Functional Polymers and Composites for Zero Gravity

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Abstract The current chapter focuses on the functional polymer and composite materials used for zero gravity applications. It discusses the various structures that are used in zero gravity (zero-G) and the material requirements for these structures. A structure in zero-G experiences harsh environmental conditions including the damaging effects of high vacuum, atomic oxygen (ATOX), radiations (ultraviolet and ionizing radiation), micrometeorites (i.e., space debris), and thermal cycling. The commonly used materials for zero gravity include polymers for thermal blankets or electronic components, adhesives, polymer aerogels, shape memory polymers, fiber reinforced composite materials, fiber metal laminates, protective coatings against atomic oxygen exposure and lunar dust adhesion, etc. All these materials have been detailed in this chapter and concluded with future trends in the domain.

Keywords Zero-G · Shape memory polymers · Fiber reinforced composites · Aerogels · Testing · Surface engineering

1 What Is Zero Gravity?

The term zero gravity is used for the state or condition when no apparent force of gravity is acting on a body and is abbreviated as zero-G. As the distance of any object from the center of earth increases, the gravitational force acting on it decreases. Newtonian mechanics defines the weight of a body as the force exerted on it due to gravitational pull. Therefore, the situation in which no gravitational forces are acting on a body is also called a state of weightlessness. Bodies undergoing free fall and

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those in orbit experience this situation. For example, manmade satellites in orbit around the earth experience zero gravity when they are on board.

1.1 Systems Used in Zero Gravity

The three main components of every space program are the satellite, the launch vehicle, and the space center. A satellite is the most common manmade system used in zero gravity, orbiting around Earth or any other body in space [1]. The very first satellite (Sputnik) was launched into space by the Soviet Union in 1957. Since then, almost 9000 satellites have been launched by more than 40 countries. The satellites provide a birds-eye view of the earth, allowing us to see large areas and collect more data at one time, as compared to terrestrial instruments. Therefore, satellites were initially used for military and defense purposes. However, they are being used widely for communication (television, telephone, etc.), navigation, weather and climate monitoring, space science, etc. [2].

The increased dependency on satellites has led to the exponential growth of this industry. The trend has moved toward smaller satellites, owing to their compact size, reduced cost, and development time. An additional benefit is the reduced launch costs and elimination of expensive propulsion systems. These small satellites are usually in Low Earth Orbit (LEO), with an altitude range from 250 to 1000 miles (not more than about one-third of the radius of Earth). Satellites in LEO can also be effectively used for satellite communications. Global communications have become more robust with LEO as signal time delays are of the order of only 5–10 ms, and it takes 90 min to orbit [3].

There are 2,666 active satellites in orbit, 1,918 of which are in low Earth orbit (LEO), as of April 2020 statistics on active satellites in space. The global small satellite market worth was 3.22 billion USD in 2020 and is projected to grow at a cumulative annual growth rate (CAGR) of 16.4% to reach 13.71 billion USD by 2030 [4]. Other systems used in zero-G include spacecraft destined to explore the Solar System, e.g., those used for lunar probes, planetary probes (Mars, Mercury, Jupiter, etc.), solar observation missions, space probes, etc. However, the focus of this chapter is on the zero-G systems in LEO, i.e., satellites.

1.2 Environment in LEO

A small satellite in LEO (zero-G) undergoes harsh environmental conditions. These include the damaging effects of high vacuum, ATOX (atomic oxygen), radiations (ultraviolet and ionizing radiations), space debris (termed micrometeorites), and thermal cycling [5]. The effect of these parameters (summarized in Table 1) plays a critical part in determining the reliability, function, and life of the system. The atmosphere of Earth is thick, consisting of gases mainly nitrogen (78%) and oxygen

Table 1 Effect of environmental conditions on zero-G systems [6]

Environment	Effect
High vacuum	Volatilization (for materials having low vapor pressure), vacuum welding, diffusion
Atomic oxygen (ATOX)	Oxidation, surface erosion, crazing/cracking of materials
Radiations (ultraviolet and ionizing radiation)	Develops lattice defects, polymer chain scission, cross-linking (for certain organic materials)
Micrometeorites (space debris)	Material fracture, mechanical failure
Thermal cycling	Embrittlement, chemical, and mechanical degradation

(21%), and eliminates much of the space radiation. However, the satellite in LEO also experiences atmospheric drag, causing it to move to lower orbits and eventually fall to the earth.

In extraterrestrial environments (Moon, Mars, etc.), dust is also a critical obstacle for space missions. The dust particulates (diameter $\leq 60\ \mu m$) are abrasive, electrostatically charged, chemically reactive, and have a tendency to adhere to exposed surfaces. About 50% of these dust particles come from the lunar regolith. During the Apollo missions, lunar dust posed unexpected difficulties such as visor, glove, and boot abrasion, deterioration of seals and thermal radiator function, and respiratory irritation [7].

1.3 Material Requirements for Satellites

Keeping in view the environment in LEO, the construction material used for the satellite should meet the following requirements [8].

a. Ability to work in a hard vacuum.
b. Erosion resistance against atomic oxygen.
c. Endurance over temperature extremes (−150 to 60 °C).
d. Prevent surrounding contamination (very low outgassing).
e. Resistance to harsh ultraviolet and ionizing radiations.

A material may or may not need to satisfy all these requirements simultaneously, depending on its application area. For example, a material directly exposed to the surface of spacecraft should satisfy all these, but those used on the inner side may have some exceptions.

2 Materials Used for Zero-G Applications

The various materials used include metals and their alloys, polymers, and composite materials. The metallic materials commonly used include aluminum, magnesium, iron, and titanium, and their properties are compared in Table 2.

However, the chapter mainly focuses on polymers and composite materials used for zero-G applications, and the detail of metallic materials is beyond the scope of this chapter.

2.1 Polymers in Space

Polymeric materials are used for numerous applications in a space system including adhesives, thermal coatings, paints, thermal insulations, seals, tapes, toughening/damping materials, thin film substrates, potting compounds, etc. The polymers for these applications are designed to last for 15–20 years, depending on the system life. Consequently, it is necessary to comprehend how space conditions affect the polymeric materials now in use [6]. Additionally, the polymeric material is qualified for space application only if it meets certain requirements, defined as per end use. Materials that might corrode the metal surface, cause an electrical short circuit, contaminate optics, or adversely affect other components are not used for these applications [8].

Polymers are either organic or inorganic in nature. The inorganic materials cannot experience loads, while organic materials have poor resistance to heat. The optimal structure must be made of a straight-arranged polymer with nonionic substituent clusters to enable adaptability in order to produce a material between these constraints. The success of inorganic polymers (commonly silicone polymers) is based on this fundamental notion [10]. Some typical applications of polymeric materials for space structures include their use in thermal blankets, heat control paints, and adhesives.

Table 2 Comparison of properties of Al, Mg, Fe, and Ti [9]

Property	Fe	Mg	Al	Ti
Yield strength (MPa)	280	90–195	~170	434
Density (kg/m^3)	7900	1700	2700	4600
Strength-to-weight ratio	35	114.7	62.9	94.3
Elongation (%)	12–45	14–45	5–25	18–30
Modulus of elasticity (GPa)	196–207	45	70	107–119
Melting point (°C)	1538	650	660	1668
Thermal expansion coefficient ($\times 10^{-5}$)	1.18	2.48	2.31	0.86
Thermal conductivity (W/m K)	79	160	235	22

2.1.1 Thermal Blankets

Thermal blankets are used in space structures to regulate their temperature, offering a stead range of operating temperature. It consists of a polymeric film, either filled with carbon black to absorb the sunlight or coated with a vapor deposited aluminum layer to reflect the sunlight. Multiple layers of these polymeric films (separated by fine nylon cloth) are used to constitute a multi-layer insulation termed as thermal blanket. The most commonly used polymers for films include polyethylene terephthalate) and polyimide (commercially available from DuPont). Additionally, a thin layer (thickness 50 nm) of indium tin oxide is deposited on polymeric films to provide a path for static electricity dissipation.

2.1.2 Paints

The paints are a key component of the structure to regulate the temperature of spacecraft. It consists of a pigment dispersed in some organic or inorganic binder. The paints are either black or white in color depending on the material used. The black paints have tendency to absorb the sunlight and keep the spacecraft at warmer temperatures, while white paints reject excess heat back into space, and have high emissivity. The polyurethanes are used for black paints, while silicones are used for white paints.

2.1.3 Adhesives

Adhesives are preferred in space structures for durable bonding of dissimilar materials, allowing significant mass reduction as compared to conventional mechanical fixation compared to traditional screws or rivets. Typical applications of adhesive include structural bonding, thread-locking compounds (to avoid loosening of fasteners under high vibration), lamination of optical elements, and cable stacking. But a key requirement is that adhesive shall withstand vibrational loads due to the spacecraft launch and must be able to withstand the impact of space environment [11].

The adhesive families commonly preferred for spaces programs include epoxies (for better mechanical performance), silicones (for better performance in thermal environment), acrylics (used as tapes), and polyurethanes. The two-part epoxy is the most widely used adhesive, in which two liquid components are mixed, and allowed to cure into a tough, and adherent solid. The properties of epoxy are modified by incorporating fillers, to get adhesives with low thermal expansion coefficient, exceptional adhesion, and high temperature stability (to 300 °C).

Other adhesives include the ones used for specialty applications, i.e., electrical conductivity, thermal conductivity, etc. The specialty grade adhesives are filled with silver or carbon powder to impart electrical conductivity, or boron nitride, alumina, and diamond dust to provide thermal coupling. Good adhesion and intimate contact are the only ways to achieve electrical or thermal continuity between uneven surfaces.

Electronic component spot bonding can also be done with conductive adhesives. The UV curing transparent adhesives constitute another class of specialty adhesives. Such adhesives are preferred for bonding together the optical elements, such as lenses and fiber optic devices.

2.1.4 Polymers for Electronic Components

Polymers are widely used in electronic components and for electronic packagings. Some of the applications include conductive adhesives, circuit boards, conformal coatings, wire insulation, etc. The circuit boards are based on polymer impregnated glass cloth. Some typical examples include an epoxy impregnated glass cloth and poly(cyanate) resin impregnated quartz cloth. For wire insulation, Teflon is preferred due to its chemical inertness; however, it has poor radiation stability. A recent development is the use of poly vinylidene fluoride (PVDF) polymer for cable insulations, used in high radiation environment. Circuit boards are coated with conformal coatings to prevent chemical deterioration and add an insulating layer to the surface. Mostly these coatings are a two-part urethane that is blended, dipped, or sprayed onto circuit boards.

2.2 Shape Memory Polymers

Shape memory polymers (SMP) are known as the stimuli-responsive polymeric materials. External stimuli, like light, temperature, electric current, etc. have the ability to cause SMP to return to their original structure. These polymers comprise a network of molecular switching segments, i.e., the hard segments and soft segments. The hard segments define the permanent shape of SMP, while soft segments become less rigid in response to a specific stimulus. This phenomenon allows to program the polymer into a temporary form. When exposed to a certain stimulus, the molecular switches are activated, releasing the stored strain energy that causes the temporary form to take on its original permanent shape. The temperature is a common external stimulus since most polymers have glass transition temperature (T_g) or melting temperature (T_m) [12]. The SMP when heated over this threshold temperature return to its permanent shape. This critical temperature is often the glass transition temperature of SMP.

Shape memory polymers offer advantages including low cost, lightweight, high storage energy ability, and recovery in response to a specific stimulus. Moreover, SMP have high strength-to-weight ratio as compared to metallic materials, as well as flexibility of design. Therefore, SMP have the potential to replace metallic components in spacecraft. Epoxy-resin is one of the prominent members of SMP family. The shape memory effect and superior performance properties (high modulus, heat resistance, creep resistance, better adhesion, electrical resistance, etc.) of epoxy-resin promote its use for deployable space applications [13].

The shape memory polymer composites (SMPC) reinforced with fibrous reinforcement show significant improvement in the mechanical properties and durability as compared to SMP. The shape memory effect of SMPC does not degrade considerably due to UV and γ radiation. A shelter or habitat is utilized to shield space travelers from the harsh conditions of space when they spend longer periods of time in outer space. Such habitats are constructed on earth and transported to space. Deployable structures are developed in order to maximize deployed volume in space while minimizing occupied space in spacecraft. One of the lightweight materials that can fulfill the need is SMPC since it can be released in space using a specific stimulus while being packaged and stowed in a lower volume [14].

2.3 Polymer Aerogels

Aerogels are ultralight polymeric materials in which the liquid component of a gel is replaced with a gas. These polymer aerogels can be used as solvent absorbents, superinsulators, or catalyst supports. Aerogels made from hydrophobic, semicrystalline polymers, have high stiffness combined with excellent flexibility [15]. The properties of aerogel depend on its chemical composition, density, and synthesis route followed. Aerogels may be created in a variety of forms, including monoliths, grains, powders, and films. The monolithic silica aerogels were used by NASA for space applications as thermal insulation material.

The structure of an aerogel is made up of small amount of silica particles tortuously locked in a 3D network with numerous dead-ends that impede its thermal transport. The lattice structure, density, and interconnectivity of particles affect how much heat is transferred through the solid structure of aerogel.

Because of the interparticle connections, silica aerogels are often weak and brittle, rendering them unsuitable for load-bearing applications. Three-point bending, uniaxial compression, and ultrasonic techniques are common ways to characterize the mechanical performance of silica aerogel. Researchers are focusing on the improvement of the mechanical strength by the incorporation of a second phase (i.e., fibers) in these aerogels. It has been reported that elastic strength and modulus are increased by 26 and 85%, respectively, by addition of 10% of fibers. Incorporation of 5% carbon nanofibers into lattice structure improved the tensile strength and compressive modulus of aerogels by 5 and 3 times, respectively.

2.4 Fiber Reinforced Polymer Composites

The fiber reinforced polymer composites are widely used for aerospace applications. The commonly preferred composites for space applications include carbon fiber reinforced polymer (CFRP) laminates, while some other types are also used [16].

Table 3 Reinforcing fibers commonly used for aerospace structures [17]

Reinforcement	Strength (MPa)	Modulus (GPa)	Application area
Glass			
– E-glass	2200–2600	65–75	Radome, rocket motor casing, secondary parts
– S-Glass	4400–4800	85–95	High load bearing parts in small passenger aircrafts
Aramid			
– Low modulus	2700–2800	80–85	Fairings, non-load bearing parts
– High modulus	2300–2400	160–170	High load bearing parts
Carbon			
– High strength	3000–3500	220–240	Satellites, dish antenna, missiles, etc.
– High modulus	2800–3000	390–450	Space structures, control surfaces

The reinforcement materials preferred for space applications are summarized in Table 3.

FRPC used for aerospace are generally fabricated from prepreg as raw materials using an autoclave fabrication technique [18]. Sometimes, the filament winding approach is also prevalent for tubular/shell-like components, i.e., rocket motor casings used for launch vehicles and missiles. Generally, such parts are post-cured at room temperature, or an oven is used for this purpose. Resin transfer molding technique is also used to fabricate special components like radomes. The examples of some popular matrix systems are summarized in Table 4, along with their attributes.

Composite materials have long been employed in space applications, and their popularity is growing. Some of the typical applications include space flight vehicles, satellites, and launch vehicles (pressure vessels for fuel, rocket motors, etc.). The low weight and environmental stability of composite materials makes them an idea material for these applications. Composite materials are also preferred for ablative and high temperature components in reentry heat shields and motors [19].

The carbon fiber reinforced polymer (CFRP) laminates are one of the most abundantly used composite materials for aerospace applications, due to the high modulus of carbon fiber [20]. The ability to bear high temperatures and low thermal expansion are the additional benefits of using carbon fiber. The CFRP is widely used on satellites and payload support structures. A typical bus structure is built from aluminum honeycomb, sandwiched between CRFP face sheets. The CFRP is preferred for structures demanding dimensional stability over extreme temperatures and is produced with low moisture absorption resins. Common CRFP applications include RF reflectors, solar array substrates, struts and booms for deployable instruments, deployable payload fairings of launch vehicles, etc. Silica or carbon fiber reinforced phenolic high temperature resistant ablative composites are typically used, and they absorb heat via changing state [21]. These composites are utilized in rocket nozzles (throats

Table 4 Matrix materials commonly used for space structures [17]

Thermosets		Thermoplastics
Epoxy	Phenol	PPEK, PPS
Most widely used (80% of total)	Cheap, low viscosity, and easy to use	High mechanical strength and good damage tolerance
Density: 1.1–1.4 g/cc	Density: 1.2–1.4 g/cc	Density: 1.3–1.4 g/cc
Strength: 40–85 MPa	Strength: 35–60 MPa	Strength: 100 MPa
Modulus: 2.7–5.5 GPa	Modulus: 2.7–4.1 GPa	Modulus: 3.5–4.4 GPa
Moisture absorption: 5–6%, causes degradation of high-temperature properties	Absorbs moisture but does not affect performance at high temperature	No moisture absorption
Good storage to make prepreg	Difficult to prepreg and store	Difficult to process, 300–400 °C temperature is required
Low shrinkage: 2–3%	High cure shrinkage	
No volatiles during process	Volatiles release during process	Very high chemical resistance
Moderately high-temperature resistance	Preferred for high-temperature applications	Creep resistance
Degradation due to UV exposure		

and exit cones), reentry vehicle heat shields, etc., and are categorized into ablatives and ceramics.

Lopez et al. [22] prepared ultra-thin CFRP using POSS nanofiller as reinforcement in cycloaliphatic epoxy matrix. These composite materials were developed for use in Low Earth Orbit (LEO), offering enhanced protection against exposure to atomic oxygen. The addition of 20% POSS demonstrated the lowest erosion yield, which amounted to a time period of 12 months in a simulated low-earth orbit environment. Unidirectional CFRP is used in housing, boom, strap elements, and solar panels of LEO satellite, owing to their anisotropic tailorable properties.

The polybenzoxazine matrix has high concentration of hydrogen and is responsible for shielding against galactic cosmic rays. Additionally, because of its low polymerization temperature, the reinforcing fibers are not harmed during the fabrication of composite material. The low viscosity of this resin allows the use of sophisticated fabrication techniques like resin infusion for composite fabrication. In terms of combined structural and radiation shielding properties, the UHMWPE reinforced composites outperform the benchmark materials [23]. According to another research, glass and Kevlar fiber composites are used in the fabrication of satellite antennas because of their high electrical conductivity and minimal transmission loss.

Natural fiber reinforced composites (NFRC) also find application in aerospace structures [24]. The flax/phenol composites were the first to be used in main spar of the Bristol Breinheim bomber. Currently natural fiber sandwich panels (flax/phenol as skin and Nomex honeycomb as core) are used in aircraft interior as ceiling, flooring, walls, lavatories, liners, etc. Compression molding is the most preferable approach for the fabrication of these sandwich panels, using prepregs, at suitable curing cycle [25].

Shape memory polymer composites (SMPC), also called as elastic memory composites (EMC), are widely used for deployable space structures. These materials are similar to the conventional FRPC, except that the matrix material used is a thermosetting shape memory polymer [26]. As discussed in earlier section, SMP exhibit the shape memory effect as a result of some stimuli. Some examples of SMPC-based structural components in aerospace include deployable panels, solar arrays, morphing structures, reflector antennas, expandable lunar habitat, mandrels, etc. [27]. Solar arrays are the energy generation systems in a space structure and are commonly packed in the vehicle before launch. The solar array is deployed to gather energy once in space. The antenna is a crucial component in satellite-to-Earth communication because it may provide essential data about space-related issues. New forms of morphing wing skin that may alter the shape in response to temperature or other environmental stimuli are also being developed by researchers.

A unique habitat is required for prolonged space adventures in order to support basic life and protect against UV radiation harm. A deployable space habitat increases the work volume in space while minimizing the volume occupied in the spacecraft. It can be launched utilizing certain stimulus in space and bundled and stored in a smaller container when not in use. Water-soluble mandrels and multi-piece mandrels are used while fabricating complex structures. However, SMPC mandrels have the benefits of temperature-dependent stiffness variation, simple demolding, reusability, and lower product cost. However, SMPC mandrels offer the advantages of variable stiffness based on external temperature, easy demolding, reusable, and a lower product cost.

2.5 Fiber Metal Laminates

The fiber metal laminates (FMLs) are defined as the panels produced by sandwiching reinforcement in between metal sheets. This combination gives a synergistic effect, incubating properties of metal and reinforcement such as damage tolerance, corrosion resistance, fatigue endurance, thermal insulation, weight reduction, specific strength, and cost-effectiveness [28]. Owing to these advantages, FMLs have proven effective in Satellites, Launch Vehicles, and Space Centers application. The most common fibrous reinforcements used for FMLs include carbon, glass, and aramid fibers. These are abbreviated as CARAL (carbon-reinforced aluminum laminate), ARAL (aramid-reinforced aluminum laminate), and GLARE (glass-reinforced aluminum laminate) [29, 30]. Hybrid reinforcements containing a combination of glass, carbon, aramid, or other fibers have also been explored by researchers [31].

Patil et al. [32] reviewed the characterization of glass/epoxy reinforced aluminum laminates. They reported that although the carbon/epoxy reinforced aluminum laminates exhibit superior mechanical performance as compared to their glass fiber counterparts, they have an issue of galvanic corrosion and unstable interface that can be addressed by treatment and processing of aluminum. Bienias et al. [33] discussed the impact resistance and damage growth in CARAL. They attributed the excellent interfacial strength and damage tolerance to the synergistic effect of stiffness and good mechanical properties of Carbon-epoxy reinforcement along with the ductile behavior of aluminum. The best ply sequence reported by the authors was 0°/90° and ±45° orientation.

One of the most crucial design considerations for space applications is to lighten a structure without sacrificing its rigidity and strength. Due to their low weight, high specific bending stiffness, strength under dispersed loads, and strong energy-absorbing capabilities, honeycomb sandwich structures have been extensively employed in the production of aircraft structures. The honeycombs produced by laying up CFRP on aluminum sheets help to reduce weight by up to 33% as compared to their metallic counterparts. Boudjemai et al. [34] analyzed the hexagonal honeycomb panels used for satellite structures, both experimentally and numerically. They concluded that the geometry and material have a direct effect on the performance of honeycomb structure.

Dinca et al. [35] reported that in comparison to GLARE, CARAL has superior damage tolerance, fatigue, fracture resistance, tensile and bending strength. These laminates are an appealing choice for satellite structure applications due to their tailorable qualities via ply orientation, good damage tolerance, fatigue endurance, corrosion resistance, lightweight, and high specific strength. However, the practical application of these materials needs excessive research in their thermal and vibrational properties for qualification of the material system.

2.6 Lunar Dust Adhesion Mitigation Materials

Lunar dust is the fine proportion of regolith, present on the Moon's surface. The lunar dust might have a negative impact on human outpost technology and crew personnel. For example, the surfaces might be damaged by the abrasive nature of dust, and the friction may have an adverse effect on coatings as well as wiring. The dust can potentially damage astronaut lungs, and cardiovascular systems, and there are increased risks of spacesuit arcing.

There are three basic types of particle adhesion mitigation strategies, namely sacrificial coverings, active, and passive systems. Due to the added weight and cost of the sacrificial coating methods, they are a less practical solution. In order to eliminate the buildup of particles, active mitigation systems need external energy (e.g., electrostatic repulsion, sintering into large particles, brush-actuated removal, etc.). Since particle adherence is inherent to the material, passive mitigation solutions don't require external energy. To solve the dust issue, any one of the three types of mitigation strategies may be used alone or in combination.

In nature, the lotus plant, Nelumbo nucifera, receives the most attention when it comes to reducing a material's surface energy for particle adherence mitigation. Water droplets in this situation have very high contact angles, quickly roll off the leaves, and also pick up surface impurities present on leaf during rolling. This combination of hierarchical surface topographies and low surface energy is mimicked in chemical coatings for lunar dust adhesion mitigation. The phenomenon is termed as "Lotus Effect," and has been reproduced by several researchers. In order to precisely change the surface topography of a range of materials, including polymers, composites, ceramics, and metals, available surface area may be reduced using photolithography and laser ablation patterning.

Another example of biomimetics for dust adhesion mitigation comes from the geckos. The geckos have the ability to climb vertical surfaces, even in dusty environments, owing to the hierarchical surface topography of their toes. The particles trapped in their toes are removed by simply stepping on a clean surface. Since contact self-cleaning is to be accomplished in dry conditions, the production of biomimetic materials that mimic these qualities is especially attractive for reducing lunar dust adhesion. The gecko-mimetic polypropylene surfaces contaminated with silica-alumina microspheres (size ~ 1–5 μm) were studied using a similar approach.

The efficiency of surface modified materials to reduce particulate adhesion was evaluated using two methods, each concentrating on either single-particle interactions or multiple-particle interactions. Atomic force microscopy (AFM) was used to measure the force of adhesion between single particles, while a customized equipment was used to measure multiple-particle adhesion. The particles adhered to the surface were separated using the sonication process in this device [7].

2.7 Atomic Oxygen Resistant Coatings for LEO

The atomic oxygen (AO) degrades the polymers and composites used for satellites in the LEO environment. Therefore, these polymers and composites need protection using AO-resistant layer. Mechanical damage to the AO-resistant coatings, however, can make the underlying polymers susceptible to erosion and reduce their service life. Therefore, self-healing AO-resistant coatings are being explored that have the capability to healing when some mechanical damage is done under LEO environment. The UPy-POSS polymeric coatings have a strong adhesion to polymers and are mechanically durable, thermally stable, and transparent. The formation of the epidermal SiO_2 layer following AO exposure is the reason why these self-healing coatings have exceptional resistance against AO [36]. After the silica coating is applied superficially, the erosion yield of Kapton is reduced by nearly three orders of magnitude. Also the surface of coating is uniform and smooth, after AO exposure and no surface shrinkage induced cracks or erosion are observed [37].

Flexible protective coatings for solar panels, silver interconnects, and fiberglass structural components have been identified as a critical technological gap. A number of protective carborane and siloxane coating systems have been developed and evaluated to bridge this gap. It is possible for each carborane unit to incorporate up to 15 oxygen atoms, owing to its unique structure. Contrary to siloxane, which breaks when exposed to AO, the carborane (siloxane) coating showed no signs of cracking. Surface analysis of coatings exposed to the LEO environment reveals the formation of a glassy borosilicate layer, providing excellent protection to substrate [38].

The life expectancy of current generation satellites is limited to 3–5 years, owing to the environmental degradation of the structural materials. The reactive atomic oxygen, along with manmade debris and natural micrometeoroids, large temperature extremes, and ultraviolet radiation have a synergistic degradation effect on most of the polymers and their composites, causing rapid degradation.

3 Zero Gravity Research Facility

Since its inception in 1966, the Zero-G Research Center has served as NASA's top ground-based microgravity research facility. It was initially built during the 1960s space race to facilitate research and development of fluid systems and spaceflight components in a weightless or microgravity environment. NASA-funded researchers from around the world are currently using the facility to develop and test experiment hardware intended for flight aboard the International Space Station or future spacecraft. They also investigate the effects of microgravity on physical phenomena like combustion and fluid physics and develop and demonstrate new technology for future space missions [39].

4 Future Trends

A remarkable nanocarbon called graphene has a few layers of carbon atoms arranged in six-membered rings. The mono- and bi-layer graphene exhibits extraordinarily unique electronic properties. It is also important to highlight that graphene has other features, including those related to gas adsorption, magnetic and electrochemical characteristics, and the effects of doping with electrons and holes [40]. These remarkable properties intersect with unique aerospace requirements, rendering it an exciting candidate for such applications.

But before they can be used in space constructions, graphene-based structures must overcome a number of obstacles. The absence of a large-scale technique for consistently and repeatedly producing high-quality graphene is one such obstacle. Before a novel material can be taken into consideration for use in space vehicles, it must undergo considerable development, testing, qualification, and certification.

This is usually done with material readily available in large quantities with minimal variability in batch-to-batch properties [41].

In addition to improved performance and reduced weight, graphene has the potential to meet some critical needs in the aerospace systems. The atomic-layer thickness, mechanical strength, and high electron mobility in graphene advocate its suitability for flexible electronics. These devices can be easily integrated into multifunctional structures. The mono-layer atomic thickness of graphene offers additional benefit of intrinsic radiation hardness, which can drastically reduce the amount of conventional radiation shielding material. Many aspects of graphene are yet to be explored, including its applications for zero-G applications. In this latest experiment, the researchers tried to use graphene's excellent thermal properties to improve the performance of cooling systems in use in satellites [42].

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