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# Metal Additive Manufacturing:Redefining Spacecraft Repair and Maintenance

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*Article*

# Metal Additive Manufacturing: Redefining Spacecraft Repair and Maintenance

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**Abstract:** Metal additive manufacturing (AM) is transforming spacecraft repair and maintenance by providing innovative, efficient, and cost-effective solutions. This article explores the potential of AM in the aerospace industry, particularly for in-space applications, where traditional repair and maintenance strategies are often impractical or too costly. We examine the advantages of AM in the production of complex, customized metal components on-demand, reducing reliance on spare parts and enabling repairs that were previously unfeasible in the harsh conditions of space. Additionally, the integration of advanced materials and precise printing techniques allows for the fabrication of lightweight yet durable components, contributing to the overall optimization of spacecraft performance.

**Keywords:** metal addictive; spacecraft repair; maintenance challenge

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The article discusses the challenges and opportunities of implementing metal AM technologies in spacecraft repair, including material properties, certification, and the need for specialized equipment. Furthermore, we consider the role of this technology in enhancing mission sustainability and reducing operational downtime. By rethinking repair and maintenance paradigms, metal additive manufacturing promises to redefine the future of space exploration and satellite operations, offering a sustainable path forward for spacecraft longevity and reliability.

## Introduction

*A. Overview of Traditional Spacecraft Repair and Maintenance Challenges*

Spacecraft repair and maintenance have always presented significant challenges, primarily due to the complex and remote nature of space environments. Traditional methods of maintenance and repair rely heavily on pre-positioned spare parts, which are expensive, difficult to transport, and often unavailable when critical needs arise. In many cases, astronauts must perform repairs in space with limited tools and materials, often requiring intricate procedures that can be time-consuming and prone to error. Moreover, spacecraft repairs can involve specialized components that must be custom-manufactured on Earth, a process that introduces delays due to the time required for transportation, assembly, and integration. The need for immediate repair solutions, especially during deep space missions or extended stays on the International Space Station (ISS), highlights the limitations of current approaches, thus underscoring the need for more efficient and flexible repair methods.

*B. The Emergence of Metal Additive Manufacturing (AM) as a Transformative Solution*

Metal additive manufacturing (AM) offers a groundbreaking solution to these challenges by enabling the on-demand production of complex metal parts directly in space. Unlike traditional manufacturing methods, AM creates parts layer by layer, allowing for the fabrication of customized components without the need for molds or extensive tooling. This capability is particularly

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advantageous for spacecraft, where space constraints and the need for lightweight yet durable parts are paramount. AM also allows for quick turnaround times, eliminating the need for lengthy shipping or assembly processes. In the context of spacecraft repair, AM enables astronauts or automated systems to produce replacement parts as needed, directly on the spacecraft or space station, reducing the dependence on Earth-based supply chains and enabling rapid in-situ repairs. Furthermore, the ability to manufacture components with intricate geometries and high precision offers significant benefits for both the functionality and longevity of spacecraft.

*C. Purpose and Significance of the Article in Exploring AM's Potential in Aerospace*

The purpose of this article is to explore the transformative potential of metal additive manufacturing in revolutionizing spacecraft repair and maintenance. By examining the advantages of AM technologies, we aim to highlight how they can address the unique challenges of space missions, enhancing the sustainability and efficiency of spacecraft operations. Through an in-depth analysis of AM's applications, material considerations, and current limitations, this article seeks to provide a comprehensive understanding of the role AM can play in shaping the future of aerospace technology.

The significance of this discussion lies in its potential to pave the way for the widespread adoption of AM in the aerospace sector, offering a viable path forward for future missions to space, including long-duration missions to the Moon, Mars, and beyond. Ultimately, this article aims to contribute to the ongoing conversation on the future of space exploration and the critical role of emerging technologies in ensuring mission success and spacecraft longevity.

## Fundamentals of Metal Additive Manufacturing

*A. Definition and Principles of Additive Manufacturing*

Additive manufacturing (AM), commonly known as 3D printing, refers to a group of manufacturing processes in which materials are deposited layer by layer to build parts directly from digital models. Unlike traditional subtractive manufacturing methods, which involve cutting away material from a larger block, AM allows for the creation of intricate geometries and complex structures without the need for molds or tooling. The process begins with a 3D CAD (computer-aided design) model of the part, which is sliced into thin layers. These layers are then successively built up, either by melting or sintering materials in a controlled environment, depending on the specific AM technology being employed. Metal additive manufacturing uses metal powders or wires as the raw material, and these materials are carefully melted or fused together to form solid metal parts. This capability to manufacture parts layer by layer offers significant flexibility and precision in designing components for complex applications, such as spacecraft repair.

*B. Different Types of Metal AM Technologies*

There are several distinct metal additive manufacturing technologies, each with its own unique processes and advantages. Among the most widely used in aerospace applications are:

Powder Bed Fusion (PBF):

Powder Bed Fusion encompasses a group of AM techniques, such as Selective Laser Melting (SLM) and Electron Beam Melting (EBM), where a fine metal powder is spread across a build platform. A laser or electron beam selectively melts the powder in the specified pattern to form each layer of the component. Once the layer is complete, the platform is lowered, and a new layer of powder is applied. This process is repeated until the part is fully constructed. PBF is well-suited for producing highly intricate, dense, and strong parts, which are crucial for spacecraft components.

Direct Energy Deposition (DED):

Direct Energy Deposition involves using a focused energy source (typically a laser, electron beam, or plasma arc) to melt metal feedstock, such as wire or powder, which is simultaneously deposited onto a substrate to build up the part. Unlike PBF, which relies on a powder bed, DED allows for the deposition of material onto an existing surface, making it ideal for repairs and additions to existing components. This flexibility is particularly useful in in-space applications, where it may be necessary to repair or modify spacecraft components without completely disassembling them.

Binder Jetting:

Binder Jetting is an AM technique in which metal powder is deposited layer by layer, and a liquid binder is selectively sprayed onto the powder to form the desired shape. After printing, the part is typically sintered in a furnace to fuse the metal powder together. While Binder Jetting is not as commonly used as PBF or DED in aerospace applications, it holds potential for producing metal parts at lower cost and faster rates, making it suitable for non-critical parts or prototyping.

Material Extrusion (Fused Deposition Modeling - FDM):

Though primarily used for plastic materials, this method can also work with metal composites. In this process, a filament of metal-infused material is extruded and deposited layer by layer. The material is heated and melted during the extrusion process, then cooled to form solid parts. Metal FDM is still evolving in aerospace, but it shows promise for producing certain metal components for less demanding applications.

*C. Benefits of Metal AM Compared to Traditional Manufacturing Techniques*

Metal additive manufacturing offers numerous advantages over traditional manufacturing methods, particularly in applications such as spacecraft repair and maintenance:

Design Freedom:

AM allows for the creation of complex geometries that are difficult or impossible to achieve with conventional machining. This includes intricate internal structures, lightweight lattice frameworks, and customized features tailored to specific requirements. For spacecraft, this flexibility enables the production of parts that optimize both functionality and weight, key factors in space applications.

On-Demand Production:

One of the most significant benefits of AM is its ability to produce parts on-demand. This eliminates the need for maintaining extensive inventories of spare parts and reduces reliance on long supply chains, which are critical challenges in space missions. On-site production of spare or replacement parts directly on the spacecraft or space station can drastically reduce downtime and extend mission durations.

Material Efficiency:

Traditional manufacturing techniques, such as casting or machining, often waste significant amounts of material. In contrast, AM is a highly material-efficient process that uses only the exact amount of material needed to build the part, minimizing waste and reducing material costs. This is particularly important when operating in space, where resources are limited and every gram of material matters.

Customization and Flexibility:

AM provides unparalleled flexibility in part customization. Components can be tailored to meet specific performance requirements or design constraints without the need for expensive tooling or

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retooling. This is ideal for the aerospace industry, where parts often need to be highly specialized to fit specific spacecraft or mission needs.

Reduced Lead Time and Cost:

The speed of AM technology significantly reduces the time required to design, prototype, and manufacture components. This is particularly beneficial in mission-critical applications where repairs or replacements must be made quickly. Additionally, the absence of tooling and molds, which are costly and time-consuming to produce, further reduces the overall cost of manufacturing parts.

Enabling In-Situ Repairs:

Metal AM technologies like Direct Energy Deposition allow for the direct repair of damaged or worn-out parts in space. This capability not only reduces the need for spare parts but also enables quick repairs without the need to return to Earth or wait for resupply missions, ensuring the continuity of operations and extending spacecraft longevity.

## Metal AM Applications in Spacecraft Repair

### *A. In-Space Repair and Maintenance Requirements*

Spacecraft repair and maintenance in the harsh and isolated environment of space present unique challenges that differ significantly from those encountered on Earth. In-space missions often operate in remote environments, such as low Earth orbit (LEO) or deep space, where resources are limited and access to Earth-based support is unavailable or impractical. This limitation makes it essential to develop reliable, efficient, and self-sustaining methods for performing repairs and maintaining spacecraft systems. The need for in-space repair solutions is particularly critical for long-duration missions, such as those to the Moon, Mars, or future deep-space exploration missions, where delays or failures in critical systems could jeopardize the success of the mission and crew safety.

Key in-space maintenance requirements include the ability to repair or replace damaged components, address system malfunctions, and modify parts to adapt to evolving mission needs. With the distance from Earth limiting the frequency of resupply missions, having the capability to produce or repair components directly on-site reduces downtime and mitigates risks. Metal additive manufacturing (AM) offers an ideal solution, providing on-demand manufacturing of durable, high-performance parts needed to address these challenges and ensure the spacecraft's continuous operation.

### *B. On-Demand Production of Spacecraft Components*

One of the most transformative aspects of metal AM is the ability to produce parts on-demand, directly in space. Traditional spacecraft maintenance depends on having spare parts readily available in space or being able to send them from Earth. However, due to the high costs and logistical challenges of transporting spare parts into orbit, this approach is not sustainable in the long run. Metal AM enables a shift toward on-site production, where astronauts or automated systems can create parts as needed, drastically reducing dependence on pre-positioned spare parts and minimizing resupply requirements.

The on-demand production of spacecraft components using AM technology allows for more flexibility and responsiveness in addressing unforeseen breakdowns or the need for custom parts during the mission. Components such as brackets, housings, structural elements, and tools can be printed and integrated into the spacecraft with minimal delay, ensuring that repairs and upgrades are performed quickly and effectively. This capacity for immediate manufacturing also improves mission flexibility, as it allows for last-minute design modifications or additions without the constraints of traditional manufacturing methods.

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*C. Customization and Complexity of Parts for Specific Spacecraft Needs*

Spacecraft often require specialized parts that are designed for unique environments and operational requirements. Whether for a particular satellite, exploration vehicle, or space station, these parts must meet precise performance criteria, including resistance to extreme temperatures, radiation, and microgravity conditions. Traditional manufacturing methods are often ill-suited to produce such custom, complex parts, especially when faced with the need for rapid production or modification.

Metal AM, however, excels in producing customized components with intricate geometries and complex internal features. By using 3D modeling and digital design files, parts can be tailored to meet the exact specifications required for specific spacecraft or mission objectives. This includes optimizing structural components to minimize weight, designing integrated cooling or fluid systems, and producing lightweight lattice structures that maintain strength and durability in space conditions. The ability to create complex, customized parts on-demand means that spacecraft components can be rapidly adjusted, upgraded, or repaired, without the need for costly redesigns or waiting for parts to be manufactured on Earth.

*D. Case Studies and Examples of Successful AM Applications in Space*

Metal additive manufacturing has already demonstrated its potential in real-world applications within the aerospace sector. Notable case studies include both space agencies and private companies that have explored the use of AM to enhance spacecraft repair and maintenance.

International Space Station (ISS) – NASA and Made In Space:

In 2016, NASA collaborated with Made In Space, a private company, to demonstrate the first-ever 3D printing of metal parts aboard the ISS. The project, known as the 3D Printing In Zero Gravity (3D Printing In Zero G) experiment, aimed to test the feasibility of AM in space for producing metal parts. During the mission, the Additive Manufacturing Facility (AMF) on the ISS was used to manufacture tools and spare parts from metal, allowing astronauts to create parts in microgravity. The success of this experiment demonstrated the potential for AM to address maintenance needs in space, providing the ability to fabricate metal components on-demand directly within the spacecraft, reducing reliance on Earth-based supply chains.

SpaceX – Falcon 9 Engine Components:

SpaceX has used metal additive manufacturing for several components in its Falcon 9 rocket engines. AM has allowed the company to produce complex, lightweight, and highly durable parts such as turbopumps and combustion chambers. These components are crucial for improving the performance and reliability of rockets and reducing the cost of manufacturing. SpaceX's success with AM has paved the way for its application in future spacecraft repair and maintenance operations, particularly as the company looks to expand its missions to the Moon, Mars, and beyond.

The European Space Agency (ESA) – Metal AM for Deep Space Exploration:

The European Space Agency (ESA) has conducted extensive research into the use of metal AM for deep space exploration. ESA's studies have explored the use of AM technologies for producing propulsion components, heat exchangers, and parts for spacecraft systems. The ability to print metal parts with complex internal structures can significantly enhance spacecraft performance by optimizing heat management and reducing overall weight. ESA is actively exploring how AM could be integrated into future space missions to Mars, as it presents an opportunity to reduce mission costs and improve the sustainability of long-duration spaceflight.

Relativity Space – Autonomous Rocket Manufacturing:

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elativity Space, a private aerospace company, is working on revolutionizing rocket manufacturing by using metal 3D printing to construct entire rocket stages. Through its "Stargate" 3D printer, the company aims to reduce the time and cost of rocket production. By using AM, Relativity Space is able to print parts with greater design freedom, complexity, and speed compared to traditional manufacturing. The company's approach also extends to the production of repairable components for future space missions, where AM could play a vital role in ensuring the functionality and longevity of space vehicles.

## Advantages of Metal AM in Spacecraft Maintenance

*A. Reducing Dependency on Spare Parts and Long Supply Chains*

One of the key challenges in spacecraft maintenance is the reliance on spare parts and the logistical complexities of transporting them to space. In traditional spacecraft operations, spare parts are pre-positioned on the spacecraft, space station, or in spaceports, often requiring costly and time-consuming resupply missions from Earth. The transportation of parts, especially for long-duration missions or missions beyond Earth's orbit, can be prohibitive in both cost and time. This issue becomes even more pronounced as space missions evolve, with missions to the Moon, Mars, and beyond requiring solutions that minimize dependency on Earth-based resupply chains.

Metal additive manufacturing (AM) provides a transformative solution to this challenge by enabling the on-demand production of metal components directly in space. With AM, astronauts can fabricate replacement parts, tools, and even custom-designed components at the point of need, reducing or even eliminating the reliance on traditional spare parts and lengthy supply chains. This capability dramatically decreases the logistical burden and costs associated with spacecraft maintenance, enabling a more self-sufficient and flexible operational model. On-demand production also enhances mission resilience, as it enables the ability to quickly address unexpected damage or wear without waiting for resupply missions.

*B. Enabling Complex, Lightweight, and Durable Components*

Spacecraft are subject to extreme conditions, including harsh temperatures, high radiation levels, and the vacuum of space, which place significant demands on their materials and components. Traditional manufacturing techniques often struggle to produce parts that meet these stringent requirements, particularly when it comes to creating components with complex geometries or lightweight structures without sacrificing strength and durability.

Metal AM excels in enabling the design and production of complex, lightweight, and durable components that are well-suited for the harsh conditions of space. The ability to manufacture parts with intricate internal structures, such as lattice frameworks, allows for weight reduction while maintaining high strength-to-weight ratios. These lightweight parts are essential for optimizing spacecraft performance, as every gram of mass saved can result in more efficient fuel consumption and reduced launch costs.

Moreover, the advanced materials used in metal AM, including titanium alloys, stainless steels, and nickel-based superalloys, provide the necessary durability and resistance to extreme temperatures, corrosion, and wear. These materials, combined with the flexibility of AM to produce customized parts with exact specifications, ensure that components meet the demanding standards required for spacecraft systems. As a result, metal AM allows for the creation of highly functional, long-lasting parts that can withstand the challenges of space environments while enhancing overall spacecraft performance.

*C. Decreasing Turnaround Times for Repairs*

In traditional spacecraft maintenance, the time required to manufacture, transport, and integrate replacement parts can be a major factor in mission downtime. In cases where a critical part is

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damaged or fails, delays in obtaining and installing replacement components can result in mission delays, operational inefficiencies, and even the failure of critical systems. This issue is particularly significant for long-duration missions, such as those to the International Space Station (ISS) or future missions to the Moon or Mars, where resupply opportunities may be limited or unavailable for extended periods.

Metal AM can significantly decrease turnaround times for repairs by enabling the rapid production of parts directly on the spacecraft or space station. Using AM technologies, damaged components can be scanned, modeled, and printed quickly without the need for shipping or assembling replacement parts. This allows for immediate repairs and minimizes mission downtime. In some cases, astronauts or robotic systems can repair or even upgrade spacecraft components autonomously, streamlining the entire repair process. Faster repairs also mean less time spent on maintenance activities, allowing more time for mission-critical tasks and scientific experiments.

*D. Enhancing Spacecraft Mission Sustainability and Operational Efficiency*

The sustainability of spacecraft missions is closely linked to the efficiency of spacecraft maintenance and the ability to keep systems operational over extended periods. Space missions—especially those to distant destinations such as Mars—require systems that can function reliably without frequent resupply missions or Earth-based assistance. In these missions, spacecraft must be capable of performing self-sustaining repairs and maintenance to avoid mission failure.

Metal AM plays a pivotal role in enhancing spacecraft mission sustainability by providing a means to continuously maintain, repair, and upgrade spacecraft components in space. By enabling the in-situ production of parts, AM reduces the need for large inventories of spare parts, which are expensive and take up valuable space and weight. This results in greater mission autonomy, reduced launch mass, and more efficient use of spacecraft resources.

In addition to its impact on sustainability, AM improves operational efficiency by streamlining the maintenance and repair process. With the ability to produce parts on-demand, spacecraft operators can minimize downtime, ensuring that the spacecraft continues to operate at peak performance. Whether it's producing a new tool to repair a specific component or creating a custom part to address an unforeseen issue, AM offers the flexibility and speed required to keep spacecraft systems fully functional for the duration of a mission. As a result, spacecraft can operate more efficiently, extending their operational lifespans and reducing the risk of mission-critical failures.

In summary, the advantages of metal AM in spacecraft maintenance are far-reaching and highly impactful. By reducing dependency on spare parts, enabling the production of complex and durable components, decreasing repair turnaround times, and enhancing overall mission sustainability and operational efficiency, metal AM provides an invaluable tool for the future of space exploration. As the aerospace industry continues to push the boundaries of space travel, the ability to quickly and effectively maintain spacecraft in the harsh environment of space will be crucial to the success of future missions.

## Technical Considerations for Metal AM in Space

*A. Material Selection and Properties for Space Applications*

The selection of materials is critical in metal additive manufacturing (AM) for spacecraft applications, as these materials must meet the stringent demands of space environments. Spacecraft operate in extreme conditions, including high radiation, microgravity, extreme temperatures, and the vacuum of space. As such, materials used in AM for space applications must possess specific properties such as high strength, thermal stability, resistance to corrosion and oxidation, and the ability to maintain performance in extreme environmental conditions.

Common materials used in metal AM for spacecraft applications include titanium alloys, stainless steels, aluminum alloys, and nickel-based superalloys. Titanium alloys, for example, offer a combination of low weight and high strength, making them ideal for structural components. Stainless

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steels are widely used for their strength, corrosion resistance, and durability in high-temperature environments. Nickel-based superalloys, known for their excellent high-temperature strength and resistance to oxidation, are essential in applications such as rocket engines and heat shields.

For successful in-space manufacturing, it is also crucial to consider the material's ability to be processed in the low-gravity environment of space, as this can influence how the material behaves during the AM process. For instance, some metal powders may behave differently in microgravity, potentially affecting the consistency and quality of the final parts. Therefore, it is important to carefully choose materials that can perform consistently in space conditions while also being compatible with AM processes.

*B. AM Process Optimization for In-Space Environments*

Optimizing AM processes for space environments presents a unique set of challenges due to the absence of gravity, varying thermal conditions, and the need for precise control over the manufacturing environment. In space, the lack of gravity can affect material deposition, cooling rates, and part consolidation, which could lead to defects such as warping, cracking, or poor layer adhesion in the final part. Therefore, AM processes must be fine-tuned to account for these factors to ensure high-quality and reliable components are produced.

Key areas of process optimization include thermal management, laser or energy beam control, and powder delivery mechanisms. In space, it is important to carefully control the temperature fluctuations that occur during the printing process, as rapid cooling or heating can impact material properties and part quality. In addition, the design and configuration of AM systems must be adapted to ensure consistent powder feed rates and material deposition despite the absence of gravity. For instance, the design of the powder bed or delivery nozzle in systems like Powder Bed Fusion (PBF) or Direct Energy Deposition (DED) may need to be modified to prevent powder from floating away or being improperly distributed.

Furthermore, the AM equipment used in space must be highly reliable and capable of operating autonomously with minimal oversight. Given the isolation and resource constraints in space, the system should be designed to perform without frequent intervention, making robust monitoring and diagnostic tools essential for ensuring the ongoing performance of the equipment.

*C. Certification and Quality Control Challenges*

One of the major hurdles in adopting metal AM for spacecraft maintenance is meeting the rigorous certification and quality control standards required for aerospace applications. The production of aerospace components involves strict testing and validation procedures to ensure safety, reliability, and performance. For AM to be effectively integrated into spacecraft maintenance and repair, the processes and materials used must be certified to meet these high standards.

Certification of AM parts for space applications requires thorough testing of mechanical properties, thermal performance, and overall structural integrity. Parts must undergo rigorous testing for factors such as fatigue resistance, thermal cycling, and impact strength to ensure they will function reliably under the harsh conditions of space. Additionally, AM parts must undergo non-destructive testing (NDT) methods such as X-ray imaging or ultrasonic testing to detect any internal defects that could compromise the part's safety and functionality.

The challenge lies in establishing standardized methods and protocols for certifying AM components, particularly since the technology is still evolving. As AM technology advances, developing clear certification pathways and aligning with existing aerospace standards will be crucial to gaining acceptance within the industry and ensuring that AM parts are deemed reliable and safe for use in spacecraft.

*D. Integration with Spacecraft Systems and Compatibility with Existing Repair Protocols*

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For metal AM to be effective in spacecraft repair and maintenance, it must be seamlessly integrated into existing spacecraft systems and repair protocols. This includes compatibility with spacecraft's structural, propulsion, thermal, and electrical systems, as well as the ability to meet operational requirements during repair procedures. The integration process must ensure that AM-produced components can be incorporated into the spacecraft without compromising the integrity or performance of existing systems.

Additionally, current spacecraft repair protocols may need to be adapted to accommodate AM. For example, existing maintenance procedures that rely on replacing pre-manufactured parts may need to be revised to incorporate the use of AM for on-site repairs. This might involve the development of new repair techniques, tools, and workflows to ensure that AM-produced parts are correctly installed, tested, and integrated into spacecraft systems.

Incorporating AM into spacecraft repair also requires training astronauts and mission planners to effectively use AM systems in space. Given that AM is a relatively new technology, crew members must be trained in both the operation of the AM equipment and the proper techniques for producing, handling, and installing AM parts. The development of standard operating procedures (SOPs) and repair protocols tailored to AM will be essential to ensure the smooth integration of AM into spacecraft maintenance operations.

Furthermore, the use of AM must be coordinated with other spacecraft technologies to ensure that parts manufactured in space are compatible with the existing systems. For instance, AM components must fit precisely within the spacecraft's mechanical assemblies, and thermal or electrical components must be tested to ensure they meet the required performance standards. Ensuring compatibility with existing hardware and systems will be critical to achieving seamless and efficient spacecraft repair processes.

## Conclusions

Metal additive manufacturing (AM) holds immense promise for transforming the way spacecraft maintenance and repair are conducted in space. By enabling on-demand, on-site production of complex, lightweight, and durable components, AM offers solutions that significantly reduce reliance on traditional spare parts and Earth-based supply chains. The ability to rapidly produce parts with intricate geometries and customized designs ensures spacecraft can remain operational even in the most challenging environments of space, where access to resupply missions is limited or non-existent.

The advantages of metal AM extend beyond simply manufacturing parts. It reduces turnaround times for repairs, enhances mission sustainability by decreasing the need for resupply missions, and improves operational efficiency by providing spacecraft with a self-sustaining means of addressing unexpected damage or wear. These benefits are crucial for the success of long-duration space missions, such as those to the Moon, Mars, and beyond, where traditional methods of maintenance would be impractical and costly.

However, while metal AM offers significant advantages, technical challenges remain. Material selection, process optimization for the unique conditions of space, certification and quality control, and integration with existing spacecraft systems are all critical factors that must be carefully addressed. Ensuring that AM technologies can meet the rigorous demands of spaceflight, both in terms of performance and safety, will require continued research, development, and collaboration across the aerospace industry.

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