https://ntrs.nasa.gov>
72. Gradl P, Brandsmeier W, Calvert M, Greene S, O'Neal D, Protz C, Richard J, Morgan K (2017) Additive manufacturing overview: propulsion applications, design for and lessons learned. <https://doi.org/10.2514/6.2018-4860>. NASA Report/Patent Number: M17-6434
73. Mosher D (2018) Defectors from SpaceX, Blue Origin, and Tesla are developing a remarkable technology called 'Stargate' to help colonize other planets. <https://www.businessinsidersg/relativity-space-3d-printed-rockets-mars-2018-10/?r=US&IR=T>. Accessed 2018-11-25
74. Relativity Space (2018) Terran 1. <https://www.relativityspace.com/terran/>. Accessed 2018-11-25
75. Masugana S (2018) Entrepreneur seeks to boldly go where no one has gone before: 3-D printing nearly an entire rocket. <https://www.latimes.com/business/la-fi-rocket-tim-ellis-relativity-20180427-story.html> Accessed 2018-11-25
76. George SM (2009) Chem Rev 110(1):111
77. Mireles O, Garcia C, Jones Z (2016) Potential for additive manufacture in nuclear thermal propulsion (NTP). <https://ntrs.nasa.gov>. Presented at nuclear and emerging technologies for space, Huntsville, AL, USA. NASA Report/Patent Number: M16-5074
78. Finseth JL (1991) Rover nuclear rocket engine program: overview of rover engine tests. Final Report. Tech. rep., Sverdrup Technology, Inc., Huntsville
79. Community Research and development information service (CORDIS) (2018) Amaze report summary. https://cordis.europa.eu/result/rcn/223006_en.html
80. Adkins N, Lavery N, Cabannes K, Montredon F, Schmidtke K (2017) APOD 15 – invar space parts. <http://amazeproject.eu/publications/>. Presented at the AMAZE Project Technology Forum, Coventry, UK
81. Montredon F (2017) Sun sensor and antenna support. <http://amazeproject.eu/publications/>. Presented at the AMAZE Project Technology Forum, Coventry, UK
82. SpaceX (2014) SpaceX launches 3D-printed part to space, creates printed engine chamber. <https://www.spacex.com/>. Accessed 2016-02-02
83. Airbus Defence and Space (2015) Airbus defence and space optimising components using 3D printing for new Eurostar E3000 satellite platforms. www.airbusdefenceandspace.com
84. EOS (2015) Airbus defence and space - additive manufacturing process by EOS optimizes satellite technology. www.eos.info
85. Lin A (2018) Engines - SEDS UCS. <https://www.sedsucs.org/projects/engines/>. Accessed 2017-09-23
86. Catina JJ, Castonguay K (2015) Use of additive manufacturing to model and develop advanced liquid propulsion designs. American Institute of Aeronautics and Astronautics. Propulsion and Energy Forum. <https://doi.org/10.2514/6.2015-4068> 10.2514/6.2015-4068
87. Kuentz L, Salem A, Singh M, Halbig MC, Salem JA (2016) Additive manufacturing and characterization of polylactic acid (PLA) composites containing metal reinforcements. <https://ntrs.nasa.gov>. Presented at the 40th International Conference and Expo on Advanced Ceramics and Composites, Daytona Beach, FL, USA. NASA Report/Patent Number: GRC-E-DAA-TN29146
88. Gagne KR, Hitt DL, McDevitt MR (2016) In: 54th AIAA aerospace sciences meeting, p 0963
89. Mehrparvar A, Pignatelli D, Carnahan J, Munakat R, Lan W, Toorian A, Hutputanasin A, Lee S (2014) The CubeSat Program, Cal Poly San Luis Obispo US
90. Utah State University. Design and Characterization of a 3D-Printed Attitude Control Thruster for an Interplanetary 6U CubeSat. <https://digitalcommons.usu.edu/smallsat/2016/TS5Propulsion/3/>
91. Wyman C (2015) Stratasy 3D printing keeps nasa satellite on time and on budget – FDM strong enough for space. <http://blog.stratasy.com/2015/02/12/nasa-3d-printing-fortus/>. Accessed 2015-12-12
92. Slejko EA, Longato E, Seriani S, Gallina P, Lughini V, Bozzolan F, Cuttin A, Fragiocomo M, Gregorio A (2018) The 4S Symposium
93. Mueller RP, Townsend II, Tamasy GJ, Evers CJ, Sibille LJ, Edmunson JE, Fiske MR, Fikes JC, Case M (2018) Additive construction with mobile emplacement (ACME)/automated construction of expeditionary structures (ACES) materials delivery system (MDS). <https://ntrs.nasa.gov>. Presented at the ASCE Earth and Space Conference 2018, Cleveland, OH, USA. NASA Report/Patent Number: KSC-E-DAA-TN48594
94. Fiske M, Edmunson J (2017) Additive construction with mobile emplacement (ACME) 3D printing structures with in-situ resources. <https://ntrs.nasa.gov>. Presented at the University of Alabama, Huntsville, AL, USA. NASA Report/Patent Number: MSFC-E-DAA-TN48929
95. Edmunson J, Fiske M, Mueller R, Alkhateb H, Alhnooukh A, Morris H, Townsend V, Fikes J, Johnston M (2018) Additive construction with mobile emplacement: multifaceted planetary construction materials development. <https://ntrs.nasa.gov>. Presented at the American Society of Civil Engineers (ASCE) Earth and Space 2018 Conference, Cleveland, OH, USA. NASA Report/Patent Number: MSFC-E-DAA-TN54927
96. Werkheiser MJ, Fiske M, Edmunson J, Khoshnevis B (2015) In: AIAA SPACE 2015 conference and exposition, p 4451
97. Khoshnevis B, Hwang D, Yao KT, Yeh Z (2006) Int J Ind Syst Eng 1(3):301
98. Ordóñez E, Edmunson J, Fiske M, Christiansen E, Miller J, Davis BA, Read J, Johnston M, Fikes J (2017) Procedia Eng 204:390
99. Meurisse A, Sperl M, Makaya A (2005) Mater Sci Eng: A 533:413–414. <https://doi.org/10.1016/j.msea.2005.08.152>
100. Cesaretti G, Dini E, Kestelie X, Colla V, Pambaguian L (2014) Acta Astronautica 93:430. <https://doi.org/10.1016/j.actaastro.2013.07.034> <http://www.sciencedirect.com/science/article/pii/S0094576513002889>
101. Colla V, Dini E (2013) Low-cost 3D printing, for science, education & sustainable development, 127–132
102. Goulas A, Binner JG, Engström DS, Harris RA, Friel RJ (2018) Proc Instit Mech Eng, Part L: J Mater: Des Appl 0(0):1464420718777932 (0). <https://doi.org/10.1177/1464420718777932>
103. Jakus AE, Koube KD, Geisendorfer NR, Shah RN (2017) Sci Rep 7:44931
104. Lietaert K, Thijs L, Neirinck B, Lapauw T, Morrison B, Lewicki C, Vaerenbergh JV (2018) Acta Astronautica 143:76. <https://doi.org/10.1016/j.actaastro.2017.11.027> <http://www.sciencedirect.com/science/article/pii/S0094576517310196>

105. Kief C (2015) 3D printing the complete cubesat. <https://ntrs.nasa.gov>. NASA Report/Patent Number: NASA FS-2015-03-32-ARC
106. Ahn D, Kweon JH, Choi J, Lee S (2012) J Mater Process Technol 212(2):339
107. Mostafaei A, Stevens EL, Hughes ET, Biery SD, Hilla C, Chmielus M (2016) Mater Des 108:126
108. A fully non-metallic gas turbine engine enabled by additive manufacturing. <https://ntrs.nasa.gov>. Presented at 22nd International Symposium on Air Breathing Engines (ISABE 2015), Phoenix, AZ, USA. NASA Report/Patent Number: ISABE-2015-20168, GRC-E-DAA-TN24606
109. Rehme O, Emmelmann C (2006) Rapid manufacturing of lattice structures with selective laser melting. <https://doi.org/10.1117/12.645848>
110. Scott J, Gupta N, Wember C, Newsom S, Wohlers T, Caffrey T (2012) Additive manufacturing: status and opportunities. Science and Technology Policy Institute
111. Frazier WE, Polakovics D, Koegel W (2001) JOM (The Journal of The Minerals, Metals & Materials Society) 53(3):16. <https://doi.org/10.1007/s11837-001-0171-z>
112. Rice RC (2003) Metallic materials properties development and standardization (MMPDS): Chapters 1–4, vol 1 (National Technical Information Service)
113. Pattnaik S, Jha PK, Karunakar DB (2014) Proc Inst Mech Eng Part L: J Mater Des Appl 228(4):249
114. Stephenson T, Swanson T (2014) Additive manufacturing: ensuring quality for spacecraft applications. <https://ntrs.nasa.gov>. Presented at 2nd Annual Additive Manufacturing in Government Conference, Washington D.C., USA. Report/Patent Number: GSFC-E-DAA-TN19182
115. Wells D (2017) Standardization in additive manufacturing: challenges in structural integrity assurance. <https://ntrs.nasa.gov>. Presented at the Additive Manufacturing For Reactor Materials and Components Public Meeting, Bethesda, MD, USA. NASA Report/Patent Number: M17-6393
116. ASTM International (2013) ASTM52921-13 standard terminology for additive manufacturing-coordinate systems and test methodologies
117. ASTM International (2015) ASTM 52900:2015(E) standard terminology for additive manufacturing – general principles – terminology. <https://doi.org/10.1520/F3177-15>
118. ASTM International (2014) ASTM F3122-14 standard guide for evaluating mechanical properties of metal materials made via additive manufacturing processes. <https://doi.org/10.1520/F3122-14>
119. ASTM International (2013) ASTM F2971-13 standard practice for reporting data for test specimens prepared by additive manufacturing. <https://doi.org/10.1520/F2971>
120. ASTM International (2014) ASTM F3091/F3091M-14, standard specification for powder bed fusion of plastic materials. https://doi.org/10.1520/F3091_F3091M-14
121. Seifi M, Gorelik M, Waller J, Hrabe N, Shamsaei N, Daniewicz S, Lewandowski JJ (2017) Jom 69(3):439
122. ASTM International (2016) ASTM A370-16 standard test methods and definitions for mechanical testing of steel products. <https://doi.org/10.1520/A0370-16>
123. ASTM International (2015) ASTM B565-04(2015) standard test method for shear testing of aluminum and aluminum-alloy rivets and cold-heading wire and rods. <https://doi.org/10.1520/B0565-04R15>
124. ASTM International (2010) ASTM E132-04(2010) standard test method for Poisson's ratio at room temperature
125. ASTM International (2014) ASTM E290-14 standard test methods for bend testing of material for ductility
126. Aguilar D, Christensen S, Fox EJ (2015) 3-D printed Utem 9085 testing and analysis. Technical report, SPHERES National Lab
127. Forster AM (2015) Materials testing standards for additive manufacturing of polymer materials: state of the art and standards applicability. <https://doi.org/10.6028/NIST.IR.8059>
128. Chuang KC, Grady JE, Draper RD, Shin ESE, Patterson C, Santelle TD (2015) The composites and advanced materials expo (CAMX). Dallas
129. Wong JY (2016) Aerosp Med Human Perform 87(6):580. <https://doi.org/10.3357/AMHP.4633.2016> <https://www.ingentaconnect.com/content/asma/amhp/2016/00000087/00000006/art00013>
130. Wells D, Clinton R (2015) Overview of flight certification methodology for additive manufacturing. <https://ntrs.nasa.gov>. Presented at Frontiers in Additive Manufacturing Engineering, Storrs, CT, USA. NASA Report/Patent Number: MSFC-E-DAA-TN24486
131. Morgan K (2016) A proposed qualification methodology for additively manufactured spaceflight propulsion hardware. <https://ntrs.nasa.gov>. Presented at 23rd Additive Manufacturing Technology and CQSDI, Cape Canaveral, FL, USA. NASA Report/Patent Number: MSFC-E-DAA-TN30330
132. Marshall Space Flight Center (2017) MSFC-STD-3716 - standard for additively manufactured spaceflight hardware by laser powder bed fusion in metals. Standard, NASA. <https://standards.nasa.gov>
133. Marshall Space Flight Center (2017) MSFC-SPEC-3717 - specification for control and qualification of laser powder bed fusion metallurgical processes. Standard, NASA. <https://standards.nasa.gov>
134. Morgan K (2017) Additive manufacturing overview: propulsion applications, design for and lessons learned. <https://ntrs.nasa.gov>. Presented at AIAA Propulsion and Energy Forum 2017, Atlanta, GA, USA. NASA Report/Patent Number: MSFC-E-DAA-TN44554
135. Williams SW, Martina F, Addison AC, Ding J, Pardal G, Colegrove P (2015) Materials Science and Technology, p 1743284715Y.000. <https://doi.org/10.1179/1743284715Y.0000000073>
136. Bandari YK, Williams SW, Ding J, Martina F (2015) In: 26th International solid freeform fabrication symposium, vol 1. Austin, pp 17–25
137. Bandari YK, Lee YS, Nandwana P, Richardson BS, Adediran AI, Love LJ (2018) In: Solid freeform fabrication 2018 - proceedings of the 29th annual international solid freeform fabrication symposium – an additive manufacturing conference, vol 1. University of Texas in Austin, pp 425–437
138. Schelmetic T (2017) Laser metal deposition with wire process used for additive manufacturing of large titanium components. <https://www.designnews.com>. Accessed 2019-02-08
139. Thyrt AR (2016) Who's got the biggest 3D-printed part? <https://www.designnews.com>. Accessed 2019-04-05
140. Murr LE (2016) J Mater Sci Technol 32(10):987. <https://doi.org/10.1016/j.jmst.2016.08.011> <http://www.sciencedirect.com/science/article/pii/S1005030216301335>
141. Kang HW, Lee SJ, Ko IK, Kengla C, Yoo JJ, Atala A (2016) Nat Biotechnol 34:312 EP. <https://doi.org/10.1038/nbt.3413>
142. Ngo TD, Kashani A, Imbalzano G, Nguyen KTQ, Hui D (2018) Compos Part B: Eng 143:172. <https://doi.org/10.1016/j.composb.2018.02.012> <http://www.sciencedirect.com/science/article/pii/S1359836817342944>
143. Thomas D (2016) Int J Adv Manuf Technol 85(5):1857. <https://doi.org/10.1007/s00170-015-7973-6>

144. Baumers M, Holweg M, Rowley J (2016) 3D printing–redistributing manufacturing project report. Available at https://www.sbs.ox.ac.uk/sites/default/files/research-projects/3DP-RDM_report.pdf. Accessed 2019-02-11
145. Cotteleer M (2014) 3D opportunity: additive manufacturing paths to performance, innovation, and growth. http://www.cellular3d.com/images/marketresearch/SIMT_AM_Conference_Keynote-Oct2014.pdf. Presented at 2014 SIMT additive manufacturing symposium
146. Martin JH, Yahata BD, Hundley JM, Mayer JA, Schaedler TA, Pollock TM (2017) Nature 549:365 EP. <https://doi.org/10.1038/nature23894>
147. Campbell T, Williams C, Ivanova O, Garrett B (2011) Technologies, potential, and implications of additive manufacturing. Atlantic Council, Washington, DC

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