Science Essence Journal Vol. 40 No. 1 (2024) | 18-36

Review Article

The Effect of Space Environments on the Material Degradations: The Current Understanding and Proposed Synergistic Effects

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Received: 4 February 2024
Revised: 28 March 2024
Accepted: 28 March 2024

ABSTRACT

The objective of this research was to study the effect of micrometeoroids (MM) and space debris (SD), atomic oxygen (AO) and vacuum on space material degradation. The synergistic effect was also proposed inferences based on the comprehensive findings of prior researches. The research was carried out in four steps including article review design, conducting review, collecting and analyzing information and article structuring and writing. The results showed that MM and SD impacted on somewhere of spacecraft, leading to delamination, crack, or fracture. Outgassing is a key degradation existing in vacuum environments, especially on polymeric-based materials. Polyetheretherketone (PEEK) performed the lowest outgassing rate comparative to Polybenzimidazole (PBI) and Polyimide (PI). AO generates from dissociation of oxygen gas in low earth orbit (LEO). Thermal AO broke apart the covalent bonds and formed volatile products. Additionally, AO reacted to some metals, causing several kinds of metal oxides. The second effect was erosion caused by hyperthermal AO. Erosion yields of polymers were higher than metals because of mechanical and chemical properties differentiation. The synergistic effect among two environmental conditions would further contribute to the degradation of space materials. In this review article, the mutual effect of MM and SD, outgassing and AO was proposed. MM and SD would impact on space material and originate the delamination and/or abrasion on the surface. Hyperthermal AO would erode and reveal material's surface and then, enlarge the damaged surface area. Thermal AO accelerated oxidation reaction and volatile products. Moreover, vacuum would enhance outgassing and release many types of gases. The proposed mechanism should be validated in the future.

Keywords: Micro-meteoroids (MM) and space debris (SD), Atomic oxygen, Outgassing, Synergistic effect, Space environment, Material degradation

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Introduction

The emerging significance of space exploration has led to an increasing deployment of spacecraft at various altitudes. Generally, the space was categorized into three distinct regions. Specifically, LEO encompassed the altitude range from 160 km to 2,000 km, constituting the primary zone affected by the upper atmosphere. Medium Earth Orbit (MEO) and High Earth Orbit (HEO) were separated by the Geostationary Earth Orbit (GEOm), located at an altitude of 35,786 km. A comprehensive overview of the distribution of operating satellites in different orbits is presented in Figure 1, sourced from the database compiled by the Union of Concerned Scientists (UCS). Notably, more than half of the satellites are being positioned in LEO, reflecting its prevalence as a favored orbital region. Conversely, MEO and HEO exhibited a sparser satellite presence, particularly when contrasted with the concentration of satellites in proximity to GEO. This distribution underscored the strategic considerations and preferences of satellite placement across diverse orbital altitudes (1) [1].

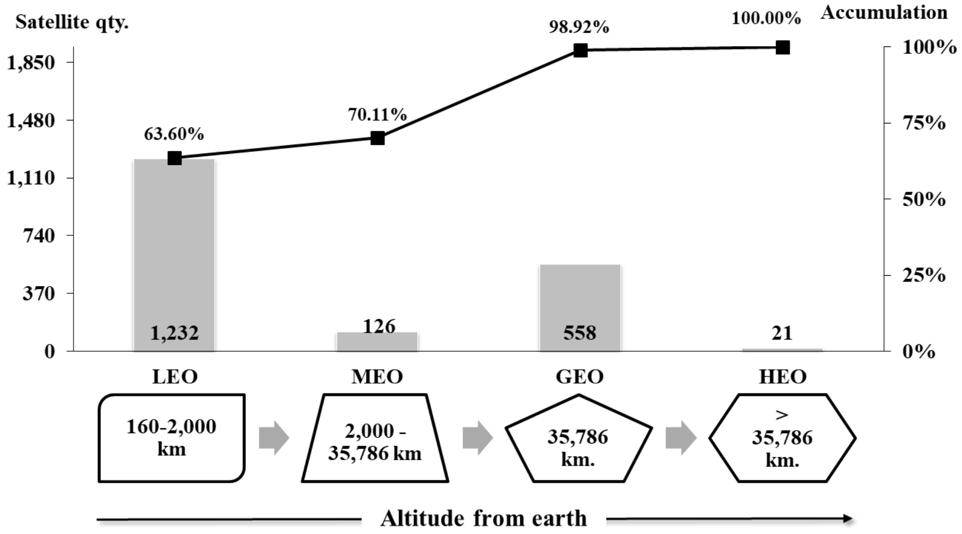


Figure 1 The quantity of satellites in each orbit ranged from the earth until 11/30/2018 [1].

The NASA Marshall Space Flight Center divided the space environment into seven distinct domains: the neutral atmosphere, plasma, radiation, meteoroids, orbital debris, thermal environment and solar environment. However, for the purpose of spacecraft operation, the solar environment was predominantly considered as a factor that influenced other components. Despite the disparate origins and consequences of these environmental components, they are essentially interconnected. External disturbances could incite a cascade of reactions within the space environment, thereby influencing its dynamic [1].

Space material is a new interdisciplinary field which is mainly integrated between space technology and material science. Materials that are used on the outside of spacecraft were systematically developed and chosen to serve a specific function to enable the spacecraft, regulate heat, generate power, or support other important components. The relationship between material and space environment is to be vitally described and clearly identified for better understanding in order to achieve at the end of the mission. Moreover, the damage analysis and performance evolution of space materials are necessary in order to investigate and evaluate under the process of research and development. The physical and chemical properties of space materials are specifically studied and developed to withstand severe space environment [2].

The objective of this research was to study the effect of micrometeoroids and space debris, atomic oxygen and vacuum on the degradation of space materials. The synergistic effect among those environments was also analyzed and proposed by inferences based on the comprehensive findings of prior researches.

The methodology for literature review

There were four steps for conducting the literature review which were independent from the review approach [3]. The steps were shown as followed: 1) Designing the review 2) Conducting review 3) Collecting and analyzing information and 4) Article structuring and writing. The review methodology could be illustrated in detail in Figure 2.

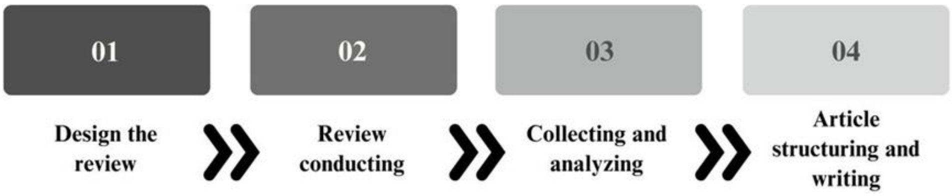


Figure 2 The methodology for literature review [3].

Designing the review

The research objectives, review plan and search strategy were developed in this step. Because the objectives of this research aimed to investigate and synthesize the effect of micrometeoroids and space debris, atomic oxygen and vacuum on space materials degradation. So, the systematic review was selected for identifying, critically evaluating relevant researches, collecting and analyzing data from previous researches. It is the most appropriate approach for conducting the review [3]. The search terms and inclusion criterion would be clarified in this step. The set of search terms and inclusion are shown in Table 1. The search terms were mainly chosen for the research title and objectives. Inclusion criterion was specified from the survey [3, 4].

Table 1 Search terms and inclusion criterion for the review

Search terms	Inclusion criterion
Micrometeoroids, Space debris, Atomic oxygen, Vacuum, Outgassing, Synergistic effect, Space materials, Space environment, Material degradation	Year of publication : 2000-2023 Article language : English Type of article : Original Review, Proceeding, Dissertation, NASA Tech. Doc. Use papers : More than 30 articles

Review conducting

When applying the inclusion criterion, the seventy to eighty articles were searched on notable research databases and selected to about fifty articles using search terms and inclusions as previously defined. The Sciencedirect database was mainly chosen because it contained many research resources, focusing on scientific discipline. The articles were screened by reading abstract first and making the selection. After that, the full-text articles were read later. This method was very appropriate for the systematic review [3].

Collecting and analyzing information

The quantitative and qualitative information could be captured from the selected articles. Importantly, this should be done corresponding to the research purpose [3].

Article structuring and writing

It was apparently very important to specify motivation and the need for writing the article. In this review, the motivations and needs for degradation of space materials review topics were written into the first section of the article, i.e. the introduction. The methodology employed in the review was distinctly announced within the second section of the article. The information from forty relevant articles was gathered, identified, analyzed, synthesized and reported into the third section of the review article [3]. Moreover, after synthesizing, the review article proposed the synergistic phenomena among micro-meteoroids and space debris, vacuum and atomic oxygen on space material degradation as well. It had the potential to enhance the quality and the contribution of the review article. The article conclusion and suggestions for future were arranged to be placed in the fourth section [4].

Review result and the proposed synergistic effect

Micro-meteoroids (MM) and Space Debris (SD)

MM and SD were categorically characterized as macroscopic particles within the space. MM originated from celestial bodies such as asteroids and comets. Conversely, SD came primarily from anthropogenic space weather [1]. SDs were classified into five groups as listed below [5];

1) Fragmentation material consisted of pieces of destroyed vehicles (antisatellite (ASAT) tests, upper stage explosions) and fragments dislodged from satellites (paint flakes, pieces of thermal blankets, etc.). This was the single largest component of the tracked debris population, about 40% of the total.

2) Nonfunctional spacecraft were intact structures that had completed their mission or had had shortened mission life due to a nondestructive malfunction, approximately 25.3% of the debris population.

3) Rocket bodies were spent in upper stages, about 19.4% of the tracked debris population.

4) Mission-related items composed of explosive bolts, vehicle shrouds, solid rocket motor debris (diameters less than 25 microns) and a population of small particles near 900 km believed to be sodium potassium (NaK) droplets. They consumed approximately 13.3% of the total.

5) Debris from unknown sources accounted for the remaining 2.0%.

The deleterious phenomenon of these particles was reveled in their potential to damage upon collision to spacecraft. The MM or SD made up of several materials ranged from metal to composite for example aluminum, steel, lead-based solder [6], Inconel [7], Titanium [8], graphite/epoxy [9-12] and SiC/Carbon [12]. The particles, specifically those with sizes ranging from 0.1 millimeter and above, had the capability to impact on spacecraft and resulted in sizes of craters ranging from a millimeter according to Figure 3 [6]. These phenomena underscored that even small-sized particles possessed the potential to cause damage exceeding their own dimensions when collision on a spacecraft.

A majority of features measuring less than 50 microns in diameter (54 out of 65 craters) exhibited distinct characteristics i.e. impact origin and contain residual material [13]. However, these features did not manifest the nearly perfect circular morphology. The configuration of the melt pit typically assumed an eccentric, elongated oval to pear- shaped depression, wherein impactor residue was situated at the broader end (see Figure 4). The selected materials from the Hubble Space Telescope (HST) during service missions were studied [14] and referred to Figure 5. It was degraded because of the hypervelocity impact objects during long exposure at about 615 km altitude in LEO. The sample was painted above the metal surface of the Wide Field and Planetary Camera 2 (WFPC2) radiator shield. The coating surface was locally removed along with the impact direction. There was a very high risk of metal substrate to directly expose to the space environment.

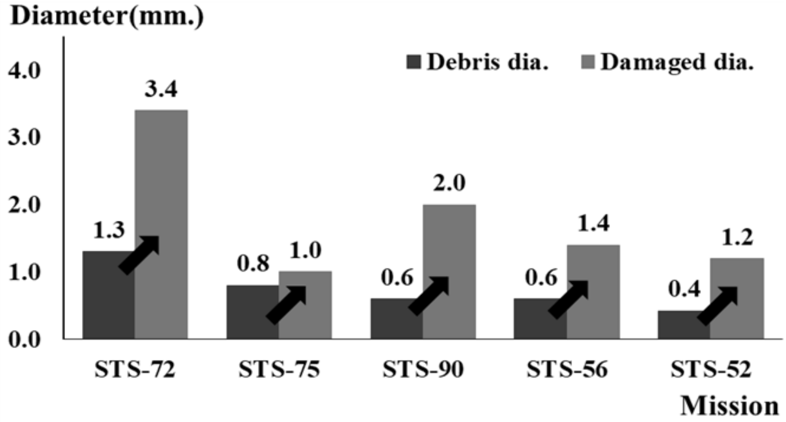


Figure 3 The diameter of orbital debris and damaged area caused by MM / SD impacted on each NASA Space Shuttle mission [6].

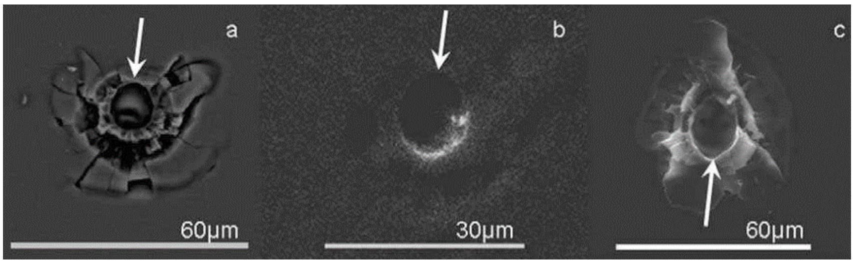


Figure 4 The detachment zone and melt pit impact events: (a) Backscattered Electron Image (BEI) (b) X-ray map for Al show SD residue in broad end of a melt pit (c) SD impacts. The white arrows indicate the likely impactor trajectory in each case [13].

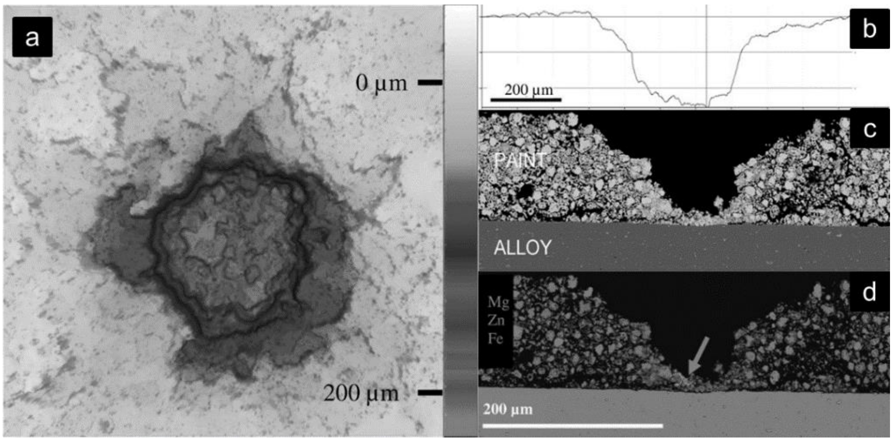


Figure 5 Small impact on WFPC2-11 a) Depth model b) Impact profile c) Cross section BEI d) WDX (Wavelength dispersive spectroscopy) mapping, revealing Mg and Fe-rich residue (arrowed) [14].

Vacuum

Space was predominantly composed of a vacuum environment. It was frequently specified as approaching a state of near-perfect vacuum, identifying its approximation to zero pressure. In these conditions, adverse effects on spacecraft were anticipated, encompassing issues such as pressure differentials, discharging, outgassing, adhesion, and cold welding, along with material evaporation, sublimation, and decomposition. These effects not only disrupted other phenomena but also led to mass and performance loss, molecular pollution, and potential damage to instruments [1].

Physics of outgassing

Outgassing refers to the process of releasing gases, trapped within a material during the material's production and storage, into the space. This phenomenon could occur in various materials and was influenced by many factors such as temperature, pressure and the composition of the material. The released gases would be volatile compounds, moisture, and other substances [15-18].

In outgassing, gases tended to evaporate when molecules were liberated. Adsorbed molecules on the material surface would be desorpted. Additionally, during the polymerization process, a lot of low-molecular-weight additives became integrated. The compounds within the material exhibited diffusion towards the surface and subsequent desorption also. The phenomenon of material evaporation was closely tied to its saturated vapor pressure. Notably, polymers employed in spacecraft applications are characterized by extremely low vapor pressure. Consequently, under typical operational temperatures, the mass loss resulting from evaporation remained marginal [17, 19].

Effect of outgassing on space materials

Four detrimental effects of outgassing in space were explained. First, the released gases posed a significant threat to optical instruments and solar cells in spacecraft. Secondly, the formation of local clouds could impact the accuracy of sensitive instrument readings because they might cover in front of mirror or optical instrument. Thirdly, molecular contamination from outgassing could degrade the performance of thermal control surfaces, especially those that covered on passive radiative cooling. Finally, the nature and extent of outgassing could lead to substantial alterations in fundamental material properties [15, 20]. The outgassing rates of materials from multiple sources were collected and illustrated in Figure 6 [16]. It was obviously shown that the outgassing of the polymer was the inferior to metals and glass. So, it has become a significant issue in space materials. PI, PEEK and PBI exhibited notably high initial outgassing rates, in the order of 10^{-3} (Pa·m^3)/(s·m^2), except for the very thin Kapton® foils (PI). The time evolution of outgassing rates revealed unique behaviors, with the thin Kapton® foils, exhibiting the most substantial decrease over time. Moreover, PEEK demonstrated a favorable outgassing behavior because it released water instead of hydrocarbons and performed the lowest outgassing rate among three kinds of polymers. Additionally, the thickness appeared to reverse the outgassing rate [21]. The polymers, particularly their amorphous structures, could absorb substantial amounts of gas. The solubility of water vapor is very high for ultrahigh vacuum (UHV) applications. The significant volume of dissolved gas, coupled with the relatively high mobility through the polymeric chains, led to a significantly higher outgassing rate compared with metals [22].

Apart from polymer-based materials, ceramic materials are also widely used in space due to their ability to sustain high temperatures ranging from in excess of 250 °C to towards 2,000 °C, as well as their chemical stability. Ceramics possess excellent thermal insulating properties, which are crucial for protecting spacecraft from the extreme temperature fluctuations experienced in space. They have been also studied for outgassing phenomena. The investigations were placed on the outgassing of oxides, nitrides and carbides over time and temperature as illustrated in Figure 7.

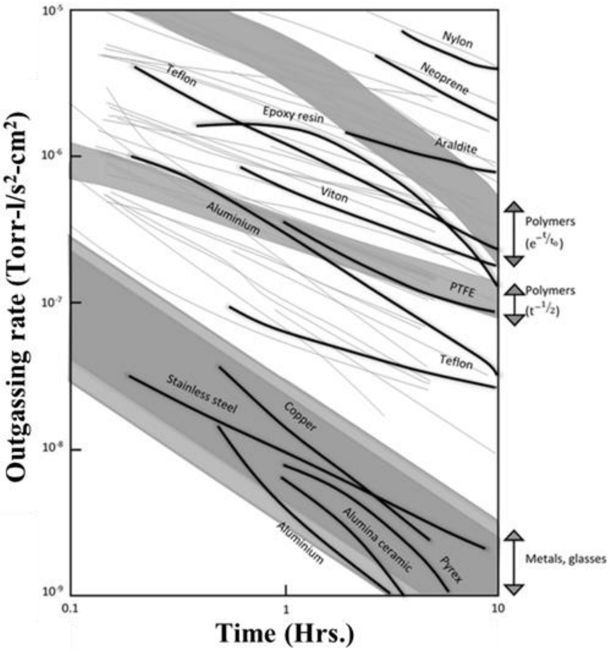


Figure 6 Comparison of outgassing rate. The gray lines show the outgassing curves from many sources. The black lines show the averages, and the shaded zone show typical areas for the specific materials [16].

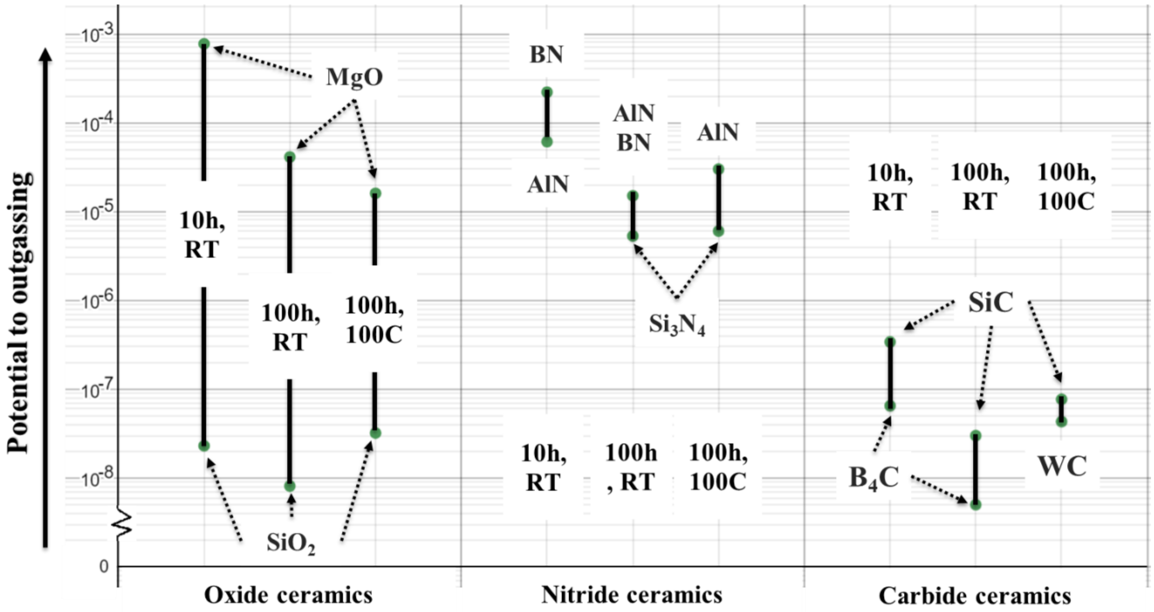


Figure 7 A comparative study among ceramic materials on outgassing rate at room temperature (RT) and 100 °C for the 10 and 100 hours exposed to 10^{-4} Pa [23].

The maximum outgassing rate of ceramic was placed on magnesia with 7.7×10^{-4} $(Pa{\cdot}m^3)/(s{\cdot}m^2)$. In contrast with silicon dioxide and boron carbide, they had the lowest outgassing rate in the order of 10^{-9} to 10^{-8} $(Pa{\cdot}m^3)/(s{\cdot}m^2)$. To improve outgassing phenomena, the heat treatment, with suitable baking time and temperature, should be considered. A typical baking condition for magnesia was suggested at 100 °C for at least 24 hours [23]. Among metallic materials, outgassing of 304 L austenitic stainless steel was examined. The initial H_2 outgassing rate of 304 L was typically known in the order of 10^{-8} to 10^{-7} $(Pa{\cdot}m^3)/(s{\cdot}m^2)$. In order to improve H_2 outgassing, the bake-out at 250 °C for 380 hours was experimented and H_2 outgassing rate was declined to 2.86×10^{-10} $(Pa{\cdot}m^3)/(s{\cdot}m^2)$. Moreover, if the 350 °C baking temperature was applied, H_2 H_2 outgassing rate was more reduced to 5.7×10^{-11} $(Pa{\cdot}m^3)/(s{\cdot}m^2)$. Therefore, the level of applied heat was an outstanding factor in diminishing outgassing rate, and was intricately related to the diffusion of H_2 atoms in stainless steel [24].

Volatile matters were analyzed by mass spectrometry (MS) or Fourier transform infrared (FT-IR) spectrometry to examine the types of gas released from space materials. It was found that, for PEEK, H_2O principally formed and only few hydrocarbons could be detected. For PBI, almost pure H_2O was observed. In the case of PI, H_2O formed the main peak at room temperature [21]. However, at higher temperatures, the outgassing of hydrocarbons increased. It was concluded that the mass spectra for Al_2O_3, SiO_2 and TiO_2 indicated only small peaks for H_2, H_2O, CO and CO_2, except for MgO which was revealed H_2O and C_2H_6O peak. The volatile matters of nitrides were H_2, C_2H_6O, CO, N_2 and CO_2. Hydrocarbon had been detected in MgO and nitrides at elevated temperatures [23]. Moreover, H_2 was detected in case of carbides and stainless steel [24].

Atomic oxygen

The characteristics of AO were described as follows; the concentration of O_2 becomes as the predominant constituent instead of nitrogen at LEO. Essentially, UV radiation, which is approximated to 5.12 electron volts (eV), possesses sufficient energy to photo-chemically dissociate of O_2 into AO as shown on reaction (1) [18, 19]. The AO had a density of 10^{-8}-10^{-7} atom/cm^3 at International Space Station (ISS) in LEO. AOs were classified into two types depending on their interaction with materials.

$$O_2 + 5.12eV \square O^- + O^- \qquad (1)$$

For thermal AO, the degradation involved chemical decomposition and oxidation. The broken covalent bonds formed volatile products in polymeric-based material. AO could oxidize some metals, resulting in several types of metal oxides depending on space temperature. The second type was hyperthermal AO. It impacted the surface of the material at approximately 8.0 km/s. It usually causes severe erosion of polymers. The combination of two types AO would result in an AO impact energy of 4.5±1 eV on the ram direction surfaces of a spacecraft in a 400 km circular orbit. However, for the highest resolution of optical observations, Very Low Earth Orbit (VELO) satellites, which operate at altitudes below 300 km, were designed [25]. The effect of AO on space materials would be increased at VLEO because the AO's density was known to be at least ten times of LEO, causing severe polymer degradation. This was a serious concern [26].

Effect of AO on space materials: Chemical changes

The oxidation of silver (Ag) was feasible in space environment at temperature around 150 °C which is formed at LEO. The oxidation process was basically shown on reaction (2);

$$2Ag + O^- \square \ Ag_2O \qquad (2)$$

The experimental results showed that when Ag was exposed to free oxygen atoms, oxidation occurred at a higher rate than at a lower temperature. During such temperature range, the detected oxide was Ag_2O only. These findings suggested that the oxidation behavior of Ag in AO was influenced by the temperature conditions [27]. The effects of AO environment were examined on polymer-based materials. AO would destroy the chemical bonds, resulting volatile fragments, such as short-chain oxidation products that might leave the surface [28, 29]. Incident AO firstly removed H_2 atoms from polymers, forming OH radicals, volatile OH and H_2O. The radical sites were tentative to further reactions with AO; after H_2 abstraction, the surface continuously generated volatile carbon-containing products such as CO and CO_2. Moreover, at VLEO, the removal of carbon conformed to a non-linear process and there were collisions with molecular N_2 having a hyperthermal energy, increasing the rate of erosion. The combined effect of hyperthermal and thermal AO resulted in diverse interactions with both carbon/graphite fibers and the resin matrix in the composite materials [26]. The degradation of the polymer matrix under high levels of AO was primarily caused by polymer bond breakage and subsequent molecular fragmentation, resulting in erosion of the polymer matrix [30]. The effect of AO on carbon-fiber-reinforced epoxy and carbon-fiber-reinforced cyanate were investigated and analyzed by X-Ray photoelectron spectroscopy. After AO exposure, the intensities of C−O−C and C=O bonds were enhanced by approximately 30.55% and 13.16%, respectively. However, the intensity of the C−C bond decreased by approximately 48.42%. The oxygen atoms dissociated the C−C bonds and generated

C–O bond. Subsequently, the C–O–C bonds reformed with the adjacent carbon atoms onwards [9]. Dissociation occurred because the kinetic energy possessed by AO at LEO was approximately 5.0 eV, which is higher than the bond dissociation energy of polymeric compounds [31]. AO underwent oxidation reactions on bare zirconium (Zr) alloy and Zr-Al-C coating condition. It was observed that the weight gain of Zr alloy exhibited a parabolic trend firstly and then, a higher weight gain value was linear. This indicated that coating Zr alloy with Zr-Al-C could improve oxidation resistance. It was noted that AO could react with the Zr-Al-C coating and produce CO or CO_2 that volatile throughout of the coating layer [32]. The carbon content of Zr-Al-C coating would be the cause of this corrosion. These phenomena resulted in porous layer instead of dense Zr-Al-C as shown in Figure 8. Furthermore, AO diffused and reacted with the Zr alloy substrate, leading to a continuous oxidation process. Therefore, ongoing research on new coating materials is essential for mitigating these challenges.

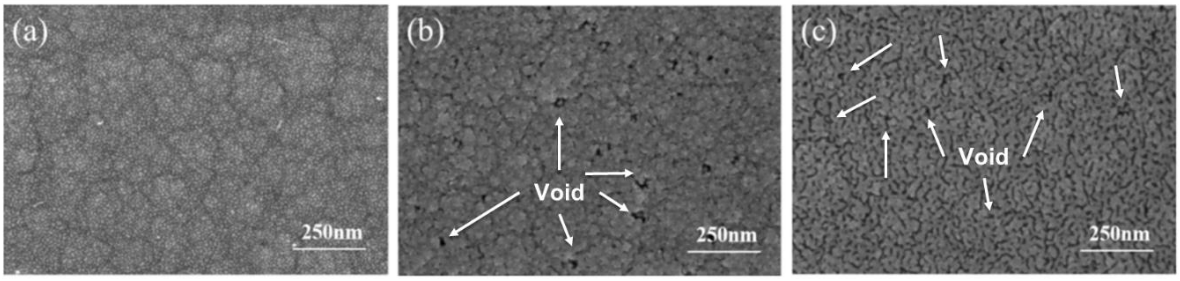


Figure 8 Zr-Al-C surface morphology (a) before, and after AO corrosion for (b) 6 hours and (c) 18 hours [32].

Effect of AO on space materials: Erosion

At sufficient energy, the AO stream impacted the material surface. This caused erosion and degradation of polymer-based materials and metals. The interaction of AO with materials resulted in mechanical degradation, loss of mass and thickness, and/or erosion [33]. Moreover, the satellite required a velocity of 7.67 km/s to sustain perpetual freefall, a condition required for orbital stability. Consequently, this orbital velocity translated to a substantial impact velocity of AO, colliding with the surfaces of spacecraft in the ram direction [19]. To measure the severity of erosion, the erosion yield and erosion depth were the most commonly known indicators. The erosion yield is the volume of material eroded per incident line [34]. In this case, the AO erosion depths on several kinds of space materials in a LEO environment at 500 km altitude and inclination of 28.5 °C were illustrated by Figure 9. In comparison to Ag, Polyethylene showed the inferior for AO erosion effect. Conversely, Teflon and silicon exhibited the highest resistance to AO erosion in compared to other polymeric materials. Also, it was clear that silicon was safe when AO combined to generate SiO_2 (as a protective film). In the case of metallic materials, silver showed the lowest resistance to AO erosion. The AO erosion depth of tungsten was the smallest in comparative to the other metals. Silver is very useful in solar-array and optical applications because of its high conductivity and reflectivity [35, 36]. The higher concentration of AO resulted in a corresponding increase in the total mass loss (TML) value. This is attributed to the nature of hyperthermal AO, characterized by both high energy and velocity. This resulted in a substantial increase in erosion. The material experienced erosion and its corrosion was directly proportional to the AO concentration. Consequently, the TML value was notably higher in direct proportion to AO concentration. Variations in TML values were observed for the matrix type of both composite materials. However, these effects were not significantly. The decrease in TML values was directly influenced by volatile matter, as the reduction in mass was primarily a consequence of the volatile compounds generated by bond-breaking, as shown in Figure 10. Thus, in instances where the AO concentrations were high, the TML values were notably greater than those in scenarios with lower AO concentrations [9, 11].

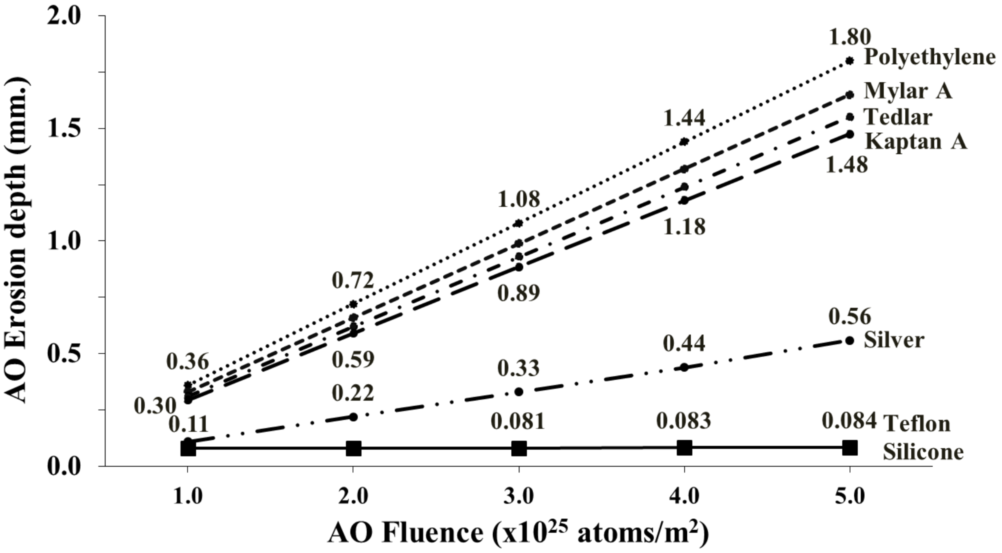
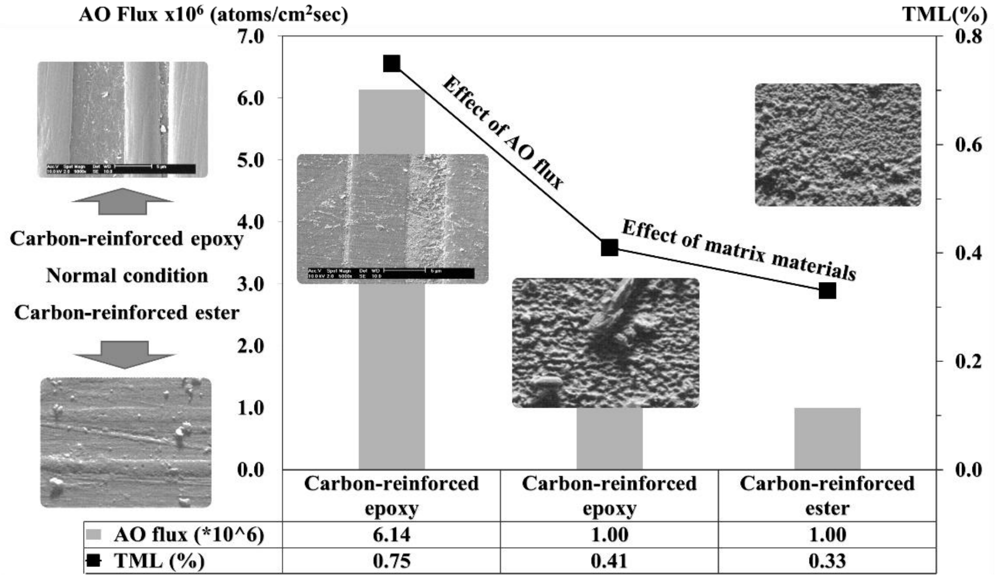


Figure 9 AO erosion depth as a function of the AO fluence for Polyethylene, Mylar A, Tedlar, Kaptan H and silver in a LEO environment at 500 km altitude and inclination of 28.5° [35].



	Carbon-reinforced epoxy	Carbon-reinforced epoxy	Carbon-reinforced ester
▨ AO flux (*10^6)	6.14	1.00	1.00
■ TML (%)	0.75	0.41	0.33

Figure 10 Degradation of polymer based composites caused by exposed AO and types of polymer matrix [9, 11].

Additionally, erosion pits also affected the electrical properties of polymeric materials. The erosion depth not only made the workpiece thinner but also increased the electrical resistance of polyamide. The main cause comes from changes in surface morphology due to the formation of pits on the surface [37].

The synergistic effect among space environments

After studying the impact of MM & SD, AO and vacuum, there were still research discussing the synergistic effect of these factors on space materials.

The synergistic between MM & SD and AO

The synergistic effect of simulated hypervelocity SD and AO on PI nanocomposite was studied and revealed. The result showed that SD caused surface fractures of PI nanocomposite due to the impact of simulated SD at a velocity range of 1.8-2.6 km/s. Furthermore, AO reacted with the surface of the PI nanocomposite, resulting in the creation of extensive new pores, as shown in Figure 11 [38].

The synergistic between temperature and AO

The effect of simulated LEO environment on TML, tensile properties and surface morphology of graphite/epoxy composites was experimented. The results, as depicted in Figure 12, showed that the synergistic effect comparatively enhances the degradation of graphite / epoxy composites in unexposed and exposed AO conditions [11].

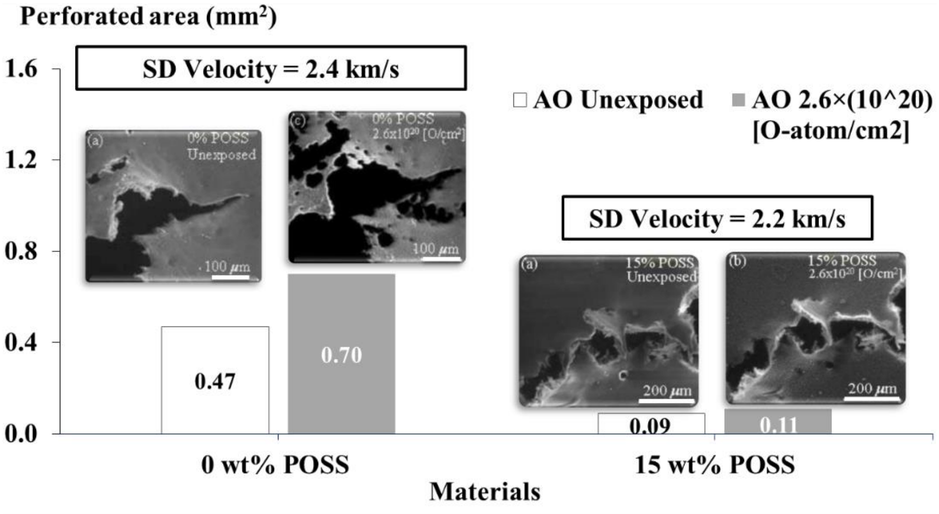


Figure 11 Perforated area values of the 0 and 15 wt% POSS (Polyhedral Oligomeric Silsesquioxanes) samples prior to and after AO erosion. All specimen was passed simulated SD before [38].

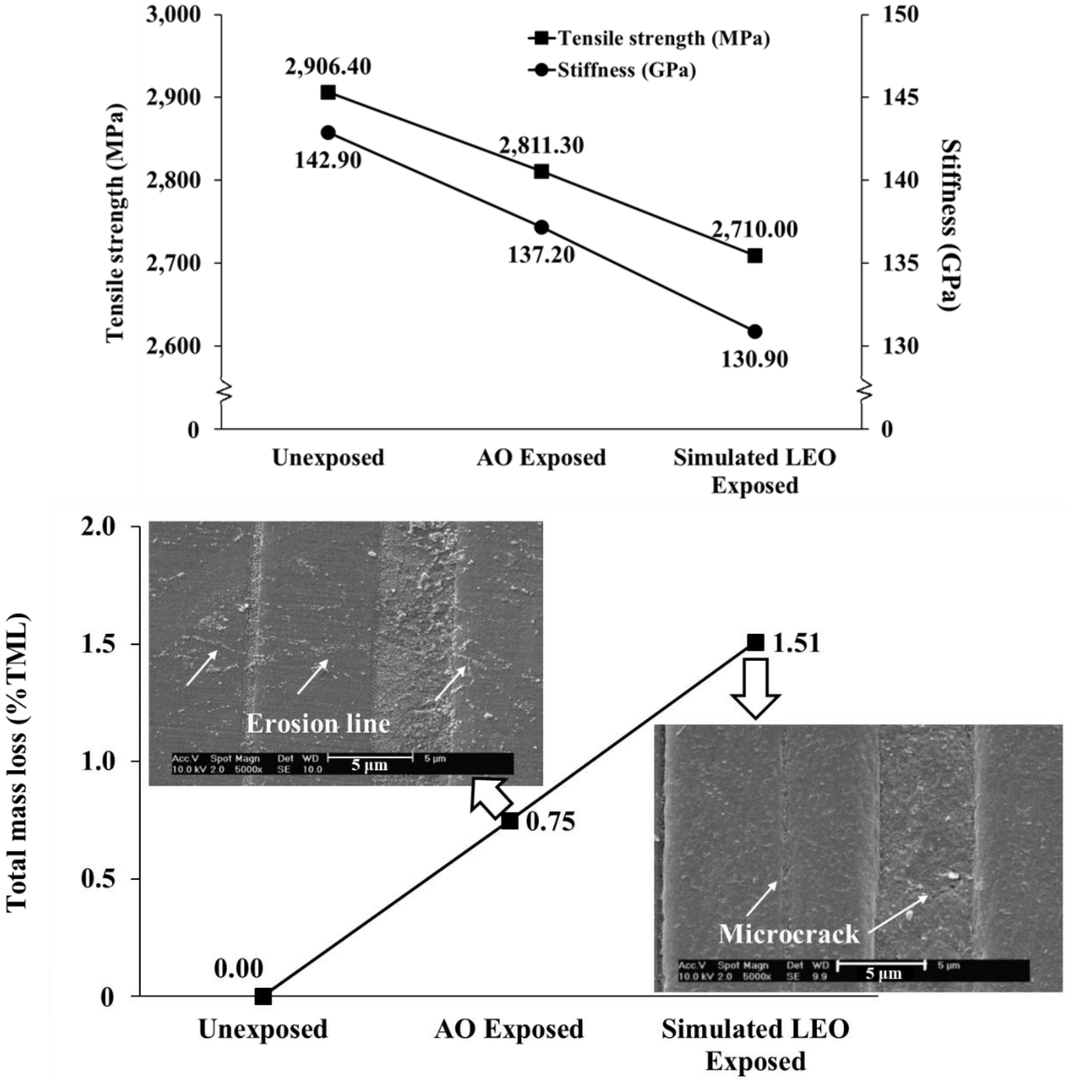


Figure 12 Effect of simulated LEO environment on tensile, stiffness and TML on graphite/epoxy composites [11].

The effect of thermal cycling (TC) and AO on polymer based composite materials that the sequent and simultaneous test among TC and AO affected to the performance of material were discussed. The tests were divided into three cases; TC then AO (TC/AO), AO then TC (AO/TC) and TC&AO simultaneously. The AO/TC case brought more mass loss than another test cases because AO erodes the material surface. Moreover, AO tended to change the chemistry of the composite material. The C−C bond was oxidized and transformed into C−O−C or C=O bond, which reduced the mechanical strength. TC/AO provided the minimum mass loss and the maximum shear strength among three cases. So that, TC might improve the specimen's resistance to the AO interaction [9].

The synergistic between temperature and vacuum

The synergistic effect between vacuum and temperature on mass loss and mechanical properties was discussed. The mass loss of silicone rubber after thermal vacuum aging was notably higher than that of other materials, particularly condensation-type silicone rubber, reaching up to 7.69%. In contrast, the mass losses for hard epoxy resin and acrylic resin curing glue were significantly smaller when compared to soft silicone rubber. There are two main factors contributing to this observation. The first factor was both epoxy resin and acrylic resin curing glue produced relatively low amounts of volatile products. The second factor was high densities and hard surfaces of epoxy resin and acrylic resin. They increased for difficulty for small volatile molecules escaping from the glue surface [39]. Additionally, the elevated temperature to 100 °C and 200 °C induced total outgassing advancement, with a notable emphasis on water evaporation. Among the polymers investigated, PEEK demonstrated the lowest outgassing rates under these elevated temperature conditions. In contrast, PBI exhibited persistently high outgassing rates even after several hours at 200 °C [21].

The effects of polymer fibers in thermal-vacuum conditions were also studied. As illustrated in Figure 13, carbon fiber, glass fiber and aramid fiber were selected for outgassing investigation. The outgassing evaluation was identified in terms of TML and collected volatile condensable materials (CVCM) values. According to NASA regulation, TML and CVCM were not allowed over 1% and 0.1%, respectively. Carbon fiber reinforced composite proved to be efficient since the measured outgassing rates fell within the regulation. Glass fiber reinforced composite revealed outgassing slightly exceeding the limits; using this material in thermal-vacuum conditions should be deeply screened. Aramid fiber reinforced composite showed the worst performances, with TML and CVCM well above the standard requirements. Carbon and fiberglass reinforced composites are believed to release mainly non-critical gases such as water vapor and carbon/nitrogen oxides. However, the presence of potentially harmful oil and plasticizers may be significantly found in the application of aramid fiber reinforced composite [10].

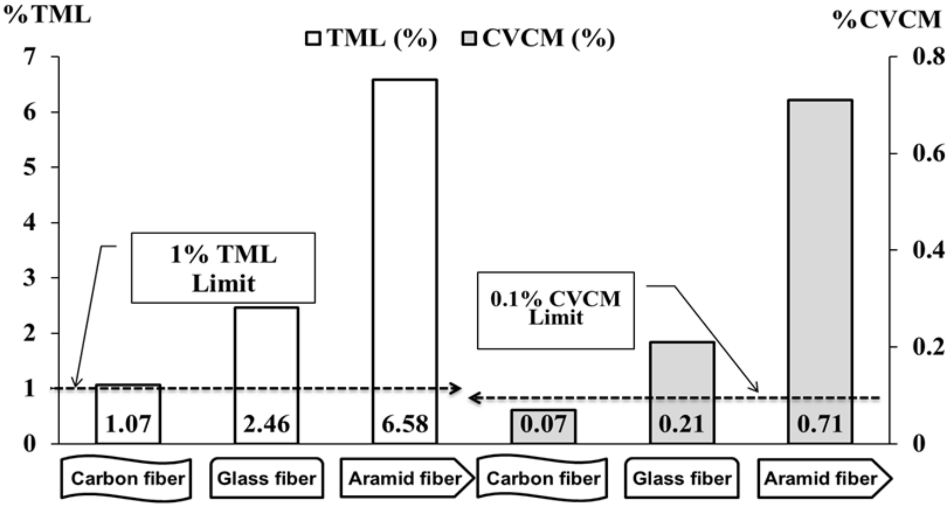


Figure 13 Outgassing of carbon fiber, glass fiber and aramid fiber reinforced epoxy in thermos-vacuum condition [10].

The synergistic between AO and vacuum

AO exhibited interactions with materials in the same manner as UV radiation. AO gave its capacity to break chemical bonds and to oxidize atoms at the surface. A specific study demonstrated a correlation between AO exposure and a marginal reduction in the outgassing of an O-ring. The transformations in material surfaces, resulting from the breaking of bonds and oxidation induced by AO, might modify the quantity of material desorbed from the surface. The erosion of material, caused by AO, could facilitate or impede the diffusion of trapped gases to the surface, affecting the subsequent outgassing. Considering decomposition as the outgassing of the degraded material itself, the degradation of material through AO erosion might amplify outgassing through decomposition. There was a possibility that any of these mechanisms could undergo changes, leading to either an increased or decreased outgassing compared to typical conditions. Alternatively, there might be no observable relationship between AO and outgassing [18].

The proposed the synergistic effect among MM and SD, Vacuum and AO

When materials are utilized in space, independent of coating condition, there is a high likelihood of encountering MM and SD, which float in space at high velocity. Such impacts of MM and SD would lead to the delamination and/or abrasion of the surface coating and/or raw surface of space materials. The delamination or abrasion of the surface increases the exposed surface area to the space environment. Hypervelocity of AO can erode the open surface of the material, enhancing the surface area in contact. Thermal AO, additionally, would react with eroded surface and lead to oxidation (in case of metallic materials) or a broken chemical structure (in case of polymer-based materials). The resulting oxidation produces new by-products that leach out from the original surface, contributing to the degradation of space material. Altogether, these factors may lead to the peeling, cracking, and reduced lifespan of the space material, impacting the overall operational performance in space missions. The exposed surface, in contact with the space environment, including vacuum and AO, undergoes degradation processes such as outgassing, oxidation and erosion. The rate of outgassing depends on the material type and the extent of the surface area directly exposed to the space environment. The proposed interaction mechanism was graphically shown in Figure 14.

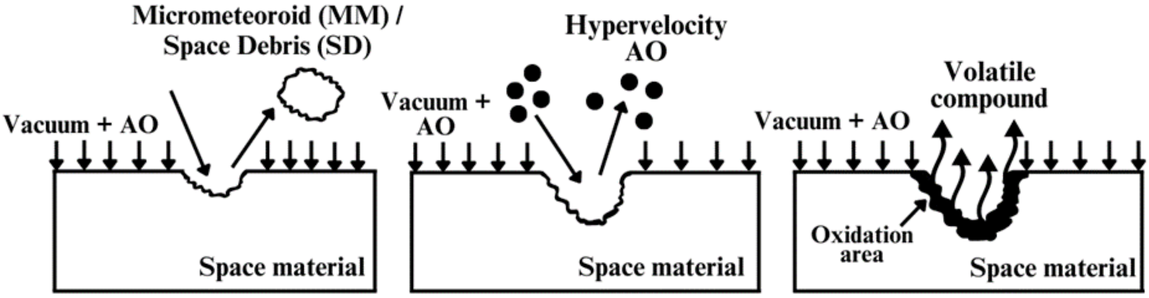


Figure 14 The proposed synergistic mechanism among MM and SD, vacuum and AO on space material degradation.

Conclusions

1. MM and SD floating in space travelled at high velocity and could collide with space material, causing surface erosion and craters.
2. Outgassing occurred when trapped species were released from the surface of a material during a mission. In a vacuum, the outgassing rate tended to be high for polymer-based materials.
3. AO was generated through the dissociation of O_2 molecules when exposed to sufficient solar energy. There were two main types: Thermal AO, which induced chemical changes in materials, and Hyperthermal AO, which induced to erode on the material surface.
4. The synergistic effect among MM & SD, vacuum, and AO resulted in increasingly severe damage to materials. This is because the damage occurs from the simultaneous interaction of multiple factors.

5. The synergistic effect among MM & SD, vacuum conditions, and AO was proposed based on inferences drawn from the comprehensive findings of prior research. The impact of MM & SD could cause materials to peel off or fracture because of collisions. Simultaneously, AO induced erosion on the material surface, leading to oxidation with metals and bond breaking in polymeric-based materials. Additionally, the vacuum environment caused outgassing, leading the material substance to evaporate or release. Therefore, when considering these combined factors, they accelerated the damage to space materials and ultimately reduced the lifespan of spacecraft.
6. In the future, it was advisable to conduct experiments and validate the synergistic mechanism among the proposed MM & SD, vacuum conditions, and AO. Additionally, it was crucial to further investigate other factors such as plasma and neutral environments, magnetic fields, and microscopic particles. This comprehensive exploration would contribute to a thorough understanding and guided the selection of suitable materials for space applications. Moreover, domestic development of new materials with enhanced resistance to space environment was still necessary to reduce reliance on import and relevant to National strategy for National Competitiveness Enhancement.

Future research and works

1. Validation of the proposed mechanism; Synergistic Effects among MM, SD, Vacuum and AO on space materials.
2. The literature review on other factors present in the space environment affecting material performance. Including:
   - Effects of the plasma environment resulting from interactions among the geomagnetic field, solar radiation, and upper atmosphere on space materials
   - Influence of magnetic fields on the magnetic, optical, and electrical properties of materials.
   - Impact of microscopic particles, such as electrons and protons, on material properties.
3. Domestic development of new materials with enhanced resistance to space environment are still necessary for reduce reliance on import and relevant to National strategy for National Competitiveness Enhancement of THAILAND.

Acknowledgement

This work was fully supported by Defence Technology Institute, Thailand.

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