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REVIEW ARTICLE

Could 3D-Printed Plastic Replace Traditional Aerospace Materials When Producing Rockets and Satellites?

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ABSTRACT: Modern aerospace materials like metals are expensive, heavy, and radioactively susceptible, so they increase cost during manufacturing and space exploration and can be vulnerable in space environments. The high design freedom of 3D printing and the durability, lightweight through structural optimization and novel design, and low cost of plastic can mitigate these issues, while contributing to sustainability by creating less waste and reusing used plastic. Through a review and analysis of the existing literature on 3D printing technologies and their applications in the space environment, this research paper examines the differences between current aerospace materials and 3D-printed plastics and assesses the potential of 3D-printed plastics as an alternative to current aerospace materials. The results of this study indicate that plastics can replace current aerospace materials in some applications, such as PEEK plastics for spacecraft structural components and ULTEM for satellite components and housings, but not all applications are well-suited for plastics, since they have disadvantages such as low heat resistance and high brittleness, and some plastics are even susceptible to cosmic radiation. To mitigate some of these disadvantages in the space environment, technologies such as multi-material 3D printing, self-healing materials, and carbon nanotubes can be potential solutions. 3D printing also contributes to futuristic long-term applications that only appeared in sci-fi movies before, and leads humanity into deeper space.

KEYWORDS: Aerospace and Aeronautical Engineering, Condensed Matter and Materials Mechanics, 3D Printing, Plastic, in-space Manufacturing.

Introduction

1.1. Context and Importance of Aerospace Engineering:

Since the space race during the Cold War, the rapid development of aerospace engineering has transformed modern life through cutting-edge technology such as GPS, weather forecasting, climate monitoring, and satellite communications. These innovations, once considered futuristic, are now essential parts of everyday life.

For decades, science fiction has imagined technologies such as reusable rockets, space stations, and robotic exploration that once seemed impossible, but have since become reality. Similarly, ideas such as space elevators, lunar bases, and asteroid mining may seem far-fetched now, but with advancements in new materials and manufacturing techniques—like 3D printing—they are becoming more feasible.

One of the most crucial challenges in aerospace engineering is material selection. This is due to the extreme conditions in space, such as the vacuum environment, broad temperature range, and detrimental cosmic radiation. Traditional aerospace materials such as titanium are durable but are usually expensive. This research will investigate new aerospace materials, especially 3D printed plastics, for their potential as affordable, lightweight, and durable alternatives to traditional materials.

In the future, 3D printed materials will have the potential to advance space exploration by helping to reduce costs and enable in-space manufacturing, as the future of aerospace takes shape on the moon, Mars, and beyond. For instance, nanomaterial technologies like carbon nanotubes could be crucial for the construction of the tether of the space elevator **(Figure 1)**,[1] which would provide a sustainable space transportation alternative to the current rockets and spacecraft.



Figure 1: Illustration of the space elevator's tether.[1]

Efficient 3D printing technology is not only a new manufacturing method on Earth but is also an opportunity to develop space industries and factories in zero gravity. Instead of transporting materials from Earth at high costs, 3D printing in space could be used to manufacture spacecraft and habitat parts. However, challenges remain in running and maintaining 3D printers in space, including the different and extreme conditions in space compared to Earth, such as microgravity and a vacuum environment.

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1.2. Statement of the Problem:

Furthermore, with the development of modern aerospace technology and the number of rockets and satellites launched into space, space debris **(Figure 2)** has proliferated during the past few decades.[5]

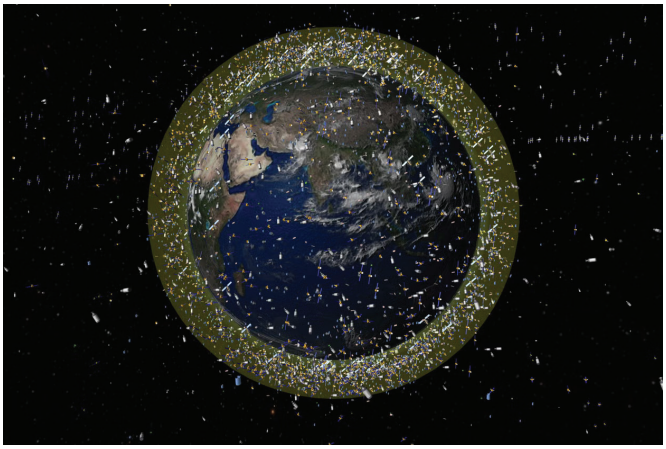


Figure 2: Space debris is floating around the Earth's orbit.[5]

These space junks can become a potential hazard and danger to aerospace equipment despite their sizes, as they usually have very high velocity (According to the research, space equipment often moves at 8 km/s, while space junk can even traverse at a higher velocity, with around 10 km/s). If they collide with spacecraft and satellites, it may lead to financial losses and casualties. Furthermore, if the broken equipment does not burn severely in the atmosphere, it can even threaten lives on the surface of the Earth.

Compared to metals, plastics are usually composed of a honeycomb structure, which is more durable and stable.[6] Traditional honeycomb is assembled from hexagonal shapes, and Tubus Waben is the only European manufacturer of PP honeycomb with circular cells, manufacturing more than 500,000 m^2 annually. The unique circular cylinder formation can accept forces from various directions and still maintain its shape. These isotropic mechanical characteristics of the individual honeycombs ensure high stability for the whole honeycomb plate and, therefore, also the final product.

To further mitigate the issues mentioned above, the aerospace industry is increasingly exploring 3D printing, also called Additive Manufacturing (AM).[7] Among the many different AM processes, the ones that are best suited for applications in the aerospace industry are Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Electron Beam Melting (EBM), and Wire and Arc Additive Manufacturing (WAAM). The reason these processes are best suited for aerospace applications is that they can produce extremely dense components without post-processing, and the materials used in these processes have comparable mechanical and electrochemical properties to those made through conventional manufacturing methods.

1.3. Research Questions and Objectives:

This study seeks to explore the feasibility of 3D-printed plastics in spacecraft and satellite construction by addressing the following key research questions:

- What is the potential of 3D printing technology when integrated with the aerospace industry?
- Can plastic replace current aerospace materials? If so, how and which part can they replace?

This research aims to investigate the possibilities of plastic integration in current and future aerospace industries. Moreover, it will aim to envisage its future potential when applied to more advanced space technology.

In order to answer these questions, this study will compare the properties (strength, weight, heat resistance, and radiation tolerance) of 3D-printed plastics to traditional aerospace materials. This study will also analyze the cost-benefit trade-offs of using 3D-printed plastics for space applications and explore the real-world applications of 3D-printed plastics in spacecraft and satellite design.

■ Discussion

2. Background and Literature Review:

2.1. Current Use of 3D Printing in Aerospace:

3D printing is currently being used in space applications. Companies like NASA, SpaceX, Blue Origin, and Relativity Space have adopted 3D printing for spacecraft components, reusable rockets, and even experimental construction on the Moon and Mars.

In-Space 3D Printing:

Researchers at the University of Glasgow have developed a prototype 3D printer for space that prints devices directly in orbit,[8] such as reflectors, communication antennas, or medicine. The printer processes granular material (a multiphase material made up of an extensive collection of closely packed solid particles surrounded by a gas or a liquid) and prints efficiently, even under space conditions.[9] The printer was extensively tested in several test flights in November 2024 and may pave the way for future space factories.[8]

In 2024, there are several breakthroughs from universities and companies worldwide:

- First 3D-Printed Metal Part Aboard The ISS
- NASA Tests Laser Beam Welding in Space
- Berkeley Researchers Send a 3D Printer Into Space
- European Space Agency (ESA) Uses IMPERIAL 3D Printer
- NASA engineers successfully tested 3D Printing Electronic Circuits for Spacecraft

Additionally, NASA's recent Archinaut project aims to 3D-print satellite parts in orbit, reducing launch waste.[10] According to NASA, the 3D printing test has already been successfully conducted in a vacuum chamber **(Figure 3)** at NASA's Ames Research Center in Moffett Field, California.



Figure 3: NASA's in-space 3D-printing experiment in a vacuum chamber.[10]

3D-Printed Food for Space Missions:

In the past decade, 3D-printed food has become a global theme that has revolutionised the food industry since it can resolve food insecurity and shortage issues.[8] However, it causes many controversies, including the high cost of 3D-printed food.

Recently, scientists and space organisations from Japan, Europe, and America have been cooperating to reuse plastic waste and turn it into edible food **(Figure 4)**.[11] The pioneer of this project is a company called Beehex, which was founded by Anjan Contractor, an engineer affiliated with NASA. First, they collect plastic waste, shred it, and put it into a bioreactor with a specific modified bacterium. Then, the bacteria eat the plastic and turn it into a biomass that can be 3D printed to form meals.



Figure 4: 3D-printed meal.[8]

According to NASA scientists, the main advantages of 3D-printed food are that it can be easily preserved in the space environment and can be carried due to its compact size. Moreover, these 3D-printed foods preserve food nutrition as well as taste, so they have the potential to be a major meal for astronauts and humans.

Reusable Rockets and 3D-Printed Engine Components:

Since the 1950s, rockets have mainly used one-time engines, which means that the rocket engine will be disposed of and burned in the atmosphere after the rocket is launched.

SpaceX and Blue Origin are exploring 3D-printed, sustainable materials for reusable space vehicles. The SpaceX Raptor engine (**Figure 5**) is one of the most notable reusable rocket engines developed recently.[12]

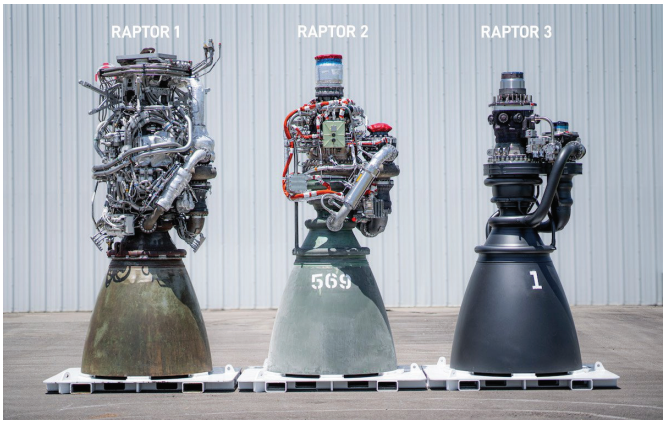


Figure 5: Evolution of Raptor engines.[12]

The above image depicts the evolution of Raptor engines. Although they are all reusable, Raptor 1 and Raptor 2 are produced using traditional manufacturing methods, while Raptor 3 (announced in 2024, the latest version of the Raptor engine) uses 3D printing technology.

Part consolidation, weight reduction, and the ability to design complex internal structures that were previously impossible to make with other manufacturing methods are some of the biggest benefits of 3D printing technologies.

The smoother and aerodynamically streamlined surface of the Raptor 3 engine enhanced its running efficiency and performance. Moreover, the simplified design contributed by additive manufacturing also lowers the production cost and difficulty while making the engine less likely to break down due to uncertainties in space.

Space Construction:

Scientists and engineers have now successfully transferred 3D printers into space, which is the first step towards manufacturing and constructing space materials instead of delivering them from Earth.

NASA has awarded more than $57.2 million in contracts to Austin-based ICON to develop construction technologies for future missions to the Moon and Mars. As part of the Moon to Mars Planetary Autonomous Construction Technologies (MMPACT) project, ICON will work with NASA's Marshall Space Flight Center to develop the Olympus construction system.[8]

This project uses local materials to fabricate infrastructure such as landing pads, habitats, and roads on the lunar surface. This contract, which runs through 2028, expands on ICON's previous work under the Small Business Innovation Research (SBIR) program and builds on its expertise in 3D printing applied to space exploration, including the construction of Mars Dune Alpha, a simulated Martian habitat for the CHAPEA analogue mission. With these innovations, NASA seeks to advance technologies essential to the sustainable exploration of new sites **(Figure 6.1)**.[8]

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Additionally, startups like Space Copy are exploring autonomous printing solutions for off-world construction. As one of the spearheads of achieving 3D printing on the Moon, Mars, and even in deeper cosmos, Space Copy's general aim is to find solutions to mitigate the problems faced, such as high expenditure and danger, when constructing infrastructure in the extreme environment of the Earth and space using conventional manufacturing methods.

The startup was launched in 2022 and wants to deploy autonomous printing solutions for remote construction and integrate custom additive manufacturing techniques for on-demand fabrication of supplies and infrastructure. Furthermore, the company is developing printers to print lunar soil simulant material. Founder Madison Feehan said her goal was to have a printer on the Moon by 2031 **(Figure 6.2)**.[8]

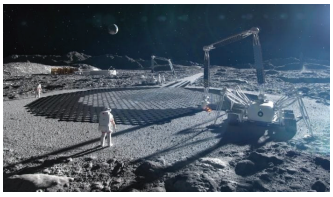


Figure 6.1: Imagination of lunar settlement.[8]

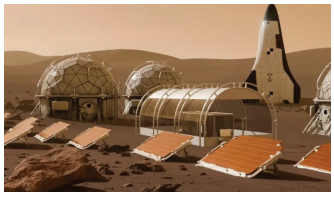


Figure 6.2: Illustration of a Mars settlement.[8]

2.2. Materials in Aerospace:

The four main types of current aerospace materials are metal alloys, metals, composites, advanced polymers, and thermal protection systems.[13,14]

Metals and Alloys:

Metals such as aluminum, titanium, and nickel-based alloys have been widely used in aerospace applications due to their high strength, durability, and resistance to extreme conditions.

Table 1: Common metals used in 3D printing.

Material	Pros	Cons	Applications
Aluminum Alloys (e.g. 2024, 5075)	Lightweight, corrosion-resistant, high strength-to-weight ratio	Lower fatigue resistance than titanium, weak at high temperatures	Aircraft wings, satellite frames
Titanium alloys (e.g., Ti-6Al-4V)	Lightweight, highly resistant to corrosion, and	Costly and challenging to maintain	Rocket engines and other components that
	very durable with high melting points		can reach high temperatures
Nickel-based superalloys (e.g., Inconel 718, Hastelloy)	Lightweight, highly resistant to corrosion, and very durable with high melting points	Heavy and expensive to manufacture	Rocket engines, turbine blades, and heat shields
Stainless steel (e.g., 17-4PH, 316L)	High strength, corrosion resistance, and weldability	Heavy has lower heat resistance than titanium and nickel alloys	Spacecraft fuselages (e.g., SpaceX Starship), fuel tanks

Composites:

Composites such as CFRP and GFRP are lightweight and durable. However, they are very expensive and lack sustainability and radiation resistance.

Table 2: Common composites used in 3D printing.

Material	Pros	Cons	Applications
Carbon Fibre-Reinforced Polymers (CFRP)	High strength-to-weight ratio, great fatigue resistance, lower fuel consumption in aircraft	Expensive & challenging to recycle, brittle under-impact	Frame structure of the wings and fuel tanks
Glass Fibre-Reinforced Polymers (GFRP)	Cheaper than carbon fibre, high corrosion resistance, lightweight	Less durable than CFRP, susceptible to UV radiations	Radomes & antenna covers, small UAV structures

Advanced Polymers:

Advanced polymers include aerospace-grade plastics such as PEEK and ULTEM, which have extreme durability and are lightweight. However, they usually have less heat resistance and higher brittleness than metal.

Table 3: Common advanced polymers used in 3D printing.

Material	Pros	Cons	Applications
PEEK (Polyether Ether Ketone)	Extreme heat & chemical resistance, high mechanical strength, low outgassing (space use)	Very expensive, difficult to 3D print, which limits PEEK's development potential	Fuel line brackets and insulation layers of the spacecraft
ULTEM (PEI - Polyetherimide)	Heat resistant, lightweight, strong, more affordable than PEEK	Less heat resistant than PEEK, high processing temperature required	Aerospace ducting system

Thermal Protection Systems:

Thermal protection systems such as ablative heat shield materials and aerogels are extremely heat-resistant and lightweight, but they are very fragile. Therefore, they often serve as the support material to construct thermal insulation layers.

Table 4: Common thermal protection systems used in 3D printing.

Material	Pros	Cons	Applications
Ablative Heat Shield Materials (e.g., PICA-X, Avcoat)	High reentry temperature resistance, extremely lightweight compared to metal shielding	Single-use, complex and expensive manufacturing	Spacecraft re-entry shields (Dragon capsule, Orion), hypersonic vehicle protection
Aerogels (Silica-Based)	Extremely lightweight, excellent heat resistant	Very fragile, expensive to manufacture (especially by 3D printing)	Insulation for spacecraft, cryogenic fuel tanks

Key Takeaways for Aerospace Material Selection:

- Metals (Aluminum, Titanium, Nickel Alloys, Stainless Steel): Used for structural strength, heat resistance, and durability.
- Composites (CFRP, GFRP): Lightweight and fuel-efficient, but expensive and hard to recycle.
- Advanced Polymers (PEEK, ULTEM): Used in space applications due to low weight and high thermal resistance.
- Thermal Protection Systems (Ablatives, Aerogels): Essential for space re-entry and high-speed flight.

Currently, plastics are used mainly for non-load-bearing structures in critical aerospace applications.

Plastics in Spacesuits (Traditional Manufacturing Techniques):

The astronauts' spacesuit is one of the most significant applications of plastic and other versatile materials in space.[15] There are two main types of spacesuits: the one that astronauts wear when they are staying or doing missions inside the spaceship and the one worn for extravehicular activities (outside the

spacecraft). Regardless of the type of spacesuit, it is like a miniature spacecraft.

The design of spacesuits can vary greatly depending on their purposes and the location in which they are to be used.[15] For instance, a spacesuit designed for Mars may differ significantly from that developed for Titan due to their different environments, including various temperatures and pressures. This is why spending several decades studying a planet is vital before sending a manned mission.

Companies such as Axiom Space are already developing reusable spacesuits, as reducing expenditures and achieving sustainability are imperative.[15] The more extended missions in space are becoming increasingly ordinary. Therefore, the spacesuits should ideally have a lifespan of at least 2 years.

Although the current designs of the spacesuits from different countries are still confidential, NASA has sufficient evidence to prove that plastic has been used as a pivotal material in spacesuits, and the following information is the source since 1999.[15] Still, it does not mean plastic usage in spacesuits has only started since 1999. This excludes the rigid upper torso and the life support assembly of the spacesuit, as their design is still not openly available.

Table 5: A list of different types of plastics used in spacesuits and their respective functions.[15]

Material	Function	Application
Teflon (PTFE - Polytetrafluoroethylene)	Heat resistance and outer protection	Outer layer of the spacesuit and helmet, protecting against extreme temperatures and friction wear.
Nomex (Polyamide)	Flame resistance and durability	Outer layer of the spacesuit, providing additional heat protection and fire resistance.
Kevlar (Polyamide)	Impact and abrasion resistance	Outer layer of the spacesuit, offering durability and protection against micrometeorite impacts.
Aluminized Mylar (BoPET)	Thermal insulation	Insulation layer of the spacesuit, reflecting radiant heat to maintain temperature control.
Nylon (Polyamide)	Flexibility and structural support	Inner liner and bladder coating, allowing flexibility while maintaining structural integrity.
Dacron (Polyester)	Pressure resistance and durability	Pressure restraint layer, maintaining internal pressure and providing additional strength.
Urethane-Coated Nylon	Flexibility and airtight pressure seal	Pressure bladder layer, ensuring an airtight seal to retain internal pressure.
Spandex (Polyurethane)	Flexibility and elasticity	Liquid cooling and ventilation garment, ensuring a snug fit and enhanced movement.
Ethylene Vinyl Acetate (EVA)	Comfort and flexibility	Liquid cooling and ventilation garment, providing cushioning and comfort.
Polycarbonate	Impact resistance and transparency	Helmet bubble, visor, and eye shades, offering lightweight, impact-resistant visibility.
Polysulfone	UV protection and durability	Sun visor and eye shades, protecting against UV radiation and providing durability.

Each plastic material serves a specific function, balancing durability, flexibility, insulation, and protection against extreme environmental factors in space.

The spacesuit used in the Apollo mission was severely damaged after a few extravehicular activities, and scientists and engineers have suggested a few modifications to spacesuits that can offer more comfort and protection. One modification feature uses textiles enhanced with shear-thickening fluid with nanocomposites to help mitigate against the problem of moon dust and Polipo Pressure sensing systems to help better detect injury during testing of a suit with better protection.[15]

Scientists suggest that plastic will still find wide applications in space exploration due to its durability and versatility.

Plastics in Spacecraft (Traditional Manufacturing Technique):

In current space exploration, the primary challenge that spacecraft are facing is the extreme temperature at both ends, which varies from -157 ˚C to 177 ˚C,[15] depending on the spacecraft's location. Therefore, spacecraft must protect crew members from extreme temperature ranges and other extreme factors in the space environment mentioned above.[15]

Table 6: A list of various plastics used in spacecraft and rockets, along with their respective functions.[15]

Material	Function	Application
Silicone-Based Insulation Tiles	Thermal insulation	Used on the surface of spacecraft and rockets to protect against extreme temperatures during re-entry.
Polyurethane	Insulation and cryogenic temperature protection	Spray-on foam insulation for cryogenic tanks (liquid oxygen and hydrogen tanks) on space launch vehicles, preventing fuel solidification.
Polyvinyl Fluoride (PVF)	Protective film for solar panels	Encapsulation layer on spacecraft solar panels, protecting against environmental degradation and UV radiation.
Glass Fiber Reinforced Polyester	Structural reinforcement and durability	Provides strength and protection for solar panels, increasing durability in space environments.
Fluorinated Ethylene-Propylene (FEP) Copolymer	Transparency and UV resistance	Protective layer on solar panels to allow light transmission while shielding against UV damage.
Ethylene Vinyl Acetate (EVA)	Cushioning and encapsulation	Encapsulation layer for solar cells, providing durability and impact resistance.
Polycarbonate	Impact resistance and transparency	Used for spacecraft windows and visors, offering lightweight and impact-resistant visibility for astronauts.
Polysulfone	UV protection and thermal resistance	Used in sun visors and eye shades to protect against UV rays.
Teflon (PTFE - Polytetrafluoroethylene)	Heat resistance and low friction	Coating material for exterior components, used in seals and gaskets due to non-stick properties and thermal resistance.
Polyetheretherketone (PEEK)	High strength and radiation resistance	Used in spacecraft components like screws, bearings, and gears for their high strength-to-weight ratio and durability in extreme conditions.

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Polyimide	High-temperature resistance and insulation	Used in wire insulation and other thermal insulation applications in spacecraft due to stability at high temperatures.
Polyethylene (PE)	Radiation shielding	Used in spacecraft to shield against cosmic radiation, particularly in thicker forms like high-density polyethylene (HDPE).
Polyethylene Terephthalate (PET) / Mylar	Thermal insulation and lightweight	Used as an insulation layer in spacecraft, often in aluminized forms to reflect heat.
Acrylonitrile Butadiene Styrene (ABS)	Structural material and processability	Frequently used in 3D-printed spacecraft parts, offering a good balance of strength and weight.
Nylon	Flexibility and strength	Used in structural components requiring flexibility, such as fabric parts of spacesuits and flexible seals in rockets.

High-performance plastics like these enable flexibility in spacecraft and rocket design, allowing for the customization and precision required to withstand the harsh conditions of space due to space junk.

3D printing allows engineers to produce components of spacecraft, such as screws and gears, with high precision. Moreover, the same type of plastic can be modified in different ways to achieve a wide range of properties. This process is called 'material selection',[16] a highly complex process due to the extreme factors, such as radiation in space.

For instance, some high-performance plastics are well-suited for the inner structure. However, as they are susceptible to radiation, they are inappropriate for constructing the surface.

In terms of combating space debris collision, a common potential threat to the security of modern aerospace equipment, self-repairing thermoplastic polymers have been found very practical, with polyethylene-co-methacrylic as a prime example, which can be applied as self-healing materials for hypervelocity collision resistance.

The pivotal mechanism behind this high resistance and durability of this material is based on the transfer of energy from the hypervelocity collision into heat, which is then absorbed by the material and causes it to melt. Subsequently, the melting will cause thermal rewelding of the area that is hit and close the hole that was created by the collision—a process called self-repairing.

Although this material is practical, its usage is currently limited by its weak mechanical properties. Therefore, scientists are now improving their properties by reinforcing them with carbon fibre.[15]

However, to combat space junk collisions, using durable materials is far from adequate.

Therefore, scientists are integrating numerous technologies for a comprehensive solution, including:

- Developing self-healing materials that can create a more durable spacecraft (which is mentioned above),
- Developing advanced detection systems that support the timely detection of the location and extent of the impact time of space junk,
- Removal of space debris (which can also contribute to sustainability)
- Using legitimate binding agreements and standards for space missions to prevent space junk from occurring in the place that rockets and satellites often bypass.

2.3. Properties and Challenges of Plastics in Space:

Atmosphere:

The first significant difference between the Earth and space environment is that the Earth has an atmosphere, whereas space is a vacuum environment.[18, 19]

This vacuum environment creates three potential problems for spacecraft:

1. Out-gassing—release of gases from spacecraft materials
2. Cold welding—the fusing of metal components
3. Heat transfer—limited to radiation

Moreover, space lacks atmosphere, so it often has an environment with extreme temperatures, whether the temperature range depends on its location relative to the starlight. If it is facing direct sunlight, then the temperature at that location can reach 150° C (302° F), while in shadows, they can be as low as -270° C (-454° F), very close to absolute zero -273.15° C (-457.15° F).[19]

Plastic, except PEEK (very expensive), has a much lower melting temperature and higher brittleness, so they are not as adaptive to extreme temperatures as metal is.

To mitigate this issue, engineers can use different colours of plastic to absorb or reflect heat energy depending on its environment.

Dark colours are chosen to face the sun when the space environment is cold because dark colours absorb much more heat and light energy than light colours. That difference is due to the minimal reflection of the light wavelength of darker shades.

Table 7: The heat resistance of various plastics.[18, 19]

Plastic Type	Melting Point	Heat Deflection Temperature	Continuous Operating Temperature	Glass Transition Temperature	Flame Resistance
Polyphenylene Sulfide (PPS)	280-300°C (536-572°F)	200-260°C (392-500°F)	200-240°C (392-464°F)	85-110°C (185-230°F)	UL 94 V-0
Polyetheretherketone (PEEK)	334-343°C (633-649°F)	150-250°C (302-482°F)	250-260°C (482-500°F)	143°C (289°F)	UL 94 V-0
Polyimide (PI)	400-450°C (752-842°F)	200-340°C (392-644°F)	300-350°C (572-662°F)	260-340°C (500-644°F)	UL 94 V-0
Polyetherimide (PEI)	220-230°C (428-446°F)	160-216°C (320-421°F)	170-200°C (338-392°F)	215-217°C (419-423°F)	UL 94 V-0
Polyamide-imide (PAI)	320-330°C (608-626°F)	200-275°C (392-527°F)	250-275°C (482-527°F)	245°C (473°F)	UL 94 V-0
Liquid Crystal Polymer (LCP)	320-360°C (608-680°F)	180-300°C (356-572°F)	200-300°C (392-572°F)	155-350°C (311-662°F)	UL 94 V-0

In terms of insulators, polyether ether ketone (PEEK) and polytetrafluoroethylene (PTFE) are the best options as superior dielectric properties, especially at high radar and microwave frequencies, which have the same frequency as the space background thermal radiations. Moreover, as both PEEK and PTFE are composed of strong covalent bonds bonded with their valence electrons, they have no free or delocalised elec-

trons. The strong covalent bonds within their structures also make them inert and stable against any chemical reactions.

Table 8: The properties of PEEK and PTFE make them good thermal insulators.[18,19]

Property	PEEK	PTFE
Main insulating feature	Strong aromatic backbone	Strong C–F bonds
Dielectric Strength	20–25 MV/m	~60 MV/m
Dielectric Constant (ε)	~3.2	~2.1
Chemical Resistance	High	Exceptional
Operating Temp (max)	~250°C	~260°C
Electron Mobility	Extremely low	Extremely low

Radiation:

Apart from the atmosphere, the radiation in space is another significant difference compared to the Earth's environment.[19]

4 Main Types of Cosmic Radiation:

1. The solar wind and flares **(Figure 7.1)** continuously blast energetic radiation into space.
2. Galactic cosmic radiation (GCR)
3. Electromagnetic and gamma rays (EM and gamma rays)
4. Solar flares continuously blast energetic radiation into space.

This Radiation can Also Lead to Several Problems with Spacecraft:

1. Heating on exposed surfaces
2. Degradation or damage to surfaces and electronic components
3. Solar pressure

The detailed reasons and solutions will be further discussed in 4.2.

Gravity:

Instead of affecting the properties of plastic directly in space environment like other extreme factors do, the lack of gravity in space would affect the 3D-printing manufacturing process.

Gravity plays a crucial role in determining how plastics behave during manufacturing, mechanical performance, and long-term stability. Changes in gravitational conditions—whether microgravity (space), hypergravity (high-G environments), or standard Earth gravity—can impact 3D printing, strength, durability, and material properties of plastics, particularly in aerospace applications.

Table 9: Gravity's effect on the mechanical properties of plastics.

Gravitational Condition	Positive Effects	Negative Effects	Aerospace Applications
1G (Earth Gravity)	Normal material flow in manufacturing, consistent density and adhesion	N/A	Standard aerospace plastic components (FDM/SLS-printed parts)
0G (Microgravity, Space)	Complex shapes with no sagging	Poor layer adhesion in 3D printing, bubbles in polymer casting	On-orbit manufacturing of tools and spacecraft parts
Hypergravity (High-G, Rocket Acceleration, Reentry)	Higher-density, stronger composites	Material compression & warping, increased brittleness under stress	PEEK/ULTEM components for reentry vehicles and hypersonic aircraft

2.4. Past Projects and Research:

2.4.1. CREST Gold Award Project (Pending Publication):

Prior studies by the Gold CREST team of Queen Ethelburga's Collegiate looked at the feasibility of using 3D printed materials such as plastic, nylon, and metal filament to construct space equipment such as rockets and satellites.[21] In this project, the CREST team (Lok Teng (Kelvin) Cheung, this research paper's writer, and Yu Jun (Lulu) Shen, a STEM student enthusiastic about material science), such as fused filament fabrication, explored alternative materials to design lighter, cheaper, and more durable space equipment. Findings were that metal filament, nylon, and plastic are the most appropriate 3D-printing materials for constructing space equipment.

The team tested a hypothesis of whether it is feasible to use 3D printing materials such as plastic, nylon, and metal filament to construct space equipment such as rockets and satellites by conducting a collision test using a wind tunnel and producing a theoretical online material illustration using Material Studio (produced by and credited to Lulu Shen).

The CREST team hypothesised that it is feasible to use 3D printing materials such as plastic, nylon, and metal filament to construct space equipment such as rockets and satellites.

Part 1: Collision Test by Using Wind Tunnel:

To assess the structural viability of 3D-printed aerospace components, digital models of satellite and rocket structures were designed using Blender and CAD software. These designs were subsequently fabricated using fused filament fabrication (FFF) 3D printing. To facilitate material identification, color-coded paint markers were applied to distinguish components based on material composition.

To evaluate the impact resistance of 3D-printed aerospace structures, a collision test was conducted in a simulated space debris environment. Due to laboratory resource constraints, a wind tunnel was constructed using a fume cupboard, screen protectors, and cardboard, as inspired by previous research on low-cost aerodynamic testing. Spillage kit absorbent material was used to represent space debris, which was accelerated using a high-velocity airflow generated by a hairdryer.

The collision experiment was designed to analyze two impact orientations:

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Horizontal impact: Space debris was propelled toward the satellite model using forced airflow within an enclosed acrylic tube to prevent uncontrolled dispersion.

Vertical impact: Debris was released from a fixed height onto the satellite model, with an acrylic enclosure used to contain dispersal.

A high-speed camera was employed to document each collision, enabling frame-by-frame analysis of impact dynamics and structural deformation.

Part 2: The Theoretical Online Material Illustration Using Material Studio (Produced by and Credited to Lulu Shen, a Research Associate in the CREST Project):

(The test details and results are available in Kelvin Cheung and Lulu Shen's CREST research paper.)

Preliminary findings indicate that while 3D-printed materials exhibit promising characteristics for lightweight aerospace structures, impact resistance varies significantly based on material composition. While metal filament composites demonstrated enhanced durability, plastic and nylon components exhibited notable deformation upon impact. These results align with existing research on the limitations of polymer-based materials in high-stress aerospace environments.

Additionally, this study highlights the adaptability required in aerospace engineering, as resource constraints necessitated the development of an improvised yet effective wind tunnel for experimental validation.

2.4.2. NASA's Lunar Habitat Work, Self-healing Materials Research:

NASA Langley researchers have developed a multi-layered self-healing material system **(Figure 7)** for impact mitigation from ballistic or hypervelocity events (e.g., micrometeoroids or orbital debris).[22] The system is constructed by sandwiching a reactive liquid monomer formulation between two solid polymer panels. While developed with space exploration in mind, the innovation has many other applications, such as fuel tanks and hydraulic insulation.

This innovation contains three layers: solid plastic front and back, sandwiching a viscous, reactive liquid middle layer. When the middle layer is penetrated, the oxygen gas will fill the gap immediately, turning the liquid into a solid.

This project matches well with Kelvin's CREST project, as this material can effectively prevent high-speed collisions between space debris and the spacecraft's surface.

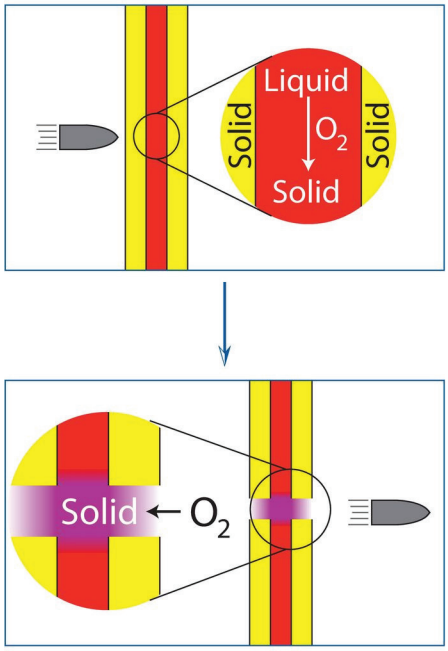


Figure 7: Mechanism of NASA's self-healing material.[22]

3. Advantages of 3D-Printed Plastics in Aerospace:

3.1. Lightweight Structure:

Table 10: The advantages and disadvantages of different types of traditional 3D printing material, numbers from.[24]

Filament	Advantages	Disadvantages	Cost Per Kg
ABS	Tough, impact-resistant; Common; Non-toxic, water- and chemical-resistant, is remarkable for preserving its colour	High melting point; Unpleasant fumes	$20 to $50 [24]
PLA	Easy to print with; Biodegradable	Prints degrade over time; Rough texture	$20 to $50 [24]
PVA	Water soluble; Fairly easy to print	Expensive; Risk of toxic fumes	>$100 [24]
Nylon	Tough; Inexpensive	High temperature requirement	$18 [24]
HDPE	Easy to dissolve; Lightweight	High temperature requirement	$30 [24]
T-Glase/PETT	Food-safe; Glass-like look	Slow to print; Heated printing bed needed	$30 [24]
Wood Filament	Attractive wood-like look	Finicky to use; Requires sanding	$60 to $100 [24]
Metal Filament	Attractive metal-like finish	Finicky to use; Expensive	$75 to $120 [24]
Carbon Fiber Mix	Mimics carbon fiber's lightweight strength	Tough on extruders; Expensive	$50 to $120 [24]
Flexible Filament	Produces flexible prints	Requires tinkering with the printer	$50 to $120 [24]
Conductive Filament	Conducts electricity; Similar to PLA	Expensive; Still experimental	$70 (for a 100g reel) [24]

From the diagram above,[24] although 3D printing methods are used to manufacture traditional aerospace raw materials (metal, carbon fibre, conductive filament) into usable products for crafting rockets and spacecraft, it is still expensive. Moreover, they are heavy, as mentioned. Therefore, the lightweight attribute of plastic shown in the diagram can be instrumental in reducing transportation and launching expenditures.

Moreover, it has already been mentioned that plastic can be easily modified by 3D printing, whereas it is more difficult for metal.

To achieve lightweight by 3D printing, there are two main ways: structural optimization and novel design.[25] The key advantage of 3D printing is design freedom. It provides a basis for structural optimization and novel design. Ensuring that fewer materials are used to manufacture the product while maintaining the same quality.

3.2. Reduced Costs & Rapid Prototyping:

Here are some ways in which 3D printing lowers the cost of product development:

- Faster and cheaper design process
- Lower labour costs
- Lower material costs
- Design agility and customisation
- New design horizons

Rapid prototyping is still one of the primary uses for additive manufacturing.[26] Prototypes that used to cost hundreds can now be made for a fraction of that cost due to the high modifying ability of 3D printing (as the user only must change the design of the CAD software), so even small-scale businesses can actively pursue product development.

Moreover, using 3D printers can reduce the number of manual engineers and mechanics, lowering wages and expenditure. Moreover, this means adding raw materials layer by layer. The printer only uses what is required to print, dramatically reducing material waste. The structural optimization of 3D printing can allow the printer to produce fewer materials and the same quality.

Moreover, as 3D printing can quickly produce intricate and complex geometric structures, it can open new technological frontiers for humans, such as advanced composite materials and mechanical components.

During the CREST project, Kelvin and Lulu were able to produce their sophisticated rocket and satellite model, which only has a height and length of around 15 cm. This enables them to illustrate the layers and specific components of the space equipment more conveniently.

3.3. Design Flexibility:

Several 3D printing techniques allow intricate model design. Three of the most iconic methods are SLS, SLA, and FDM.[27]

Selective laser sintering (SLS) uses a high-powered laser to fuse powdered thermoplastics (e.g., Nylon, PEEK, ULTEM) layer by layer. No support structures are needed (powder acts as support), allowing for complex geometries. It is best for aerospace-grade plastics since they have the highest precision, but are costly.

Stereolithography (SLA) uses a UV laser to cure a liquid resin layer by layer. It is best for ultra-high detail prototypes as it has exceptionally high resolution and can create a smooth and brittle surface. Most importantly, it can print out transparent structures, which is excellent for optical components.

Fused deposition modelling (FDM) uses a heated nozzle to extrude thermoplastic filament (e.g., ABS, Nylon, PEEK, ULTEM), building the object layer by layer. It is simple and affordable, but has a lower resolution than SLS or SLA. Therefore, it is most appropriate for cost-effective prototyping and manufacturing of large parts.

3.4. Advantages Overview:

3D-printed plastic greatly benefited from its lightweight properties and the rapid development of modern technologies such as computer science, artificial intelligence, and industrial 3D printing techniques.[24-27] These provide them with high flexibility during design and integration, as engineers could control the composition and amount of various plastics, ultimately developing the most appropriate composite material for constructing different parts of the aerospace equipment. Moreover, 3D printing allows engineers to construct aerospace equipment such as rockets, spacecraft, and satellites in a new optimal geometric structure. A prime example is to construct a more streamlined and aerodynamic body.

4. Drawbacks and Limitations:

4.1. Thermal and Mechanical Constraints:

As mentioned above, plastics such as PEEK and ULTEM have lower thermal resistance than metals such as titanium and nickel.[13,14] Although they are very durable and can combat high-velocity collisions from space debris, they must add metal composites, coatings, and thermal protection systems such as ablatives and aerogels.

Table 11: Materials to avoid.[13]

Material	Why Not?
PLA (Polylactic Acid)	Too brittle, low heat resistance (~60°C), unsuitable for aerospace.[13]
ABS (Acrylonitrile Butadiene Styrene)	Decent strength but prone to warping and outgassing, making it risky for space applications.[13]
PETG (Polyethylene Terephthalate Glycol)	Good chemical resistance but not strong enough for structural aerospace parts.[13]

These materials are too brittle, which means they may scatter and break in frigid space temperatures when away from sunlight, and are insufficiently durable. Therefore, besides adding metal composites for reinforcement, NASA's self-healing materials are also feasible.

4.2. Radiation Susceptibility:

In the universe, radiation can have a significant impact on aerospace plastic.[28]

There are three main types of radiation: ultraviolet (UV) radiation degradation, embrittlement from high-energy radiation (gamma & X-rays, cosmic rays), and atomic oxygen (AO) erosion.

Since solar UV radiation with a wavelength of around 100-400 nm in space is much more intense than on Earth due to the lack of an atmosphere, it can break molecular bonds, causing surface erosion, discoloration, cracking, and loss of mechanical strength. They commonly affect polymers with poor UV resistance, such as PEEK, ULTEM, ABS, and Nylon. Although some polymers, such as Kapton (Polymide film), have high UV resistance, they can still be affected. This can cause degradation of insulation materials on spacecraft and satellites and loss of mechanical integrity in polymer-based components over time. To resolve these issues, coatings such as aluminized or silica-based coatings can prevent UV exposure, and UV stabilizers can be added to polymer formulations.

High-energy radiation such as gamma rays, X-rays, and cosmic rays can cause polymer chain scission, which can lead to loss of elasticity of the material (becomes more brittle), an

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increase in cracking of mechanical failure, and colour changes due to chemical breakdown. Polymers such as PEEK, ULTEM, Kapton, PTFE (Teflon), and polyethylene-based materials are commonly affected. It is because, except for Kapton and PTFE (Teflon), all of them do not have high enough resistance against high-energy radiation. This can lead to aerospace issues such as failure of seals, gaskets, and insulation layers due to embrittlement and degradation of structural components in satellites over long missions. Feasible solutions include installing radiation shielding using metallic coatings or carbon-based additives and using radiation materials like Kapton and PTFE to minimize the consequences.

In low Earth orbit (LEO) (~200–600 km altitude), atomic oxygen (O) is highly reactive and erodes polymer surfaces by breaking molecular bonds, causing surface roughness and mass loss. This can lead to component failure over time. Some polymers that have moderate or low resistance, such as PEEK, nylon, polyesters, and polyurethanes, are commonly affected. Consequently, this can contribute to erosion of thermal blankets, insulation on satellites and spacecraft, and structural degradation of polymer-based components. Adding metallic or SiO_2 coatings, protecting against AO, or using AO-resistant polymers like Kapton are possible solutions to tackle these issues.

Table 12: Radiation effects on aerospace polymers in number format.[29]

Material	UV Resistance	Radiation Resistance (Cosmic/Gamma Rays)	Atomic Oxygen Resistance	Use in Space
PEEK	3	2 (Moderate)	2 (Moderate)	Structural spacecraft parts
ULTEM (PEI)	3	2 (Moderate)	2 (Moderate)	Satellite components, housings
Kapton (Polyimide)	5 (Excellent)	5 (High)	5 (Excellent)	Thermal insulation, space blankets
PTFE (Teflon)	4 (High)	5 (Excellent)	4 (High)	Lubricants, seals, coatings
ABS/Nylon	1 (Poor)	1 (Low)	1 (Poor)	Not recommended for space

Best Space-Resistant Polymers: Kapton & PTFE
Worst Choice for Space: ABS & Nylon (severe degradation)

4.3 Drawbacks Overview:

The properties of plastic are like a double-edged sword. Although they are lightweight and flexible, most are also susceptible to heat and cosmic radiation and have mechanical drawbacks such as brittleness.[13,14,28,29] Therefore, scientists should analyze the advantages and disadvantages of different materials, so that they can find the most appropriate materials for constructing different components of the space equipment or constructing composite materials using state-of-the-art 3D printing technologies. For instance, although Kapton (polyimide) has high resistance to cosmic radiation, it is expensive and susceptible to chemical erosion, so it should mainly be used in connectors that use fewer materials or form a composite with PEEK for constructing the surface of the rocket to save expenditure. It is also important to analyse the long-term impact (e.g., environmental and economic impact) to examine whether the drawbacks and risks of the material can be balanced by the benefits it brings. These impacts will be mentioned in the next section (5 Outlook).

5. Outlook:

5.1. Environmental Impact:

As mentioned above, rocket launching events can emit a substantial amount of CO_2 and greenhouse gases, which contribute significantly to global climate change.[2] This is mainly caused by the large amount of fuel burnt due to the heavy weight of the materials.

Therefore, using 3D printed plastic, which has a much lower density and high strength-to-weight ratio, can reduce the amount the material being used during manufacturing by structural optimisation and novel design.[30] Therefore, there will be less plastic waste produced. The launch expenditure can be reduced significantly as the rocket is lighter and less fuel is consumed, contributing to sustainability.

In the past, scientists and engineers have been seeking effective ways to reuse and recycle plastic, as it is an ordinary material in daily life, and they are non-biodegradable.[31] According to the UN official website, plastic takes around 20-500 years to degrade. Therefore, combining plastic and 3D printing with the aerospace industries can effectively reuse the plastic; this is what many companies like NASA and SpaceX are now striving for.

Compared to traditional manufacturing processes like machining or injection molding, additive manufacturing builds parts layer by layer, minimizing material waste.[32] By using only the material required to produce components, 3D printing reduces waste significantly.

This precision not only lowers raw material costs but also supports sustainable manufacturing practices in the aerospace industry.

However, 3D printed plastic can cause a series of challenges, such as microplastic production when it encounters extreme heat and radiation from the universe during ascend.[33] Microplastics can be found everywhere on Earth and even in the human body, affecting the ecosystem substantially.

Additionally, using plastic in 3D printing is intensive. This may weaken the sustainability advantage brought by minimised material waste.

5.2. Economics of In-space Manufacturing:

Table 13: Economic aspects of 3D-printed aerospace materials with quantitative data.[34,35]

Material	Cost Factors	Pros	Cons
PEEK	$270–$370/kg.[35]	High-performance → Used in critical applications	Expensive due to processing costs
ULTEM	$100–$300/kg.[34]	Cheaper than PEEK, still aerospace-grade	High processing temperature
Carbon Fiber-Reinforced Polymers	$50–$150/kg.[34]	Cost-effective for lightweight structures	Difficult to recycle
Nylon + Carbon Fiber	$50–$100/kg.[34]	Affordable alternative to pure carbon fiber	Weaker than metals
PC (Polycarbonate)	$30–$70/kg.[34]	Good durability per cost	Limited aerospace use
PLA	$20–$40/kg.[34]	Very cheap (great for prototyping)	Not aerospace-grade

From the diagram, the most cost-effective choice is carbon-fiber reinforced polymers (good strength-to-cost ratio) and ULTEM (cheaper alternative to PEEK).

Currently, space enterprises such as NASA, ESA, SpaceX, Blue Origin, and ICON (using 3D printing in lunar construction) are spearheads in using 3D printing to reduce manufacturing time and cost.[36] For instance, NASA reduced the production time from more than a year to only four months, with a 70% cost reduction. 3D printing also enabled the fuel injector's design to be reduced from 160 pieces to just two.

However, as mentioned above, plastic has several drawbacks, such as weak heat resistance. Therefore, it must be mixed with metal filament, a material source that can increase the manufacturing cost. The large amount of energy and electricity used in plastic in 3D printing can also increase the production expenditure.

5.3. Future Research Questions:

Advancement Needed & New Technologies:

Although plastic has several advantages, including durability and radiation resistance, compared to metals such as aluminium, titanium, and nickel, there are still significant disadvantages compared to its adversaries.

Plastic is less heat-resistant and more brittle compared to metal, which means that it might be vulnerable in extreme temperatures. As a result, metal composites may have to be mixed with plastic to mitigate this issue, and multi-material 3D printing technology is crucial to cope with this challenge.

The already mentioned self-assembling structures, currently being developed by NASA, are also appropriate to resolve this issue, which can further reduce cost as it does not require metal composite to be included.[22]

The material technology of carbon nanotubes is the ideal solution for this issue due to its unique lightweight, durability, and flexibility (It can even be used to construct the space elevator's tether).[1] However, it is a supernatural material (a material that should not exist with respect to the physics principle, but it does exist in nature), so mass production is still a challenge for aerospace engineers.

Potential Long-term Application:

1. In-space Construction:

The durability and radiation resistance, and the high design freedom of 3D printing make lunar and Mars settlement possible.[8] In-space 3D printing can also manufacture the required materials at the extraterrestrial construction site, making planet colonisation and interstellar immigration possible.

2. Space Elevator:

Space elevators are a sustainable transportation alternative to current rocket.[1] It mainly uses gravitational and centrifugal forces to ascend and descend. Therefore, it only consumes electricity during half of the journey (the first half of the ascent and the second half of the descent).

The key material of the space elevator is carbon nanotubes, as it is ideal for constructing the elevator's tether.[1] Although it has impeccable durability, lightweight, and flexibility, its mass production has not been achieved. 3D printing is a potential solution to resolve this issue.

With the space elevator's high velocity, large capacity, and sustainability. Humanity can deliver more resources to space or collect extraterrestrial resources back to Earth. Moreover, this innovation is the foundation of a space fortress, which may be achieved by using in-space 3D printing technology.

■ Conclusion

6.1. Answer to the Research Question & Key Findings:

This research aims to investigate the feasible ways of integrating 3D-printed plastic into current and future aerospace industries. The answer to this question is yes, but it depends on whether it is used appropriately.

The reason that 3D printing can be used in aerospace industries is that its structural optimisation and novel design, and high design freedom allow aerospace components to be manufactured with much less material, cost, and complexity, but with similar quality. Furthermore, 3D printing is sustainable.

The only concern is that current 3D printing technology usually requires a large amount of energy and electricity. To sum up, aerospace-grade plastics such as PEEK and ULTEM mainly have mechanical properties such as high corrosion resistance and durability against high-velocity collisions from space debris. Therefore, they are suitable for constructing the outer shell and frame structure of space equipment such as rockets and satellites. High-performance polymers like PEEK and ULTEM offer up to 60-80% weight savings over metals, with comparable specific strengths and vastly superior corrosion resistance and electrical insulation. However, they are typically 3-10x more expensive than current aerospace materials such as aluminum and 20-50% weaker in absolute tensile strength compared to top-tier carbon fiber composites.

These 3D-printed plastic also has low density and high strength-to-weight ratio compared to metals such as that are currently used in aerospace industries, these include alumin-

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ium, titanium, and nickel, etc, so that a smaller amount of material can be used to achieve lightweight and reduced cost. Plastics such as Kapton (polyimide) and PTFE (Teflon) have high resistance to cosmic radiation. Therefore, they can be used to construct the insulating layer of a spacecraft. However, apart from PEEK (very expensive, highly resistant to heat, can be used to construct engines and fuel tanks, PTFE is a good thermal insulator, but it has a relatively lower melting point than PEEK. Most 3D-printed plastics are susceptible to extreme heat.

Some plastics, such as PLA, are also brittle. Consequently, metal filaments or other material technologies such as self-healing material and carbon nanotubes must be applied to achieve security.

Therefore, for current aerospace industries, metal is still not fully replaceable by 3D-printed plastic, and their corrosion resistance and strength make them still the main material to construct spacecraft wings, frame structure, and rocket engines. Plastics such as PEEK can be used to construct rocket engines and fuel tanks because of their high thermal resistance. PTFE can be used for connectors as it is thermally stable and flexible, on the condition that it is combined with materials with higher melting points, such as PEEK. Also, composites such as CFRP and GFRP can be used to construct frame structures and insulation layers since they are durable, lightweight, and resistant to cosmic radiation. Individuals and companies worldwide must collaborate and merge the fields with which they are familiar with, respectively.

3D-printed plastic is not only a technological breakthrough that can assist current aerospace industries, but can also provide insight and lay the foundation to more futuristic space technologies, such as in-space construction and space elevators, guiding humanity to the deeper cosmos.

The new generation will have an unprecedented opportunity to influence and accelerate the contemporary space race: not as geopolitical adversaries but in advancing human potential.

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