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Advanced Materials for Space Exploration

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ABSTRACT

This paper explores the critical role of advanced materials in space exploration, emphasizing their necessity for sustaining human presence in space and ensuring the success of various space missions. It begins with an overview of space exploration history, followed by an examination of the challenges faced by traditional materials in space environments. The discussion then delves into cutting-edge materials such as nanomaterials and metamaterials, highlighting their unique properties and potential applications in spacecraft and habitats. Future prospects and trends in materials development, particularly in sustainability and recyclability, are also addressed, underscoring the importance of innovative material science in the continued expansion of human activities in space.

Keywords: Space exploration, Advanced materials, Nanomaterials, Metamaterials and Spacecraft.

INTRODUCTION

Space exploration is an important aspect of the development of science and technology on Earth and in the material universe. We need to develop a variety of advanced materials to deal with different environments and develop corresponding functional devices and systems [1]. In space, spacecraft and equipment are all flying in the universe. The temperature is affected by radiation heating, vacuum, and forced convection of gas, so it is difficult to maintain the temperature balance of spacecraft and equipment. The working speed of spacecraft can reach 7.8 km per second, the working speed of a space telescope can reach 14.4 km per second, the working speed of an interplanetary probe, and the escape speed of the shuttle system can reach 16.8 km per second Advanced materials play a crucial role in the development of spacecraft that can withstand these extreme speeds and conditions [2, 3]. Space fuel cells are divided into atmospheric fuel cells and non-atmospheric fuel cells by oxygen. The working environment of atmospheric fuel cells is rich in oxygen, so they can use the oxygen of the working environment instead of carrying their own oxygen. In space, manned spacecraft generally use non-atmospheric fuel cells because non-atmospheric fuel cells have some advantages that atmospheric fuel cells do not have [4]. To produce power, both fuel cells require hydrogen and oxygen, but the fuel cell in space uses its own oxygen and hydrogen to produce power. In a non-atmospheric space environment, the direct power consumption of the fuel cell is approximately 90 square amps at the initial peak. The maximum discharge current of our experiment is restricted to 50 square amps, and the maximum current is 20 amps per circuit. We can use 3 non-atmospheric hydrogen fuel cells to increase the power given the total required power of the non-atmospheric fuel cell power management system. The voltage difference is 300 W [5].

HISTORICAL OVERVIEW OF SPACE EXPLORATION

This chapter introduces the reader to the different materials and technology, initiatives, and activities in place for human spacefaring. In the following, some history about exploration is provided. Projected timelines regarding specific developments and trade studies in this work are not part of this initial work. For many centuries, artificial objects were sent into the sky. These objects were simple and not directed by any form of propulsion. They were used for celebrations and educational purposes. True rockets, using combustion for producing thrust, were developed only much later. These early rockets were mostly used for firepower purposes. If we look at space exploration from the point that objects, riding on rockets, are sent into space, we note that the history of space is very short [6]. As a historical note, the Russian space dog Laika became the first animal in space, orbiting the Earth once before succumbing to overheating in

1957. In 1959, the first missions to the Moon were launched. These missions were part of the Russian Luna program. In 1961, Russian astronaut Yuri Gagarin was the first human to orbit the Earth. In 1969, America completed the first human landing on the moon. The Lunar Module landed on the Moon's surface on July 20, 1969. Flash-forward to 2020, and Artemis I will be the first uncrewed test flight of the Mission 2 (M2) spacecraft module on NASA's Space Launch System (SLS) rocket. Future M2 flights will carry astronauts on missions to the Moon. For timely and safe human spaceflight to succeed, it is expected that materials research and qualification will set the mastery required to develop the minimum set of materials, ensuring that humans become the critical element [7, 8].

IMPORTANCE OF ADVANCED MATERIALS IN SPACE EXPLORATION

One of the keys to successful space exploration is the development of strong, lightweight materials that can stand up to the harsh environments in space. Any long-term human presence in space needs materials that can withstand the rigors of launch, closer to-home orbits, and interplanetary travel. New materials and fabrication methods are needed to protect structures from debris and solar radiation that can cause premature aging and metal fatigue. Materials that repel water or contaminants and help to maintain a surface free of materials that clog equipment are needed for long-term missions or habitats. Techniques for recycling materials will also be needed. The use of additive manufacturing has already provided a new toolbox of materials that allows for the design of new multilayered materials to provide better environmental protection or controllability. A large effort, both currently and planned, for space materials is on structures and radiation protection for habitats and space exploration vehicles [9]. The use of lightweight, high-strength materials also has a positive impact for reducing the costs of launching vehicles into space. Many aerospace companies are developing components with super aluminum alloys that are lighter and more ductile than titanium but high-grade. The specific requirements for these light materials include having higher temperature ranges, damage tolerance, thermal conductivity, resistance to embrittlement, and the ability to prevent corrosion from water. The physical equipment including protective suits and weather shielding techniques are not the only structures affected. The building of habitats and bases on the Moon and Mars and the equipment needed for their construction will have many of the same underlying material science requirements to protect and guide our designs. The development of more robust materials and building constructs will help to support additional domestic and international demands for space activities. The resistance to dust adhesion, the lack of magnetic materials, and initial launch of equipment and other materials into space, all require specialized materials and new technologies to develop use of in-situ methods for resource utilization [10, 11].

CHALLENGES OF TRADITIONAL MATERIALS IN SPACE

Introduction Materials, the prime building blocks of everything that we see around ourselves, undergo stringent environments during their service lives, most importantly in aerospace, defense, and nuclear applications. Advances in extraterrestrial surface explorations in recent years and anticipated longer time spans in deep space missions have paved the way for investigating newer, sophisticated materials that would have higher thermal stabilities, wear resistance, hardness, oxidation resistance, and on-the-fly malleability. In addition, significant research in hypersonic flight vehicles aims to make travel faster, regularly between hemispheres by cutting down travel durations to hours of scheduled flights. It is clear that the materials that are of interest while discussing space environment must be simulated by appropriate methods and characterized precisely [12]. Challenges of Traditional Materials in Outer Space of all the things that an exposed material undergoes anywhere in the lifetime, the greatest and harshest environments are to be seen in outer space. Materials in low Earth orbits see the broad stern belts, solar winds, temperatures in the range of -250 °C to 200 °C, and yet again experience the harsh radiation environment beyond the Jeffery-Hamel line. In contrast, the full severity of the aforementioned environments is experienced by materials carrying transient lands and/or exploring the outer surfaces of Venus or Mars, ranging from temperatures above 500 °C in Venus to a chilling -225 °C of winters in Mars. While none of the modern-day materials are selectively tailored to exceed the attack of all the stated environments, they still comprehend new challenges that need to be tackled to be useful in such applications. Materials, while exposed, are victims of high-energy particles to ionizing or displacement damage which sets in motion long-term events. Resilient to thermal cycling, microstructural erosion, and volumetric swelling continue over a protracted period of time and can cause severe detriment to the shocked material. Consequently, there is a higher likelihood of sudden catastrophic failure; a daunting prospect within space applications where it is often impossible to repair or retrieve failed components or systems [13].

CUTTING-EDGE MATERIALS FOR SPACE APPLICATIONS

The materials and structures used in current and future space missions must be multifunctional, smart, and even possess self-healing characteristics. Thus, their development lies at the very heart of any future colonization or extended exploration of the solar system and beyond. The following "big three" classes of cutting-edge materials are deemed promising for potential applications in the field of space exploration [14]. To address the various technical challenges faced in space exploration and technologies, researchers are adopting a materials science and engineering approach to offer innovative solutions that will revolutionize the field. Some of these solutions may originate from research areas that are still in their infancy or have not yet been extensively studied. Nevertheless, the present feature article presents advanced and forward-looking ideas that can be adopted and explored in the near future. In this article, we narrow our attention to only three classes of cutting-edge materials that have recently, or may soon, revolutionize space technology [15]. One such class includes those featured in the following articles. Optical metamaterials and metasurfaces reach their optical performance by virtue of their subwavelength structures, which are both anisotropic, in that they operate differently along different spatial directions, and contain shape parameters that are more advanced than those found in other materials. They may find immediate applicability in novel optical materials for space and deorbiting thin-film sails at the tensile skin relevant to the paper. Plasma metamaterials that are being explored for future quantum sensors are also of relevance to potential space-based gravitational wave observatories [16].

NANOMATERIALS AND NANOTECHNOLOGY IN SPACE

Potential applications of nanomaterials in space are mainly related to the functional surfaces of structural materials. Nanomaterials can increase energy conversion efficiencies; for instance, organic and inorganic nanophase materials can enhance thermomechanical and thermoelectric efficiencies. In addition, nanomaterials can improve tribological properties, decrease surface optical properties, and improve thermal performance. Nanomaterials can also be employed as propellants and enhance the performance of solid rockets and spacecraft engines [17]. The study of the surface phenomena of minerals under low (or micro-) gravity conditions demonstrates the importance of shape, surface, and size effects in nanomaterials. The development of organized nanostructures and organization in thin films for space mirrors, thermal controls, antennas, and sensors will pave the way for strong reactive materials, scavengers, protectants, accelerators, or components of detection devices in thin layer shapes. Furthermore, basic physical phenomena—such as van der Waals forces among well-defined nanometer-thin layers, which deviate with bond lines or grain boundaries on the nanometer scale—are extremely sensitive and can cause strong environmental damage if the layer strength is weakened by substructural morphologies. These phenomena can only be tested in outer space. The frequently stated shortage of space is the only limitation to future nano- or micro-investigations [18].

FUTURE PROSPECTS AND TRENDS IN ADVANCED SPACE MATERIALS

Over the years, enormous technological progress has been made in the field of advanced materials, both in terms of experimentation and theory. Although the past has been devoted to the new invention of space materials used for different spacecraft, the current trend covers basic studies of more effectively used known materials, especially those drawn from polymeric and metal classes. The current trend also includes fundamental and experimental studies of carbon and other materials based on fullerene C60, bringing in new prospects for utilization. The outcome of these basic studies could usher in scientific and technological dividends with commercially benign ways that have been little appreciated to date. It is anticipated that the network of institutions presently undertaking this or allied work will challenge prevailing opinion. The elite of the world has access to previously undisclosed targets of a smorgasbord of funding bodies with an eventual objective of reforming the international community towards the development of stable and advanced materials for commercial employment in space by any and all spacefaring nations, irrespective of development status [19]. In the not-too-distant future, rendering plastic and electronic materials stable and easy to use for space utilization is expected. The development of advanced materials is also expected to facilitate new kinds of chemical propulsion, both for manned and unmanned spacecraft, so that they may become a meaningful cornerstone of commercial space operations globally. It is anticipated that materials development in what may be termed "The Tenneer's Decade" will have an international role through the ROCETS (Rapid Online Collective Klique of Engineers Triggered for Space) initiative. We are on the threshold of a revolution in the process of advanced materials, brought about by new wit and new tools [20].

SUSTAINABLE AND RECYCLABLE MATERIALS IN SPACE

The current tendency in space mission conception is looking for sustainable habits, promoting a paradigm of zero-waste economy that limits environmental pollution. These missions are conceived to last for a couple of years in the worst case and should theoretically generate a small amount of waste that could be left in place, abandoned for the future, or burned upon return to Earth. This limited scope enables leaving the world open to disposal of the accidentally created new hazardous compounds and microorganisms into the cosmos away from our eyes. No doubt that much more care for the environment might be dispensed in view of the short time frame of such confinement. Future very long-duration missions impose a more sustainable behavior, directly or indirectly, supported in all aspects, e.g., life support, food, water, etc., for the well-being of the astronauts and the reduction of the team distress. Recyclability is an irreversible field name, and different definitions of this concept may be found in the literature. But, in this work, we refer to the ability to recycle a product or a component of that product to be reused as material to cut the raw material demand and therefore resources and energy, with the related economies and GHG emissions. The above considered, in the specific framework of the feasibility of the selection of innovative materials for structures in space missions within a closed environment, the materials have to be selected taking into account their behavior in terms not only of resistance, weight, and thermal insulating properties, but also their recyclability, which should represent an added value [21]. Space materials are the foundation of space equipment such as manned spacecraft and extravehicular space suits. These materials are also used to provide power for space missions and deliver payloads to space, among other things. It is undisputed that such advanced space materials have been widely used and are becoming more and more important. They are vital for advanced space exploration [1]. With respect to the application prospect of space materials, Martin Zwig observes that "now and in the future our ability to travel and explore space will continue to depend on how well we can harness and exploit the extraordinary potential of advanced materials." Nowadays, composite materials, intermetallic materials, and solid propulsion materials are still the main hotspots for studying. Some institutions and universities have also studied some advanced materials with space applications, which have laid an important and good foundation for advanced space exploration. However, due to the particularity of the space environment, the advanced materials used need to deal with many complex space environments and multiple threats, such as high vacuum, large temperature differences, high-energy particles, and solar ultraviolet radiation, etc. Therefore, the application and landing of advanced materials in space still face many obstacles and challenges. As a result, from the perspective of advanced space materials, the paper describes the importance, development trend, and technical level of advanced space materials in detail. In fact, most advanced materials have been increasingly used in space fields based on the continuously increased demand for new material performance. The weight of advanced materials used by Goddard Space Flight Center during the years 1959-1962 was 6% of all the materials in weight, and it increased up to 54%. With respect to propulsion and power in deep space, the electric propulsion of life is almost eternal. After the last limited fuel is over, even though the orbit of geostationary satellites will decay only a little every year, they will still serve as space debris and attract more space debris. In such spaces, solar energy can be changed to an ion beam to offer necessary traveling impulse. Not only lifetime and explosion-proof capacity but also extremely high performance is needed for an electric thruster, whose part materials are called electric thrusting materials [22]. In addition, with respect to the structural materials, advanced high-temperature structural materials can be used as an important application, such as part of engines of the next generation of spacecraft, especially those energy-saving, environmentally friendly commercial spacecraft. Different space environments need different kinds of electric thruster structural materials, but with two common characteristics: high melting point and poor diffusion [23].

CONCLUSION

Advanced materials are indispensable for the future of space exploration. Their development and application address the multifaceted challenges posed by the harsh space environment, from extreme temperatures to radiation exposure. Innovations in materials science, such as nanotechnology and metamaterials, offer promising solutions for enhancing the durability, functionality, and sustainability of spacecraft and habitats. As space missions become more ambitious, the continuous evolution of materials will be vital in overcoming existing limitations and ensuring the safety and success of human endeavors beyond Earth. The pursuit of sustainable and recyclable materials further aligns space exploration with broader environmental and economic goals, paving the way for long-term human presence in space.

REFERENCES

1. Afshinnekoo E, Scott RT, MacKay MJ, Pariset E, Cekanaviciute E, Barker R, Gilroy S, Hassane D, Smith SM, Zwart SR, Nelman-Gonzalez M. Fundamental biological features of spaceflight: advancing the field to enable deep-space exploration. Cell. 2020 Nov 25;183(5):1162-84. cell.com

2. Ji JH, Li HT, Zhang JB, Fang L, Li D, Wang S, Cao Y, Deng L, Li BQ, Xian H, Gao XD. CHES: a space-borne astrometric mission for the detection of habitable planets of the nearby solar-type stars. Research in Astronomy and Astrophysics. 2022 Jul 8;22(7):072003. [PDF]
3. Wu J, Xu Y, Bai Q. Introduction to space science. 2021. [HTML]
4. Liu J, Yuan B, Yang Z, Qiu H. Population state-driven surrogate-assisted differential evolution for expensive constrained optimization problems with mixed-integer variables. Complex & Intelligent Systems. 2024. springer.com
5. De Sá MH, Pinto A, Oliveira VB. Passive direct methanol fuel cells as a sustainable alternative to batteries in hearing aid devices–An overview. International Journal of Hydrogen Energy. 2022. sciencedirect.com
6. Pregowska A, Masztalerz K, Garlińska M, Osial M. A worldwide journey through distance education—from the post office to virtual, augmented and mixed realities, and education during the COVID-19 pandemic. Education Sciences. 2021. mdpi.com
7. Menzio MR. The Secrets of Soviet Cosmonauts. 2022. [HTML]
8. Capaccioli M. Dog's Heart. Red Moon: The Soviet Conquest of Space. 2024. [HTML]
9. Naito M, Kodaira S, Ogawara R, Tobita K, Someya Y, Kusumoto T, Kusano H, Kitamura H, Koike M, Uchihori Y, Yamanaka M. Investigation of shielding material properties for effective space radiation protection. Life sciences in space research. 2020 Aug 1;26:69-76. sciencedirect.com
10. Gialanella S, Malandruccolo A. Aerospace alloys. 2020. unitn.it
11. Bai J, Yang Y, Wen C, Chen J, Zhou G, Jiang B, Peng X, Pan F. Applications of magnesium alloys for aerospace: A review. Journal of Magnesium and Alloys. 2023 Nov 4. sciencedirect.com
12. Kalapodis N, Kampas G, Ktenidou OJ. A review towards the design of extraterrestrial structures: From regolith to human outposts. Acta Astronautica. 2020. sciencedirect.com
13. Zhang X, Du B, Hu P, Cheng Y, Han J. Thermal response, oxidation and ablation of ultra–high temperature ceramics, C/SiC, C/C, graphite and graphite–ceramics. Journal of Materials Science & Technology. 2022 Mar 10;102:137-58. [HTML]
14. Khatib M, Zohar O, Haick H. Self‐ healing soft sensors: from material design to implementation. Advanced Materials. 2021. researchgate.net
15. Zhong S, Zhang K, Bagheri M, Burken JG, Gu A, Li B, Ma X, Marrone BL, Ren ZJ, Schrier J, Shi W. Machine learning: new ideas and tools in environmental science and engineering. Environmental science & technology. 2021 Aug 17;55(19):12741-54. nsf.gov
16. Alvarez‐ Fernandez A, Cummins C, Saba M, Steiner U, Fleury G, Ponsinet V, Guldin S. Block copolymer directed metamaterials and metasurfaces for novel optical devices. Advanced Optical Materials. 2021 Aug;9(16):2100175. wiley.com
17. Kim A, Kumar P, Annamalai PK, Patel R. Recent advances in the nanomaterials, design, fabrication approaches of thermoelectric nanogenerators for various applications. Advanced Materials Interfaces. 2022 Dec;9(35):2201659. uq.edu.au
18. Esfandyari H, Sarmadivaleh M, Esmaeilzadeh F, Ali M, Iglauer S, Keshavarz A. Experimental evaluation of rock mineralogy on hydrogen-wettability: Implications for hydrogen geo-storage. Journal of Energy Storage. 2022 Aug 1;52:104866. [HTML]
19. Khan K, Tareen AK, Aslam M, Wang R, Zhang Y, Mahmood A, Ouyang Z, Zhang H, Guo Z. Recent developments in emerging two-dimensional materials and their applications. Journal of Materials Chemistry C. 2020;8(2):387-440. academia.edu
20. Levchenko I, Xu S, Mazouffre S, Lev D, Pedrini D, Goebel D, Garrigues L, Taccogna F, Bazaka K. Perspectives, frontiers, and new horizons for plasma-based space electric propulsion. Physics of Plasmas. 2020 Feb 1;27(2). aip.org
21. Maiwald V, Schubert D, Quantius D, Zabel P. From space back to Earth: supporting sustainable development with spaceflight technologies. Sustainable Earth. 2021. springer.com
22. O'Connor A, Park C, Baciak JE, Manuel MV. Mitigating space radiation using magnesium (-lithium) and boron carbide composites. Acta Astronautica. 2024. sciencedirect.com
23. Sciti D, Vinci A, Zoli L, Galizia P, Failla S, Mungiguerra S, Di Martino GD, Cecere A, Savino R. Propulsion tests on ultra-high-temperature ceramic matrix composites for reusable rocket nozzles. Journal of Advanced Ceramics. 2023 Jul 1;12(7). [HTML]

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