Young Manufacturing Leaders Network

Additive Manufacturing for the replacement of parts during orbit

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Abstract

The utilisation of additive manufacturing (AM) in space exploration has garnered significant attention due to its potential to revolutionise space missions. This white paper focusses specifically on the application of polymer and metal AM in space, exploring the advancements, challenges and future prospects in this regard. The ability to fabricate complex and customised polymer-based or metal-based components on demand in the space environment offers numerous advantages, including reduced mission costs, improved sustainability and enhanced mission flexibility and safety. The findings of this white paper contribute to a deeper understanding of the capabilities and limitations of polymer and metal AM in the context of space exploration, paving the way for further advancements in this field.

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1 Introduction

Additive manufacturing (AM) has attracted a huge amount of interest in the last decades, and it has been increasingly adopted in industry. For prototyping or components with small batch sizes, AM processes enable the fast development of products and experimental setups while reducing production costs. Several AM processes are currently available for various materials and polymers. In the field of polymers, the most established processes are fused filament fusion (FFF) and vat photo-polymerization (VPP).

In recent years, the advantages of AM have also become evident in the space industry. In the aerospace industry, each component is thoughtfully designed to guarantee maximum safety while minimising the weight and dimensions of that component. Any additional weight increases the required amount of fuel and reduces autonomy. A famous example is the International Space Station (ISS), for which each rocket launch to provide material or transport astronauts is associated with considerable costs. In addition to transportation, the space is also limited on the ISS, requiring the careful prioritisation of materials delivered to space. There are, for example, about 13 tons of hardware spares and replacement units on the ISS and a further 17 tons on earth ready to transport to space.

One approach to reducing the required quantity of materials in space is to manufacture objects on demand in space. By producing objects on demand, only the parts that are truly needed will be produced. This would drastically reduce the amount of material and spare parts needed in space, leading to enhanced opportunities regarding spaceship autonomy and, thus, enabling the exploration of distant destinations, such as Mars.

Thereby, AM could play a key role in producing parts of almost any complexity directly in space. Currently, the space agencies are focusing on the 3D printing of polymers. One of the most important factors in the utilisation of AM in space is the safety of the crew. Even if, on earth, many of the parts required for a space mission are produced with metal AM processes, such as selective laser melting (SLM), these processes are currently difficult to transfer to space due to the reduced gravity that characterises the space environment. Compared to metal AM processes, FFF requires significantly less energy and occupies less space.

Furthermore, the filaments are not critical to the safety of the crew and can be processed close to humans without any hazards. In 2014, National Aeronautics and Space Administration (NASA) tested a 3D printer in space to demonstrate and verify the part quality of parts printed in a microgravity environment. Based on two consecutive space operations, specimens and use cases have been printed in space and, subsequently, analysed on earth to compare the resulting part quality with that of parts manufactured under earth gravity. The results demonstrated no significant influences on the part of microgravity on part quality. However, it is still difficult to predict and ensure the part quality of additively manufactured parts. Therefore, additively manufactured parts to be used in critical applications require intensive post-processing, including non-destructive analysis methods, such as X-ray analysis. Due to space limitations, these kinds of inspection are currently not available on the ISS, limiting the application of additively manufactured parts to non-critical applications, for example, a ratchet wrench or antenna parts.

2 Polymer additive manufacturing for in-space production

Polymers find a wide range of applications in space exploration due to their unique properties and versatility. Some key applications of polymers in space include structural components, thermal protection systems, radiation shielding and flexible electronics.

Regarding structural components, polymers can be used to manufacture the structural components of spacecraft, satellites and space stations. They offer lightweight alternatives to traditional metal structures, reducing the overall weight of spacecraft and improving fuel efficiency. Polymer-based materials, such as carbon-fiber-reinforced composites, provide high strength-to-weight ratios and excellent thermal stability, making them suitable for structural applications in space.

In thermal protection systems, polymers are utilised to shield spacecraft from the extreme heat generated during atmospheric reentry. For example, ablative materials, such as phenolic resins, form a protective char layer that dissipates heat during reentry, preventing excessive temperatures from reaching the spacecraft's structure. Polymers can be employed as radiation shielding materials to protect sensitive electronic components and astronauts from harmful radiation in space. High-density polymers, such as polyethylene, are effective in absorbing and scattering radiation particles, reducing their impact on vital systems and personnel. Polymers are used in flexible electronics as well. These polymers have flexible and stretchable properties because they are used in the production of flexible electronic devices for space applications. These materials allow for the development of lightweight, conformable and durable electronic circuits, sensors, and displays that can withstand the mechanical stresses encountered during launch and operation in space. Finally, polymer AM, also known as 3D printing, enables the production of complex components on demand in space. Astronauts can utilise 3D printers equipped with polymer feedstock to fabricate tools, spare parts, and experimental equipment during missions, reducing the need for pre-manufactured items and minimising reliance on resupply missions from Earth.

It is worth mentioning that the space environment has introduced significant challenges. One of the most prominent of these is microgravity, or the near absence of gravity, which can significantly impact the process of polymer printing in space. The key effects of microgravity on polymer printing are as follows:

- Fluid Flow and Deposition: In a microgravity environment, the absence of buoyancy-driven convection and sedimentation can alter the behavior of polymer fluids. The flow patterns and deposition characteristics of printing materials can be affected, leading to differences in the quality and consistency of the printed structures. Without the gravitational force, fluid behavior becomes dominated by surface tension and capillary forces, resulting in different flow dynamics.
- Bubble Formation: In terrestrial printing processes, bubbles and voids that may be present in the printing material tend to rise to the top due to buoyancy forces. However, in microgravity, bubbles tend to remain trapped within the material, affecting its integrity and causing defects in the printed objects. The lack of buoyancy-driven bubble migration can result in poor material quality and compromised structural integrity.
- Layer Adhesion and Bonding: Adequate layer adhesion is critical to the mechanical strength and overall integrity of 3D printed structures. In microgravity, the absence of gravitational forces can lead to reduced interlayer contact and weaker bonding between adjacent layers. This can result in decreased mechanical properties and structural integrity on the part of the printed objects.
- Diffusion and Evaporation: In a microgravity environment, in the case of a VPP process, the absence of gravity-driven convection can impact the diffusion and evaporation rates of the solvents and volatile components used in polymer printing processes. Diffusion and evaporation may become slower or less efficient, affecting the curing or solidification of the printed material and potentially leading to incomplete or non-uniform solidification.
- Print Head Control and Material Flow: Microgravity conditions can affect the control of print heads and the extrusion of polymers. Without gravity, the forces acting on the print head and the material flow dynamics may change, potentially leading to challenges in maintaining precise

control over the printing process. Adjustments may be necessary in print-head design, material-extrusion mechanisms, and overall printing-system architecture to ensure proper material deposition.

Understanding and mitigating the effects of microgravity on polymer printing are crucial to successful AM in space. Researchers and engineers are actively exploring strategies via which to adapt printing processes and materials to microgravity environments. These efforts include modifying printing parameters, developing new printing techniques and optimising material formulations to account for the unique conditions of space. By addressing the challenges posed by microgravity, advancements can be made in terms of achieving high-quality, reliable and structurally robust polymer-printed objects in space.

Furthermore, the development of new materials is important in improving critical properties, such as as temperature resistance, outgassing and atomic oxygen and UV and radiation resistance. Space polymers should have a wide temperature operating range to withstand the significant temperature fluctuations encountered in space. They should exhibit good thermal stability, both at low temperatures, for launch, and in the extreme heat of atmospheric reentry. High-temperature polymers, such as polyimides and polyetheretherketone (PEEK), are commonly used because of their excellent thermal resistance; however, their use may be limited by the fact that PEEK's melting and glass transition temperatures are extremely high for a polymer, requiring a printing temperature of at least 370 °C, which translates into a high shrink rate and partial polymer degradation. Thus, state-of-the-art hardware is required for proper printing.

Regarding outgassing, materials used in space must have low outgassing properties to prevent the release of volatile organic compounds (VOCs) and other gases that can contaminate sensitive equipment or optics. Low-outgassing polymers, such as polytetrafluoroethylene (PTFE) and polyetherimide (PEI), are often preferred because of their minimal off-gassing characteristics. The presence of atomic oxygen in low Earth orbit can cause the erosion and degradation of materials. Polymers with high resistance to atomic oxygen, such as polyimides and fluoropolymers, for example, polytetrafluoroethylene (PTFE), are commonly used to protect spacecraft surfaces. Exposure to UV and radiation requires materials that can withstand their damaging effects. Ultraviolet stabilizers and radiation-resistant additives can be incorporated into polymers to enhance their resistance. Examples include polyethylene, polyimides and polyethylene terephthalate (PET).

3 Metal additive manufacturing for in-space production

While the use of AM in space, especially AM using metal, does confer considerable advantages, there is a major constraint in this regard in the form of the primary differentiating factor between the environment on Earth and in space, the absence of gravity. Many of these methods involve the usage of fine, loose powders of the selected metal as raw materials for creation of the final part. The issue with such methods is that powder-based AM requires the stabilisation and setting of powders under natural gravitational force as a part of the working mechanism. Additionally, the consumption and management of these powders pose safety hazards under zero-gravity conditions. Powder-based AM techniques, such as selective laser sintering (SLS), would not be the best choice in an environment like space and would be difficult to manage, primarily due to issues with powder stabilisation and containment.

Nevertheless, efforts have also been made to defy these odds and make use of metal powder for the 3D printing of parts. For example, the Federal Institute for Materials Research and Testing has successfully tested the 3D printing of metal tools in zero gravity. Researchers there made use of a protective gas atmosphere based on nitrogen to solve the powder-bed-stability problem. Their printer used a machine to pump nitrogen through the powder layers and thus stabilise the material bed. This technology was previously tested on two flight paths as well and was sufficient to stabilise the powder bed. Similar testing of powder-based AM in microgravity environments is also being carried out by various universities and research institutes, wherein gases are passed through the powder bed to stabilise the powders for the 3D printing process and nullify the effects of minimal or zero gravity.

To find a robust solution that will allow printing metal in space, direct energy deposition (DED) technology is being heavily considered. Also known as DED, this method is very flexible in nature and utilises a focussed energy source, such as a laser, to melt a material, which is simultaneously deposited by a nozzle onto a specified surface, where it solidifies, fusing materials together to form the required structure. As a part of the Metal 3D project, which is led by the European Space Agency (ESA), a custom-made metal 3D printer will be installed on board the International Space Station (ISS) and be the first of its kind to be able to print from space. Various other industrial and academic organisations, such as Airbus Defense and Space, AddUp Solutions, Highftech Engineering and Cranfield University, are also partnering to make this possible. Due to the risk of metal powder floating out of the build area, the ambitious Metal 3D project will be employing the wire direct energy deposition (W-DED) method. A metal wire (316L stainless steel wire) will be fed through a nozzle and immediately melted by a laser, allowing to then fuse with the other material to create the final 3D printed object. The laser is a table that is movable along three linear axes and around one rotary axis. The entire printer assembly will be operated under a controlled nitrogen atmosphere to limit oxidation and reduce the risk of combustion.

Regardless of the method used for 3D printing metal in space, there are a few other factors that are specific to the zero-gravity environment of space and must be considered while printing. Firstly, the absence of gravity significantly eliminates any sort of drooping or sagging on the part of layers and, consequently, reduces the need for any kind of supports and makes post-processing easier. However, at the same time, this very absence can also lead to poor interlayer bonding due to a lack of forces to push layers closer together. Such a phenomenon will have to be tweaked by modifying the speed of extrusion to increase the pressure of filament deposition or reduce the gap between the topmost layer and the nozzle, increase material squishing and improve interlayer bonding.

All in all, huge strides are being made towards 3D printing metal in space. The type of research and testing being carried out in this field can have an immense impact on cost reduction, spare-equipment fabrication and storage and onsite repairs in future space flights.

4 Future prospects and research directions

To further establish the utilisation of 3D printing in space, the following key issues require additional research:

- Multi-material and composite printing enable the integration of different materials, such as polymers, metals and ceramics, in a single printed object. The ability to create functional gradients, embedded sensors and complex internal structures expands the possibilities for creating high-performance components and systems optimised for the unique demands of space environments. More research is needed in this area to test the manufacturing of these components.
- Recycling and Circular Economy are crucial for applications in space. Three-dimensional printing in space can facilitate recycling and closed-loop systems. Thus, printed objects that are no longer needed can be recycled and reprocessed into new feedstock, reducing waste generation and resource consumption. However, the recycling of materials comes with

significant challenges, as the material deteriorates and multi-material or composite components must first be separated properly.

- Ongoing research and development efforts are focussed on optimising 3D printing materials, processes and equipment for space applications. New materials with enhanced performance characteristics, such as improved strength, heat resistance and radiation tolerance, are required specifically for AM in space. To cope with the process uncertainty involved, further research is required to enhance process control, precision and automation and thus obtain higher-quality and more reliable 3D printed components.

5 Bibliography

Sacco, E., & Moon, S. K. (2019). Additive manufacturing for space: status and promises. The International Journal of Advanced Manufacturing Technology, 105, 4123-4146.

Zocca, A., Wilbig, J., Waske, A., Günster, J., Widjaja, M. P., Neumann, C., ... & Tian, X. (2022). Challenges in the technology development for additive manufacturing in space. Chinese Journal of Mechanical Engineering: Additive Manufacturing Frontiers, 1(1), 100018.

Hoffmann, M., and Elwany, A. (November 3, 2022). In-Space Additive Manufacturing: A Review. ASME. J. Manuf. Sci. Eng. February 2023; 145(2): 020801. https://doi.org/10.1115/1.4055603

https://www.nasa.gov/mission_pages/station/research/news/3d-printing-in-space-long-duration-spaceflight-applications

Dunn, J. J., Hutchison, D. N., Kemmer, A. M., Ellsworth, A. Z., Snyder, M., White, W. B., & Blair, B. R. (2010). 3D printing in space: enabling new markets and accelerating the growth of orbital infrastructure. Proc. Space Manufacturing, 14, 29-31.

Wong, J. Y. (2016). 3D printing applications for space missions. Aerospace Medicine and Human Performance, 87(6), 580-582.

https://www.nasa.gov/sites/default/files/atoms/files/additive_mfg.pdf

Frazier, W. E. (2014). Metal additive manufacturing: a review. Journal of Materials Engineering and performance, 23, 1917-1928.

Yakout, M., Elbestawi, M. A., & Veldhuis, S. C. (2018). A Review of Metal Additive Manufacturing Technologies. Solid State Phenomena, 278, 1–14. https://doi.org/10.4028/www.scientific.net/ssp.278.1

Bandyopadhyay, A., Zhang, Y., & Bose, S. (2020). Recent developments in metal additive manufacturing. Current opinion in chemical engineering, 28, 96-104.

https://www.3ders.org/articles/20180425-german-bam-institute-3d-prints-a-metal-tool-for-the-first-time-in-zero-gravity.html

https://3dprinting.com/metal/bam-institute-3d-prints-metal-tools-in-zero-gravity/

Zocca, A., Lüchtenborg, J., Mühler, T., Wilbig, J., Mohr, G., Villatte, T., ... & Günster, J. (2019). Enabling the 3D printing of metal components in μ-gravity. Advanced Materials Technologies, 4(10), 1900506.

Gibson, I., Rosen, D., Stucker, B. (2015). Directed Energy Deposition Processes. In: Additive Manufacturing Technologies. Springer, New York, NY. https://doi.org/10.1007/978-1-4939-2113-3_10

Saboori, A., Aversa, A., Marchese, G., Biamino, S., Lombardi, M., & Fino, P. (2019). Application of Directed Energy Deposition-Based Additive Manufacturing in Repair. Applied Sciences, 9(16), 3316. https://doi.org/10.3390/app9163316

https://addupsolutions.com/2022/03/01/3d-printing-space/