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3D-Printed Satellite Components for Rapid Deployment

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Abstract: - Microsatellites for space applications have been the subject of significant research in recent years. They are applicable for many imaging and inspection purposes in space, are cost-effective, and may be rapidly created. A rapidly expanding category of technology is 3D printing, capable of fabricating a wide array of forms from various polymers, metals, and other materials. The convergence between both strategies, however, remains minimal. This overview presents initial methodologies for 3D printing microsatellites and analogous space applications, detailing material requirements and characteristics of standard 3D printing materials, thereby facilitating recommendations for future experiments and highlighting pertinent challenges to consider.

Keywords: microsatellites; 3D printing, polymer; metal; spacecraft; temperature; irradiation

1. INTRODUCTION

Microsatellites have been extensively studied via experimentation and modeling in recent years, particularly because to their rapid and cost-effective construction. Common uses of these microsatellites include earth observation, satellite servicing, on-orbit inspection, and space exploration, necessitating advanced technology for rendezvous control and navigation.

A significant difficulty for microsatellites and other spacecraft pertains to the materials suitable for their production. Heat shields can facilitate the return of the microsatellite together with its equipment to Earth [4]. Conversely, throughout their operational duration, the instruments within the microsatellite must be maintained at standard electronic temperatures, approximately at room temperature, and during non-operational periods, within a temperature range of −20 to 50 °C [4], while the exterior of the microsatellite may encounter significantly fluctuating temperatures. In addition to these robust temperature specifications, solar or cosmic radiation may be relevant depending on the application.

The second emergent technology considered here is 3D printing, commonly referred to as fast prototyping. These phrases denote a wide array of varied strategies used for several purposes [5]. Fused deposition modeling (FDM) is characteristic of cost-effective desktop printers, enabling the printing of various polymers that may be infused with other materials [6]. This method may also be used to fabricate composites of 3D printed polymers and textile fabrics, hence enhancing mechanical qualities and manufacturing speed relative to solely 3D printed items [7–10].

Stereolithography (SLA) is an established process mostly used for the fabrication of polymer or ceramic items and may also be integrated with other materials, including textile textiles.

These and other 3D printing methodologies may fabricate items from a diverse array of polymers, metals, ceramics, and composites.

Initially, we provide a summary of current typical uses for microsatellites, followed by the requisite materials. An overview of current research using 3D printing for various components of microsatellites is presented.

2. MICROSATELLITE APPLICATIONS

Microsatellites are often characterized by a mass of 10–100 kg, nanosatellites by a mass of 1–10 kg, and minisatellites by a mass of 100–500 kg. The microsatellites are deployed by a carrier rocket and detached upon reaching the designated orbit, often via pyrotechnics, which requires shock-resistant installation of the electronics. Microsatellites may be used for several uses, including communication, scientific research, military purposes, and earth observation [13]. Recently, Gao et al. utilized satellite observations for a within-season emergence methodology to delineate crop green-up days by employing high spatial resolution data of 10 m and a temporal resolution of 2-day revisits, obtained from the Vegetation and Environment monitoring New MicroSatellite (VENμS) for experimental fields in Maryland during the 2019 growth season. The data were compared with those

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obtained from Operational Sentinel-2 (10 m resolution, 5-day return) and normal HLS (30 m resolution, 3–4-day revisit) to evaluate the efficacy of the within-season methodology across varying temporal and geographic resolutions [15]. Typically, observations of agricultural development stages with satellite time series are significant, while the use of pure satellite data is limited. They need various image processing procedures to provide enough data [16–18] and must be assessed for a minimum of one season, often over extended periods, to prevent any misinterpretations of the pictures [19–21]. Optimally, satellite observations are integrated with terrestrial assessments [22–24].

Optical inspections of the Earth may be used for urban planning, precision agriculture, or forestry, as seen in Figure 1, provided that undesirable temperature fluctuations of the CMOS sensor and analogous issues are mitigated. Investigations of global navigation satellite systems in the radio frequency range may be used to assess ocean surface wind speed.

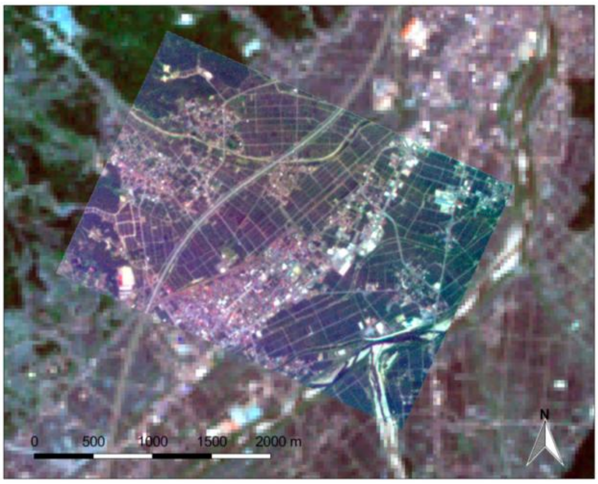

Figure 1. True-color image of the RISING-2 high-precision telescope, overlaying a common composite image of the Landsat 7 Enhanced Thematic Mapper Plus, both taken in 2014 [26].

Another use of microsatellites in low-Earth orbits is the examination of gravity atmospheric waves, specifically large-scale air pressure fluctuations between the mesosphere and the mesopause/thermosphere, using the "Mesospheric Airglow/Aerosol Tomography Spectroscopy" sensor [29,30]. The Cyclone Global Navigation Satellite System (CYGNSS) mission examines tropical cyclones in connection to ocean surface conditions, air thermodynamics, convective dynamics, and radiation. The microsatellite MicroCarb employs an infrared spectrometer to monitor and analyze CO2 surface fluxes between carbon sources and sinks [32]. In very-low Earth orbits, specifically at altitudes of 250–500 km, microsatellites are deployed for communication and Earth observation. This configuration facilitates the reduction of size and power consumption of optical and radar instruments; however, it also requires increased power to counteract atmospheric drag forces. Diverse scientific studies, particularly in microgravity, may be conducted using CubeSats, compact cubic units often deployed on the International Space Station (ISS) or as auxiliary payloads on launch vehicles. By 2020, over 1,000 CubeSats had been sent into low Earth orbit, with several trips to the Moon or Mars in the planning stages. It is important to note that interplanetary trips and de-orbiting missions of space junk need specialized propulsion technology in addition to material requirements [37]. A 2017 study classified CubeSat missions into primary objectives, including Earth science, deep space exploration, heliophysics, astrophysics, spaceborne laboratories, and technology demonstration, demonstrating that these specialized microsatellites are applicable across a wide range of small satellite applications [38].

Magnetospheric investigations may be conducted with one primary microsatellite and many subordinate nanosatellites [39,40]. In contrast to Earth observations typically conducted from low-Earth orbits, this approach employs extremely elliptical orbits, necessitating distinct features for the materials used.

Clusters of self-organizing connectable microsatellites may advance to execute increasingly complex functions, such as maintaining spacecraft cohesion, constructing extensive array structures for space debris defense, and temporarily substituting broken components.

This brief summary of current research indicates that several uses of microsatellites are feasible, requiring an extensive array of material qualities that will be assessed in the subsequent section.

3. MATERIAL REQUIREMENTS OF MICROSATELLITES

In low Earth orbit (LEO, about 200–700 km), atomic oxygen and ionizing radiation provide significant challenges, alongside ultrahigh vacuum, plasma, and hypervelocity collisions from micrometeoroids and space debris. In very low Earth orbits (VLEO, about 250–500 km), the flow of atomic oxygen is significantly increased [33,44]. Conversely, in a geosynchronous Earth orbit (~36,000 km), charged particles and ionizing radiation induce the most significant material deterioration [45,46].

Research indicated significant deterioration in the mechanical integrity and a reduction in thickness of fluorinated ethylene propylene films used in the insulating blanket of the Hubble Space Telescope, attributable to a combination of atomic oxygen, solar radiation, and thermal cycling [47]. Thermal cycling in Low Earth Orbit typically spans from around −100 to 100 °C [48].

Grossman et al. provide a detailed examination of the impact of the LEO environment on polymers. Solar vacuum ultraviolet (VUV) exposure may deteriorate the thermo-optical and mechanical characteristics of polymers. Ionizing radiation adversely affects electronic components, solar cells, and polymers. Vacuum induces outgassing of polymers, resulting in surface contamination and a decline in mechanical characteristics [43]. In their review, they delineate the following categories of polymers [43]: Fluoropolymers, like the previously described fluorinated ethylene propylene, exhibit greater resistance to atomic oxygen but increased sensitivity to ultraviolet light. Polymers containing C–H bonds did not experience mass loss from VUV irradiation, but those without C–H bonds did. Silicones exhibit much reduced erosion from atomic oxygen, although are prone to outgassing. Conversely, ionizing radiation or VUV may induce cross-linking, therefore immobilizing outgassing pollutants. Composites are often used, although particularly susceptible to disintegration. Grossman et al. propose the use of a silicone-based protective layer to safeguard against atomic oxygen.

Metals, like carbon fibers, are also susceptible to corrosion from atomic oxygen [49]. In his review work, Reddy indicated that atomic oxygen degraded graphite/epoxy composites. Metallized polymer films and organic paints, used for thermal regulation, are often impacted by atomic oxygen. Conversely, metal or metal-oxide coatings may be used for oxygen protection [50].

Furthermore, it is essential to note that both the material and the shape of 3D printed components significantly influence their mechanical, thermal, and other qualities. Prior research on several groups indicates that FDM printed components have very low surface roughness but significant waviness, while parts manufactured using selective laser melting, selective laser sintering, or powder bed fusion show distinct surface characteristics [51–54]. Since any deviations from a completely level surface diminish the mechanical characteristics of an item [55], it may be essential to remove the surface roughness and waviness by chemical, thermal or mechanical after-treatments. Conversely, the majority of 3D printed products have voids as a result of their manufacturing procedures [56–60]. If such holes cannot be entirely eliminated, they must also be considered when assessing the mechanical and thermal qualities of 3D printed components for spacecraft.

This concise review illustrates the challenges anticipated with the use of 3D printing for the fabrication of microsatellite components. Nonetheless, recent work provides first insights into the potential outcomes of integrating these two new technologies.

4. 3D PRINTING MATERIALS USABLE FOR MICROSATELLITES

3D printing for space applications is commonplace, since many things used in the space industry are custom-fabricated, in addition to the potential for bulk reduction and the creation of intricate components. The specific use for several microsatellite components, however, has not often been documented so far. Recently, Li et al. examined permalloy magnetic shields for fiber optic gyroscopes in spacecraft, fabricated using selective laser melting (SLM) [62]. Selective Laser Melting (SLM) is a laser-based 3D printing technique characterized by great precision, enabling the fabrication of metal objects. Permalloy, a material suitable for selective laser melting (SLM), has low coercivity and high permeability, making it advantageous for applications in motors, power transformers, and magnetic shielding. Li et al. developed lightweight magnetic shields by SLM printing, achieving comparable saturation magnetization and coercive fields to those obtained via traditional processing techniques, therefore indicating the potential of this technique for magnetic shields in tiny spacecraft [62].

Zhou et al. [63] discuss an application of 3D printed phase-change materials. They used Selective Laser Melting (SLM) of AlSi10Mg to fabricate a lightweight thermal controller for spacecraft, weighing less than fifty percent of conventional designs.

Ababneh et al. examined the feasibility of 3D printing lightweight heat pipes for the thermal regulation of solid-state power amplifiers. Solid-state amplifiers provide several benefits over traveling wave tube amplifiers, particularly when using GaN as a semiconductor, enabling a substantial reduction in both size and energy consumption relative to traveling wave tube amplifiers. Nonetheless, the heat flux dissipation of contemporary thermal management systems is about two orders of magnitude insufficient. This experiment included the 3D printing of a titanium heat pipe using direct metal laser sintering, demonstrating adequate heat transfer capabilities and the potential for substantial reductions in radiator size and weight [64].

Guo et al. used selective laser melting (SLM) to fabricate molybdenum and titanium ion optics, specifically ion engine grids, for electric thrusters in spacecraft. Following the management of the 3D printing process for molybdenum, the additively made extraction system demonstrated normal operation throughout a long-term test and shown no symptoms of deterioration thereafter (Figure 2) [65].

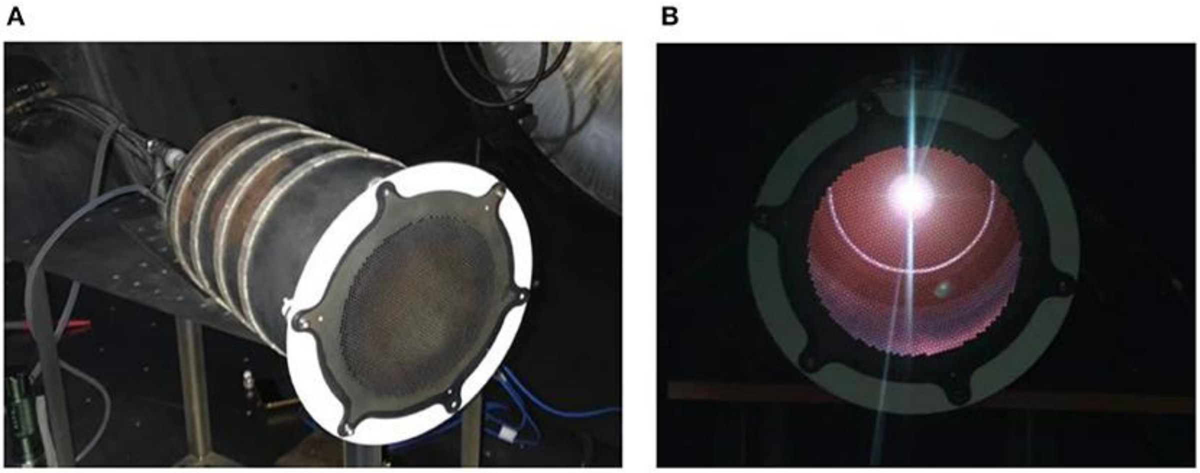

Figure 2. (a) Ion source with screen grid assembly, (b) ion source ignition [65].

Harmansa et al. researched a propulsion system using the electrolysis of water. The system included a water reservoir, an electrolysis apparatus with gas storage facilities, and a chemical thruster. In the water storage subsystem, 3D-printed propellant management devices were included as a proof of concept [66].

In contrast to the previously described applications intended for use inside a satellite or components of propulsion systems, Abdullah et al. focused on the heat shield, a component of a satellite that endures the most intense thermal stress [67]. A composite was 3D printed using carbon fiber and polyether ether ketone (PEEK), a material suitable for high-temperature applications. A laser-based direct energy deposition 3D printer was used to directly produce a carbon fiber/PEEK composite, despite PEEK being printable on specialized FDM printers (Figure 3). The components were subjected to mechanical and arc heating evaluations in an arc heated wind tunnel, under ultraviolet irradiation, and during thermal cycles ranging from −70 to 140 °C. This novel 3D printed composite material exhibited little susceptibility to temperature cycles and UV irradiation, shown qualities comparable to traditionally manufactured carbon fiber/PEEK heat shields, and was therefore proposed as a new heat shield material for re-entry flights.

CONCLUSION

This brief summary demonstrates that 3D printing has just begun to reveal its potential in the expansive domain of spacecraft, particularly in microsatellites. Although contemporary 3D printing is frequently perceived as a rudimentary technology that facilitates the production of items using inexpensive FDM printers, the examples presented here demonstrate that 3D printed objects do not inherently exhibit diminished material properties relative to alternative manufacturing methods, while simultaneously enabling the creation of novel, intricate geometries.

It is important to note that while several material-related concerns have to be investigated, 3D printing is already beginning to establish its role in the commercial manufacture of micro-satellites, rockets, and other aerospace components. The German firm EOS GmbH, for instance, provides 3D printing of numerous components for satellites and rockets using many 3D printing processes. Rocket Lab use 3D printing to manufacture rocket engines for NASA [78]. SpaceX and Blue Origin use 3D-printed components in valves and engines for their spacecraft. The direct 3D printing of solar panel supports in space is anticipated in the near future [81]. These examples, among several others transitioning from research to commercial use, highlight the novel prospects presented by 3D printing for spacecraft, with the ongoing need for researches into new materials with improved mechanical and thermal qualities.

We anticipate that this mini-review elucidates contemporary obstacles and opportunities, encouraging academics focused on microsatellites and various 3D printing technologies to collaborate, therefore facilitating the development of next-generation debris-compliant microsatellites.

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