Young Manufacturing Leaders Network

In-Space Closed Loop Additive Manufacturing

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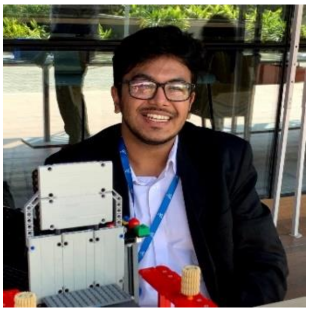

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Abstract

Additive manufacturing (AM), as a technology, is introduced, along with its benefits in terms of small batches and high customisation. The concept of in-space manufacturing and its potential to improve and advance the space industry, as well as its necessity for space exploration, are discussed. Due to the nature of aerospace components and availability issues regarding materials and processes in space, AM, by its very nature, possesses many benefits that make it a very appealing technology for manufacturing in orbit or on celestial bodies, such as the Moon or Mars. For this reason, funded research that is being carried out by the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA), as well as companies that are currently working on AM for space applications, is mentioned. A particular emphasis is placed on space processes, with their benefits and challenges, along with the potential of AM technologies. Many AM processes are mentioned, and their applicability is discussed. The benefits of AM processes are amplified from the cost, efficiency and environmental points of view with the incorporation of closed-loop AM and recovery opportunities. Some current closed-loop technologies and applications that utilise closed-loop AM are presented. This paper then focuses on research specific to the space industry using case studies related to both polymer and metal applications.

Index

1 Towards Circular Additive Manufacturing in Space

1.1 Additive Manufacturing

Additive manufacturing (AM) is the process of creating a physical part from a computer-aided design (CAD) file via the addition of material, typically layer by layer, as a constructive manufacturing process, as compared to conventional subtractive methods of removing material until a desired shape is achieved, such as machining (Sacco & Ki Moon, 2019). Through this technique, as long as the material is sufficient for the application, the part fits inside the build volume of the chosen machine and the part adheres to a number of geometrical conditions, one could 3D print parts for as many applications as one needs and only be limited by what could be created through software. Additive manufacturing is a name given to several processes using polymer, metal, ceramics, composites and even tissue. A relatively new manufacturing technique, this process has been known as rapid prototyping due to its quick implementation, as well as its lack of ability regarding end-use parts. However, as the technology has developed, it has shifted, with many of its applications being seen in final products across a range of industries, including the automotive, biomedical and aerospace industries. Due to improvements in availability; dimensional accuracy and mechanical, thermal and chemical properties, additive manufacturing is beginning to thrive as a fabrication process, particularly when for complex parts in small batches (Sacco & Ki Moon, 2019). This, combined with the extremely fast turnaround from initial design to final part as compared to other manufacturing techniques and the freedom of designing for purpose rather than manufacturing while, at the same time, eliminating the restrictions imposed by high-cost tooling, shows the promise of AM in the space industry (Williams & Butler-Jones, 2019).

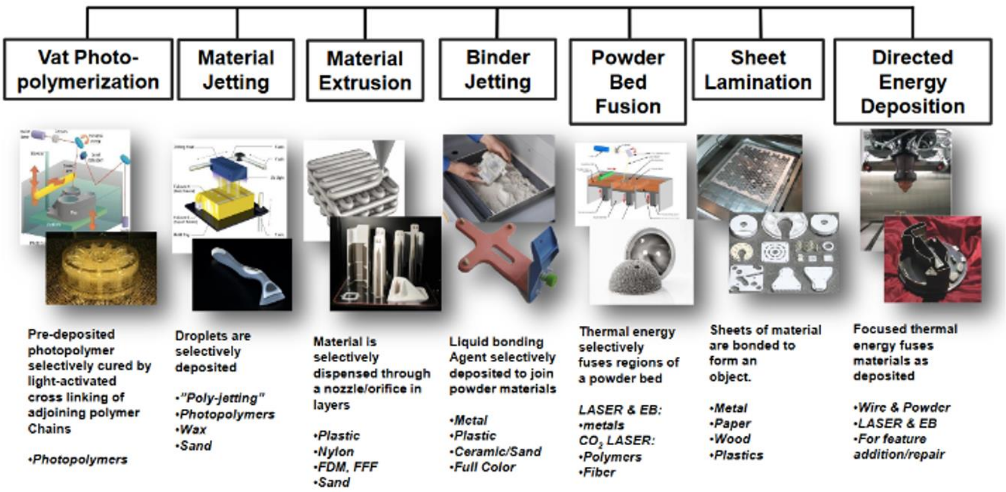

Figure 1: Seven AM processes according to the ASTM F42 Committee on additive manufacturing (Kardys, 2017)

1.2 In-Space Additive Manufacturing

In 2014, a company called Made In Space sent the first 3D printer to the ISS, where a wrench was created, making this the first time an AM part was produced in space (Zocca, Wilbig, Waske, & Gunster, 2022). This part was designed on earth before it was sent as a digital file to the ISS, where the crew were able to print a 3D version out of ABS polymer. With this development, the potential for creating parts needed in space while in space grew massively (Fateria & Kaouk, 2018). Sending parts to space that are needed is a source of many problems, such as volume limitations, mass limitations and the cost and environmental impact of launching payloads into orbit (Owens & Oliver, 2017). There is a high cost involved in sending mass and volume into orbit (Ishfaq & Asad, 2022). If a part can be created in orbit, on the ISS or on a celestial body, we would see reductions in cost and time required and a positive environmental impact, as well as increasing the chances of travelling further from resupply lines and, thus, further from the Earth. Currently, maintenance logistics support, combined with the need for quick and efficient resupply, is a serious issue related to the progression from low earth orbit (LEO) to the prospect of deeper space exploration. This is a risk due to the potential loss of crew if issues arise while out of reach of reasonable supply lines (Owens & Oliver, 2017). In space, manufacturing serves as the technical solution to this issue, paving the way for deeper exploration. Rather than sending a huge set of tools occupying a large volume on the launch vehicle to the ISS, both places where space is a commodity, if the required tools can be manufactured on board the ISS, there will be less taxpayer money spent and carbon emissions required. Crews will have the ability to manufacture the tools that they require when they are required. This will result in less storage space being needed in orbit (Ishfaq & Asad, 2022). Unpreventably, parts can fail in service and need to be repaired or replaced. The deeper into space we progress, the more difficult and expensive it will be to resupply or oversupply space stations to ensure that there is no loss of functionality. With the incorporation of in-space AM, the need to predict what will fail will be diminished because the crew have the potential to design and produce the parts they need through AM as they need them. In addition, ISM paves the way for the crew to manufacture items that were not planned for until the need for them arose during the mission, providing a powerful contingency option in the face of unseen circumstances (Owens & Oliver, 2017).

From an engineering standpoint, the parts required for space must be designed and optimised primarily to survive the intense launch loads they are subjected to as they leave the earth. Thus, they are designed for launch rather than their intended purposes in space, which typically involve less demanding loads than those at launch (Owens & Oliver, 2017). Removing the need to over-engineer a component by a huge factor or limit its size so that it can fit into a launch fairing could thus improve effectiveness, promote space and mass efficiency during launch and expand the capabilities of components that are vital to applications off planet. Instead, raw materials can be sent to space, and as long as there are means of manufacturing these materials into end-use parts, it is reasonable to assume that less raw mass can replicate the functionality of substantitally more mass if the technology needed to create parts on demand is available. Due to its versatility, freedom of design and quick turnaround from design to part, AM offers a great opportunity to advance this area of manufacturing in space.

NASA's In-Space Manufacturing (ISM) project is managed at NASA's Marshall Space Flight Center (MSFC), in Huntsville, Alabama. This project conveys the huge potential of ISM. The primary focus of ISM is facilitating the use of the International Space Station (ISS) as a testbed to mature the manufacturing technologies needed to support sparing, repair and recycling within the crewed environment on long-duration, long-endurance missions. Long-duration missions correspond to the typical time a crew member spends on ISS (6 months to 1 year). Long-endurance missions refer to mission scenarios in which the cargo resupply is limited (Prater, Edmunsson, & Fiske, 2019) The ISS serves as the perfect location for the testing and development of ISM for various reasons. The off-planet lab is a viable test of whether technologies can be used in LEO (low Earth orbit). In order to reach the ISS, all the hardware needed for the technology must meet the high standards and protocols for use on the ISS, which are likely to be as stringent as any other standards and protocols it will need to meet if implemented in space in the future. Any debris generated during the manufacturing process must be removed prior to the opening of the chamber due to safety measures associated with toxicity and flammability. The ISS has a maximum power limit of 2,000 W of energy and a maximum volume limit of 16 cubic feet, both of which serve as reasonable constraints for machines and systems to be later integrated economically in an off-planet setting (Hoffmann & Elwany, 2021). Finally and possibly the most obviously, the microgravity on the ISS allows the accurate testing and validation of in-space technologies, which are challenging and costly to achieve on earth.

1.3 Closed-Loop Additive Manufacturing in Space

Owens and Owens (2017) discuss the fact that one of the most significant benefits of ISM may be that it enables recycling and/or in-situ resource utilisation (ISRU) for maintenance logistics. Previously, recycling has been used to great effect for the reduction of the consumables needed for ECLSS (environmental control and Life support systems). In-situ resource utilisation has the potential to reduce logistics demands even further for crewed missions to the Moon and Mars. When ISM is available, failed components can be converted into raw materials that can be used to manufacture new components, and new components can be manufactured on site using local materials. In terms of maintenance logistics, which are essential to success when off planet, Owens refers to this as a revolutionary capability, as it can drastically reduce the amount of mass required for long-endurance missions. Though fewer parts will need to be brought to space if they can be manufactured in orbit, unless there is a closed-loop infrastructure in place, the raw material, either polymer, metal or ceramic, will still need to be launched from Earth, where it can be produced. Until feedstock material can be produced in space effectively and economically, this negates many of the advantages of in-space manufacturing. However, this solution represents the ability to recycle parts that were previously printed, and once their purpose is achieved, the part is recycled and can be reprinted into another part, thus achieving two applications for the same amount of feedstock that had to be launched from Earth. If the parts can be continuously recycled and reprinted, then once they are launched, the process can become a closed loop. Projects such as the refabricator from Firmamentum are investigating this process. Firmamentum has sent a machine to the ISS that will not only print PEI ULTEM, which is a popular material for AM, particularly for space applications (Hoffmann & Elwany, 2021), but also repurpose PEI parts that have fulfilled their purpose and failed prints. In early 2019, Tethers Unlimited and NASA's ISM project installed the Refabricator payload on the ISS. The Refabricator was designed to reprocess blocks of ULTEM 9085 into filament, the required feedstock for fused filament fabrication (FFF) processes. Importantly, during the recycling process, the material is remelted in a process called positrusion. This process serves the purpose of removing the grinding or pelletisation processes from the operation and, thus, mitigating the negative impacts of recycling on the integrity of the material due to material shear. The refabricator has another function in which plastic waste, such as bags, packaging and eating utensils, can be loaded into the machine, where they too are repurposed into feedstock material for the 3D printing of non-load-bearing components (Werkheiser, 2015). Specimens produced with the refabricator system arrived for testing at MSFC in early 2020. The specimen set will include tensile specimens for mechanical testing and segments of filament for chemical analysis. TUI is engaged in parallel Small Business Innovative Research's efforts to redesign the refabricator so as to support the recycling of multiple materials.

Another reason for a push towards closed-loop AM in space is space debris. Airbus is sending a machine capable of printing metal in space, and it aims to use satellite space debris, which is to be recycled and printed in space. This metal can represent an economical solution regarding the proposed base on the moon, for which many components and pieces of the structure could be manufactured in space. Named the Metal3D, this machine will be only one component in a range of technologies developed by Airbus in collaboration with Redwire, with the goal of setting up a space factory. This factory has the exciting goal of using printers such as the Metal3D and robot arms to ultimately recycle satellites and manufacture entire satellites in space by 2026.

2 Materials, In-Space AM Processes and Recovery Opportunities

2.1 Background

In-space environmental conditions, such as reduced gravity, temperature variation, electromagnetic interference, radiation and vacuum conditions act as potential barriers to the adaptation of existing AM feedstocks and production technologies due to alterations in their respective process conditions. Validation and development testing campaigns for the adaptation of existing AM technologies to in-space conditions can prove difficult due to challenges in simulating and replicating these environmental conditions during testing. Mico-gravity-induced parabolic flights have been implemented to mimic the effects of reduced gravitational forces in space; however, other environmental factors are neglected (Zocca, et al., 2019).

While in-space conditions are potentially problematic for the adapation of existing technologies, these same conditions have already been shown to be enabling factors for the development of new manufacturing technologies. Made In Space, in addition to the undertakings previously highlighted, is taking advantage of in-space environmental conditions, such as μ-gravity, to develop space-enabled advanced manufacturing technologies that are not possible under terrestrial conditions. The space-enabled manufacturing technologies that have been investigated to date include but are not limited to exotic optical fibre production, high-grade superalloy-casting metals, ceramics fabricated via stereolithography processes and industrial crystals (O'Konek, Kugler, DiMarzio, & Lawless, 2019).

While space-specific multi-material manufacturing technologies are already under development, such as hyperbaric pressure laser chemical vapour deposition (Wekheiser, 2015), Made In Space Inc.'s VULCAN and NASA's Fab Lab (Zocca, et al., 2022), this work will seek to specifically assess the potential of the closed-loop manufacturing of metallic and polymer systems due to the abundance of existing space waste, which can act as feedstock.

2.2 Polymers

Overview

Polymers can be classified into two distinct groups based on their molecular structures, thermoplastic and thermosetting polymers. Thermoplastic polymers are categorised by melt behaviour at elevated temperatures and the formation of a pliable viscous liquid due to the weaking of intermolecular forces upon the application of heat. This melt and solidification behaviour makes thermoplastic polymers favourable for many moulding- and extrusion-based fabrication processes. Thermosetting polymers are characterised by the presence of strong inter-molecular forces stemming from the covalent intermolecular cross-links formed during curing processes. The cross-linking of molecular chains in thermosetting polymers leads to high mechanical and thermal stability, making this family of polymers difficult to break down into constituent elements and reprocess (Zocca, et al., 2022).

Among the AM processes the photopolymerisation, material jetting, powder-bed fusion, material jetting and material extrusion processes are most commonly implemented for polymer-based fabrication. The polymer feedstock for these processes is in the form of liquid resins or gels and solid powders, sheets or filaments (Kardys, 2017).

Thermoplastic polymers are often utilised for AM in fusion-based processes due their typically low thermal resistance and rheology flow characteristics, making them easy to process. In 2016, the first additively manufactured component was fabricated on the ISS using the thermoplastic polymer ABS plastic and a printer fabricated by Made In Space Inc. Since then, material-processing abilities have expanded to PEI, commercial name ULTEM, high density polyethylene and polycarbonate using the same machine FDM instrument (Zocca, et al., 2022)

Polyethylene-based packaging material is predominantly used for the transport of small loads and consumables during missions. This polymer has been shown to display minimal degradation during the thermo-mechanical recycling of terrestrial food packaging through the use of differential scanning calorimeter and thermogravimetric analysis processes, showing negligible changes in molecular structure during traditional recycling techniques(Hart, Frketic, & Brown, 2018)

While they are a proven technology terrestrially and in-space, polymer-based material extrusion processes have drawbacks. Factors that can greatly affect the strength of fabricated parts include high levels porosity, the rasterised nature of parts, reduced part performance when using recycling feedstock, the interlayer adhesive strength being less than that of the bulk polymer and parts manufactured via FFF typically being less strong those manufactured using traditional manufacturing processes. Additionally, the parts display anisotropic behaviour, with the performance of the part being heavily influenced by the direction of polymer deposition (Tao, et al., 2021).

Material recovery opportunities

Recycling technologies can be used to recover value from the material used in AM processes, including polymers. The commodity-based thermoplastic polymers implemented in traditional FFF processes display low thermal resistance and tribological properties, allowing for easy processability. Factors that can greatly affect the strength of fabricated parts include high levels of porosity, the rasterised nature of parts, the interlayer adhesive strength being less than that of the bulk polymer and parts manufactured via FFF typically being less strong those manufactured via traditional manufacturing processes (Tao, et al., 2021).

The fabrication of feedstock from recycled polymeric material can be accomplished through mechanical, thermal and/or chemical processes. Changes to the molecular structure of polymers during recycling processes can alter the polymer rheological properties, thermal transitions, processing parameters and mechanical performance of the produced parts. The molecular weight of polymers is linked with the physical and mechanical properties of a polymer. It has a proportional relationship with several key material properties, such as thermal transition temperatures, viscosity and mechanical performance (Keleş, Eric H, & Jimmy, 2018) (Cress, et al., 2021). The scission of molecular chains during mechanical and thermal recycling processes can lead to a reduction in the molecular weight of polymers via the induced shear caused by elongation. This leads to degradation in part performance for printed parts produced from recycled feedstocks. This has been proven to be the case in the common thermoplastic FFF feed stock PLA, in which, following recycling, a reduction in mechanical performance was recorded in conjunction with molecular scission, as identified by Fourier transform infrared spectroscopy (Zhao, Chengchen, Fu, Nusrat, & Jianzhong, 2018).

Characterization techniques can be implemented to monitor changes in a polymer's properties following a recycling process. By assessing key polymer properties, such as the critical thermal transitions; molecular weight and the broadness of molecular weight distribution, which is known as the polydispersity index, following recycling processes, predictions regarding the degradation of thermal and mechanical performance can be made. In the literature, common characterisation techniques for quantifying polymer degradation include the following (Cress, et al., 2021):

- differential scanning calorimetry and thermogravimetric analysis for thermal transitions
- FTIR for chemical degradation
- gel permeation chromatography for molecular characteristics

- X-ray fluoresce spectroscopy for contamination
- tensile testing and hardness testing to assess mechanical performance

Additives in the form of filler and plasticisers can minimise the degradation of polymer properties and greatly increase polymer processability, increasing the potential of recyclable feedstocks. The addition of polyethylene glycols, as an additive, to PLA improved its melt characteristics but at the cost of the reduction of part strength, which was attributed to greater part porosity. While additives can be beneficial, for ISM, they will need to be optimised for the selected feedstock (Tao, et al., 2021).

Void density in printed parts can be monitored with both quantitative and qualitative metrics through a variety of non-destructive characterisation techniques, such as mass measurements as compared to the expected mass based on computational models, microscopy, computed tomography and ultrasonic scans, to offer a non-exhaustive list of techniques. These techniques can be used either terrestrially post-mission or in-space to monitor and validate the readiness of the parts produced. As ISM is merely a tool to aid in the completion of in-space missions, an in-space quality check should be high throughput and easy to operate, making mass-comparison measurements a preferred metric for quality control.

2.3 Metals

Overview

Metals are also used in AM techniques. Metallic alloys are commonplace in space due to their high resilience and strength, even in harsh environments. The common usage of these materials in space has led to the generation of over 9,600,000 kilos of trackable space debris traveling at ~25,000 km/hr (Mukherjee, 2021). With large quantities of this debris originating from large metallic rockets' upper stages, rocket bodies and defunct satellites, the in-space utilisation of these components is possible.

The many common metallic-additive-manufacturing techniques listed in Figure 1 present numerous challenges in micro-gravity conditions. Fusion or melting based processes face a lack of bouncy-driven convection. This alters melt pool solidification and sedimentation-based mixing, resulting in microstructural difference and performance variations as compared with terrestrially fabricated parts.

Of the seven groups defined, binder jetting, powder-bed fusion, sheet lamination and direct energy deposition were identified as processes that could be directly used for the fabrication of metallic components. The indirect manufacturing techniques identified in **Errore. L'origine riferimento non è s tata trovata.** use binder or polymer support material to produce green bodies or structures to facilitate the sintering or casting processes (Kardys, 2017).

These multi-step in-direct AM techniques have already been identified as promising routes to the fabrication of new designs that are not possible without micro-gravity conditions, such as the Redwire Turbine Superalloy Casting Module, which seeks to produce high-performance polycrystalline turbine blades (Riley, 2021). However, due to the often-complicated post-processing, typically lower part strength and poor dimensional control arising from sintering or post-process heating, indirect additive manufacturing techniques are not preferred in terms of facilitating an in-space manufacturing economy. The direct AM techniques use a feedstock of powder, wire or sheets, along with laser or ultrasonic energy sources. Plasma, arc or electron beams are used to iteratively join feedstock in additive processes (Kardys, 2017).

Fabrication of continuous wire or sheet feedstock is typically performed using hot-die drawing or rolling processes. Powder feedstock, in additive processes, is required to have a spherical geometry with tight geometrical tolerances. These powders can be fabricated though mechanical or physical-chemical methods. Mechanical powder fabrication methods include milling or atomisation processes, in which a high-pressure metallic melt is dispensed as a liquid or gas, solidifying into powder. Gas, water, plasma and centrifugal processes can be used in these atomisation processes. Physical-chemical fabrication methods include electrolysis, the carbonyl process and plasma spheroidisation. These processes are associated with a chemical compositional change, in addition to morphological changes. Physical and chemical deposition methods can be used to control particulate size to nanometer-level precision during powder fabrication, but they are not commonly implemented, due to limitations in terms of powder yield (Sufiiarov & Popovich, 2016).

Material recovery opportunities

Cis Lunar Industries, in conjunction with NanoRacks, is developing Micro Space Foundry for on-orbit recycling and metal production. This reprocessing technique uses a vacuum electromagnetic induction furnace to generate standardised metallic feedstock for rocket propellant in various geometrical forms (Messier, 2022). This technology is to be soon proven in micro-gravity induced by parabolic flight; if successful, this technology could prove to be a ubiquitous recycling technique via which to produce feedstock for a variety of processes, including wire-fed direct energy deposition.

While micro-gravity conditions present challenges for powder-based additive manufacturing processes, recent advancements in recycling and atomisation to produce feedstock for these technologies have made them more appealing to explore. 6K Additive, a division of 6K, has developed an ultra-high-temperature metal-reprocessing technology to recreate metallic powders with high-temperature resistance alloys. This UniMelt technology uses two-step microwave plasma reaching 6,000 °C to atomise metal and create metallic powders for additive manufacturing technologies. This technology is estimated by Foresight Management to lead to a 91% reduction in energy usage and a 91.5% reduction in carbon emissions as compared to the current state-of-the-art powder-production processes while reducing costs by 15%. In the testing of a high-temperature nickel alloy numbered 625, 99.9% part density and mechanical performance were retained following atomisation (6K, 2022). Enabling technologies such as the UniMelt will be essential for the in-space recycling of materials due to the high preference for high-temperature titanium, superalloys and refractory alloys in the form of space waste, which has traditionally been difficult to reprocess.

Powder-bed-fusion AM processes selectively fuse regions of thin layers of powdered material to iteratively build components. These techniques are commonplace in many highly regulated industries for the fabrication of metallic components due to high design flexibility, a lack of waste material and low-cost post-processing steps. The lack of gravitational forces is a major barrier to implementing powder-bed technologies in space due to the lack of gravitational fixation of the powder to the print bed, leading to inhomogeneous powder distribution and vibrational forces becoming problematic due a reduction in dampening. Zocca et al. (2019) tested a laser-beam-melted gas-flow-assisted powder-deposition unit during micro-gravity induced by parabolic flight campaigns to assess the feasibility of powder-bed-based additive manufacturing techniques. The powder-fixation instrument, as seen in Figure 2, used a porous support plate to allow a partial vacuum to be drawn from below using a vacuum pump. The flow from the vacuum pump induces a drag force in the build plate's direction, fixating the powder.

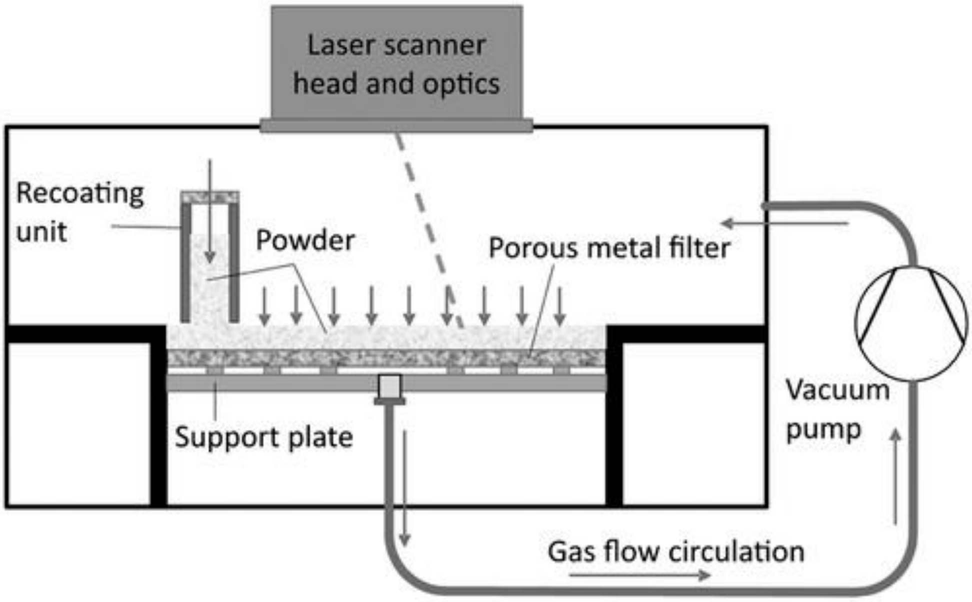

Figure 2: Powder deposition unit (Zocca, et al., 2019)

First attempts at the in-space recycling of metallic scrap material are being made by Metal3D, a subsidiary of Airbus, and Airbus itself, as part of a European Space Agency project seeking to capture and recycle space debris. Airbus, in conjunction with ClearSpace SA, have developed the RemoveDEBRIS satellite, which will aim to use an articulating arm design, deployable nets and drag sails to recover the 100 kg of components left behind by the launch of ESA's Vega rocket. Using this recovered debris, it is planned for Metal3D's Bound Metal Deposition recycling process, which uses a 1,200-°C melt process for the processing of steel alloys technology, to recycle this material for use as feedstock during ISM (Lim, 2021).

Demonstration components manufactured from 316L stainless steel via laser-beam-melting gas-flow-assisted powder-deposition techniques showed no micro-gravity-induced defects or part irregularities for parts with fabricated vacuum forces equivalent to gravitational forces. Post-fabrication terrestrial microscopy analysis and micro-computed tomography scans showed there was no significant difference in part microstructure or part porosity as compared to that expected with standard fabrication protocols (Zocca, et al., 2019). The need for an inert atmosphere to prevent the oxidation of high-temperature metal and high energy demands will require further optimisation.

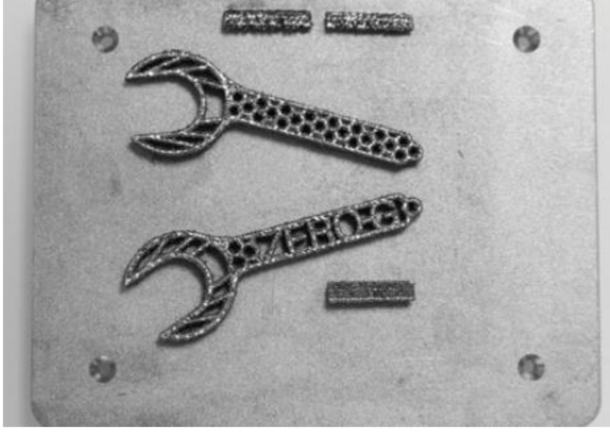

Figure 3: First metallic demonstration components manufactured in micro-gravity

3 Sustainability Considerations and Lifecycle Assessment for In-Space Additive Manufacturing

In-space manufacturing can be classified into intravehicular ISM (takes place inside a pressurised structure), extravehicular ISM (takes place in the external space environment) and planetary ISM (takes place at constructed habitats and other architectures, thus being equivalent to industry on planet earth). Opportunities for 3D printing/AM in space include component repair, material characterisation, process improvement, process development and the capability to manufacture new designs. The feasibility of printing parts using AM technology in space has been demonstrated via multiple efforts since 2014 (e.g., NASA's 3D printer, the POP3D printer created by the Italian Space Agency (ISA) and 3D printer payload created by Made in Space. Material shortages, space conditions, power availability, quality control and the infrastructure required are a few of the identified challenges.

Because the manufacturing applications for ISM are nascent, the sustainability focus is currently on building, repairing and updating manufacturing capabilities. Recycling components is a viable approach to meeting future material requirements for ISM. There is an increasing interest in the utilisation of recyclable materials for in-space manufacturing applications (e.g., biodegradable materials, such as polyvinyl alcohol (PVA) have been suggested as a feasible option for ISM applications).

There is an increasing interest in studying sustainability and the environmental implications of space activities. Lifecycle assessment (LCA) for manufacturing processes for space applications is an emerging area of research. The European Space Agency's (ESA's) *Clean Space Initiative* represents an important contribution to this field. T. Maury et al. (2020) reviewed the application of LCA to space activities and the associated methodological challenges. The focus has been on space activities in general, such as components and materials used for space applications, followed by space segments.

The challenges include access to quality inventory data, especially space-specific specialised materials and chemicals, as well as the limited development of impact-assessment methods and characterisation of factors specific to the space environment. Two inventory databases are currently under development to overcome these challenges: *Strathclyde Space Systems Database* and the *ESA LCA Database*. The meta-level (energy and cost) savings from the use of AM in space due to a significant reduction in carrying mass have been studied (40 to 90%). Resource (materials and energy) management and optimisation also have significant roles in ISM. Resource depletion is one of the potential impact categories relevant to space missions and associated activities, which may lead to increased overall costs. Resource criticality assessments would help prevent additional costs.

Recommendations regarding material requirements and the estimated inputs (e.g., energy and material consumption) and emissions (greenhouse gases' emissions and solid waste generated) are crucial factors in assessing the lifecycle environmental impacts of in-space AM processes. A natural starting point in this regard is to understand the processing steps involved in manufacturing components using 3D printing/AM. Prior studies on the develop LCA of AM processes would be helpful in acquiring this information and generating inventory databases. A potential challenge would be to develop lifecycle impacts assessment models to estimate environmental impacts because the currently developed models are valid for Earth-system processes. This would require an understanding the space environment and its various systems and operating conditions.

The potential challenges regarding the LCA of AM for space applications include a lack of data sources related to manufacturing processes and associated impacts (environmental, social and economic). Resource (materials and energy) management and optimisation would be necessary to enable AM for space applications, especially from a cost-implications perspective. The various entities and stakeholders involved should be identified to allow a holistic understanding of various impacts (in various dimensions) and determine the areas of protection (AoP) and thus define the endpoints of an lifecycle impacts assessment methodology. A viable approach to conducting LCA for AM in space would be to estimate the environmental impacts of potential scenarios.

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