

CHARACTERIZATION OF ANODIZED ALUMINUM ALLOY AL6061-T6 UNDER SIMULATED LEO PLASMA CONDITIONS

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ABSTRACT. The space plasma has relatively low energy but is dense in the low Earth orbit (LEO). In this study, we prepared various samples of anodic alloy surfaces with coating thicknesses of 20, 25, 35, and 45 μm to identify the most suitable characteristics for space applications. Ground-based tests were conducted at the Laboratory of Lean Satellite Enterprises and In-Orbit Experiments at the Kyushu Institute of Technology. A radio frequency (RF) plasma source was used to generate a simulated LEO plasma using argon gas in a vacuum chamber. The plasma properties were measured with a Langmuir probe under different test conditions. A negatively biased voltage of -450 V was applied to the samples to study charging/discharging phenomena. The samples were exposed to Ar-plasma for 1–2 h. The physical properties and structural morphology of various alloy samples were analyzed before and after exposure to plasma. This analysis involved ultraviolet (UV)/visible (Vis)/ Near-Infrared (NIR) absorption spectra, Energy Dispersive X-ray (EDX) analysis, and surface roughness testing. The results showed that space plasma notably impacts the physical properties and morphology of the alloys. A coated thickness of around 25 μm is considered more suitable for spacecraft surface structures due to its improved optical stability and resistance to plasma degradation, as indicated by the experimental results.

Keywords: anodized aluminum alloy, simulated LEO plasma, RF plasma source, coating thickness, UV/Vis/NIR spectra, EDX analysis

1. INTRODUCTION

Understanding the characteristics and effects of space plasma in low Earth orbit (LEO) is essential for the reliable operation of satellites. The space plasma in LEO is relatively dense compared to that in higher altitudes. This is because LEO ranges from about 160 to 2,000 km above the Earth's surface, where the remnants of the Earth's atmosphere still linger. This residual atmosphere includes a higher concentration of particles, which can become ionized and form plasma. Due to the higher mobility of electrons compared to ions, they are more easily collected by positively charged surfaces, leading to the rapid development of high potentials on spacecraft with high operating voltages (Tahara et.al., 1995). Electrons, having higher mobility than ions, are more likely to be collected by positively charged surfaces. In the LEO plasma environment, both neutral and charged particles surrounding the spacecraft significantly influence the expansion of arc plasma, leading to specific arcing characteristics. Electrostatic



interactions between the surface materials and the surrounding plasma, including the creation of negative or positive sheaths, as well as the charging and discharging phenomena are common occurrences. Spacecraft can accumulate electrostatic charges on their surfaces due to different charging currents caused by space plasma within Earth's magnetic field (Shimizu and Ueda, 2016; Hillard and Ferguson, 1995). When a spacecraft operates in a plasma environment, it will reach an equilibrium state by acquiring a surface charge and establishing a surface potential to minimize the net current flow to zero (Inojosa et al., 2023, Takahashi et al., 2014; Gupta et al., 2014; Komarov et al., 2023; Kang et al., 2024). Photovoltaic solar arrays in large LEO spacecraft are seen as the primary reason for charging. For spacecraft with aluminum surface structures, these arrays are electrically connected to the aluminum structure and float at negative potentials. This results in the main conductive body having a higher negative potential compared to the surrounding plasma. When spacecraft use a higher voltage, solar arrays with exposed interconnects, cell edges, and surfaces that charge over 100 V negative about the plasma environment may experience arcing. This arcing can manifest as plasma arcs or arcs to adjacent conductors. In addition, momentary or sustained intense discharges and arcs are likely to occur on the spacecraft's surface (Poznyak et al., 2024; Withanage et al., 2023; Tahara and Masuyama, 2006; Zhu et al., 2022). Large arcs can cause local surface disruption, brief power interruptions, immediate contamination, and significant electromagnetic interference. Depending on the plasma condition and properties near the spacecraft surface, these arcs can also lead to the degradation of surfaces and structures (Takahashi et al., 2014; Abdel-Aziz, Abd El-Hameed, 2013; Abdel-Aziz et al., 2021). Environmental factors alter spacecraft materials' chemical structures and optical and electrical properties (Chatar et al., 2024; Tribble et al., 1996; Araujo et al., 2023; Tahara et al., 1997; Mora-Sanchez et al., 2021; and Karpe et al., 2023). Aluminum alloys are highly favored materials for satellite surfaces and structures. Aluminum alloy Al6061 is the most commonly used alloy in the 6xxx series. It is preferred for its excellent formability, lightweight nature, cost-effectiveness, high strength-to-weight ratio, and superior corrosion resistance. Al6061 exhibits strong mechanical properties and is easily weldable (Staley and Lege, 1993; Dursun and Soutis, 2020). The anodization process is used to create durable Al_2O_3 coatings on aluminum alloys, enhancing their properties. This process increases the rigidity of the alloys, improving their resistance to corrosion and abrasion. The anodic oxide film acts as a protective barrier, effectively preventing degradation of the metal surface and ensuring structural integrity. In addition to this protective function, anodized oxide coatings also influence the optical behavior of the material, enabling effective control of its absorption and reflectance properties (Paz Martínez et al., 2020; de Sousa Araujo et al., 2024). The resulting anodic oxide layer enhances the thermal stability of the spacecraft's external surfaces (Kang et al., 2024; Zhu et al., 2022; Prater, 2008; Hennessy et al., 2016; Govindaraju et al., 2009; Abd El-Hameed et al., 2017). The local film suspension and the resulting porous layer can reduce oxidation efficiency (Abdel-Aziz et al., 2024; Zhou et al., 1999). However, for spacecraft surfaces, when an anodic layer coating is used on the top of an aluminum surface, the surface becomes an insulator and behaves like a capacitor with two electrodes of aluminum. In this case, the dielectric layer is enclosed between the two conducting surfaces "anodized surface–plasma–aluminum plate." At higher biased potentials, the electrical breakdown would arise through the insulating anodized layer, with the current provided by the discharging of the capacitor. Therefore, space plasma exposure can create discharge/arcs on the surfaces (Abdel-Aziz et al., 2021; Hillard and Vagner, 2000; Yang et al., 2023; Fukuda et al., 2017; Tursun khanova et al., 2023; Komarov et al., 2023).

In this study, we investigated the effect of radio frequency (RF) plasma on the anodic oxide layer of aluminum samples Al6061-T6 with different coating thicknesses. Our focus was on the charging and current behavior of negatively biased samples when exposed to plasma, rather than the discharge and breakdown of insulators due to plasma effects. The samples were

exposed to plasma for varying durations to assess their current waveform behavior, discharging, and arc events resulting from the different exposure times. The morphology and physical characteristics of the samples were analyzed before and after plasma exposure to identify the most suitable coating thickness in terms of optical performance for spacecraft surface structures.

2. ANODIC OXIDE COATINGS OF THE ALLOY SAMPLES AL6061

Samples of the aluminum alloy Al6061-T6, with dimensions of approximately 5 cm × 5 cm × 2 mm) were taken. The alloy sample plates were cleaned using trichloroethylene in an ultrasonic bath for 10 min at room temperature ($25 \pm 5^\circ\text{C}$). The alloys were then etched for 60 sec in an alkaline solution containing 150 g/L sodium carbonate, 120 g/L tri-sodium orthophosphate, 1 g/L sodium lauryl sulfate, and 60 g/L sodium hydroxide at a temperature of $60 \pm 5^\circ\text{C}$. After alkaline cleaning, the plates were thoroughly washed with water and dried. The electrochemical technique was applied to the aluminum alloy Al6061 sample plates for the anodization process.

In this method, an electrolyte solution was prepared using 20 wt % sulfuric acid (H_2SO_4), with the electrolyte maintained at a temperature of 0°C . The aluminum alloy sample required to be anodized was immersed in the solution and used as the anode. The period for the anodic process was selected to be 60 min. This time was applied to all samples to form the anodic oxide film on the sample surface. The applied voltage in the circuit varied from 1 to 2 V according to the desired thickness of the anodic oxide coating. The thickness of the coating increases with higher voltage values. Consequently, oxide coatings of varying thicknesses were deposited on the surface of the samples. Using a thickness gauge, the thickness was measured at 10 different places on the specimen, and the average value was calculated. The samples were subsequently colored using an organic dye, resulting in black surfaces, as shown in Figure 1. Afterward, the sealing process was applied to the samples by immersing them in hot distilled water ($>98^\circ\text{C}$) for about 15 min. This method reduces the pores in the coating and seals the surface of the samples (ALWITT et al., 1992). In addition to its effect on the anodic oxide layer thickness, the applied voltage during the anodizing process plays a critical role in determining the electrochemical and physicochemical conditions at the electrode–electrolyte interface. An increase in voltage leads to a higher current density, which enhances the transport of ions and electrons, thereby accelerating mass transfer and modifying the kinetics of oxide growth. This intensification influences the mechanisms of condensation, species exchange, diffusion, and crystallization within the anodic film. As a result, the structural characteristics of the formed layer—such as porosity, crystallinity, internal stress distribution, and mechanical integrity—are also affected. These properties contribute directly to the functional performance of the anodic coatings. While the present study emphasizes thickness measurements and morphological evaluation, future investigations will involve a broader range of characterization techniques, including X-ray diffraction (XRD), nanindentation, and spectroscopic methods, to provide a more comprehensive understanding of the material properties influenced by the anodizing parameters.

Furthermore, it is important to note that after the anodizing process, the samples underwent organic dye coloring to enhance contrast in subsequent plasma exposure experiments. Although this surface modification step is common in anodic treatment protocols, it may induce changes in the physicochemical surface properties of the anodized layer, such as surface energy, chemical composition, and light absorption characteristics. These factors could potentially affect the interaction between the plasma flux and the surface. In the current study, the effect of the dye layer on the surface–plasma interaction was not considered in detail. Future studies will investigate this factor using comparative analysis between dyed and non-dyed anodized surfaces.

In addition, while four anodized samples with different oxide thicknesses (20, 25, 35, and 45 μm) were fabricated, only two representative samples were selected for plasma exposure experiments to allow focused analysis. The text has been revised to avoid potential ambiguity by referring only to the samples that were subjected to further investigation.



Figure 1. Testing of aluminum alloy samples Al6061-T6

3. GROUND-BASED EXPERIMENTS

Ground-based experiments were performed to study how plasma affects aluminum alloy samples. The samples were placed in a controlled environment in the setup described in Section 3.1. The conditions and properties of the plasma, as detailed in Section 3.2, were closely observed and analyzed to determine their influence on the characteristics of the samples.

3.1. Setup

The experimental setup comprised a discharge unit housed within a square-shaped steel chamber measuring 100 cm in diameter, 115 cm in width, and 75 cm in height. This chamber was equipped with the operational components, including the pumping systems, a plasma source, and gas flow mechanisms. The pumping systems included a mechanical pump and a high vacuum pump (turbo pump). Initially, the mechanical pump was activated, followed by opening the valve connected between the mechanical pump and the high vacuum pump known as the discharge pump valve. The vacuum chamber was evacuated using a cryogenic pump backed by the two pumps connected in series. The two-pump scan generated a rough vacuum in the order of 10^{-2} Pa. Once the system reached this pressure, the cryogenic pump was activated, further reducing the evacuation pressure to around 10^{-5} Pa. A pulsed RF plasma device served as the plasma source, operating at up to 100 W and providing frequencies of up to 300 MHz/sec. This “RF” source ignites the plasma and maintains its survival, where RFs are used to move the gas molecules, so that collisions occur followed by the formation of ions and electrons, and subsequently, the plasma is generated. For the experiments, the plasma was produced with a frequency of 13.56 MHz by an RF generator of model number T857-2 combined with a matching box of model numbers L/CON300PF and C-102Y. The source meter was connected to the system and operated through the software program Lab Tracer 0.2. Argon gas was fed into the vacuum system at a flow rate of 10 standard cubic centimeters per minute

(SCCM), controlled by a flow meter, and the power level was set below 20 W. This gas was selected because of its well-established role. Argon was selected as the plasma species due to its well-established role in simulating inert space plasma interactions and its wide use in material processing applications. Although it does not represent the full composition of the LEO plasma, LEO plasma primarily consists of atomic oxygen (O), molecular nitrogen (N₂), and various ionized species such as O⁺, N⁺, and NO⁺, while the experiment utilized pure argon plasma to isolate surface interaction effects without introducing additional chemical reactions. It provides a controlled environment to study fundamental ion–surface interactions. As an inert noble gas, argon does not chemically react under normal conditions; however, in plasma form, it effectively transfers momentum to the surface atoms, leading to sputtering, breaking of weak bonds, and potential structural modifications of the surface oxide layer. These characteristics make it a standard reference ion in plasma–surface interaction studies, including thin film deposition, surface cleaning, and oxide layer modification. The choice of argon allows a focused analysis of physical effects such as ion bombardment, energy transfer, and surface erosion, which are critical for evaluating the durability of satellite surface materials in space-like environments. During the experiments, the gas pressure inside the chamber was maintained at a steady 0.02 Pa. The installation of the vacuum chamber and plasma source is shown in Figure 2.

To generate argon (Ar) plasma, the discharge unit was operated until the pressure reached around 1.89×10^{-4} Pa. Subsequently, the argon gas was introduced into the chamber to a length of 50–60 cm, raising the pressure to approximately 1.9×10^{-2} Pa.

3.2. Conditions and plasma properties

To determine the properties of the Ar-plasma generated inside the chamber, a single Langmuir probe was installed in the evacuated chamber and used (see Figure 3). The probe had a spherical tip with a diameter of 3 mm. Various plasma parameters, such as density and temperature, can be evaluated using the data measured by the probe. The current (I) and voltage (V) of the plasma were measured and recorded using a source meter, and the data were stored through the Lab Tracer program. The recorded data were then plotted as an I–V curve. From this plotted curve, the plasma parameters were calculated using Maxwellian equations. These parameters are presented in Table 1. The conditions and estimated plasma properties are comparable to previously reported data on simulated LEO plasma conditions (Cho et al., 2002; Kern and Bilén, 2003; Zhu et al., 2022; He et al., 2023).

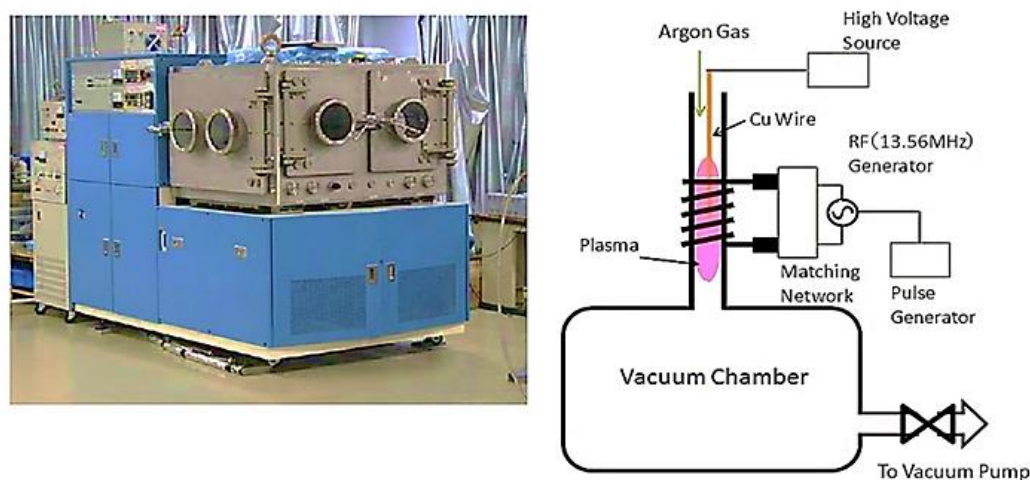


Figure 2. CRYO vacuum chamber and plasma generation principle

Table 1. Calculated values of the plasma parameters

Parameters	Calculated values
Floating potential	7.5 V
Electron saturation current	19×10^{-5} A
Electron temperature (Te)	3 eV
Electron density (ne)	$4.47 \times 10^6/\text{cm}^3$
Debye length λD	λD (cm) ≈ 0.61 (cm)

The plasma conditions generated in the laboratory setup were selected to approximate, as closely as possible, the known parameters of the LEO environment. However, direct comparison should take into account the variation of plasma characteristics with altitude, local time, and geomagnetic conditions. According to reported data, typical plasma parameters in LEO include electron densities ranging from 10^4 to 10^6 cm^{-3} and electron temperatures in the range of 0.1–10 eV. In our experiment, the measured electron density was on the order of 10^6 cm^{-3} and the electron temperature was within the expected range. While exact replication of the space environment is not feasible, the generated plasma provides a realistic and controlled model to investigate surface–plasma interaction effects (Hastings and Garrett, 1996; Brace, 1998; Lai, 2012).

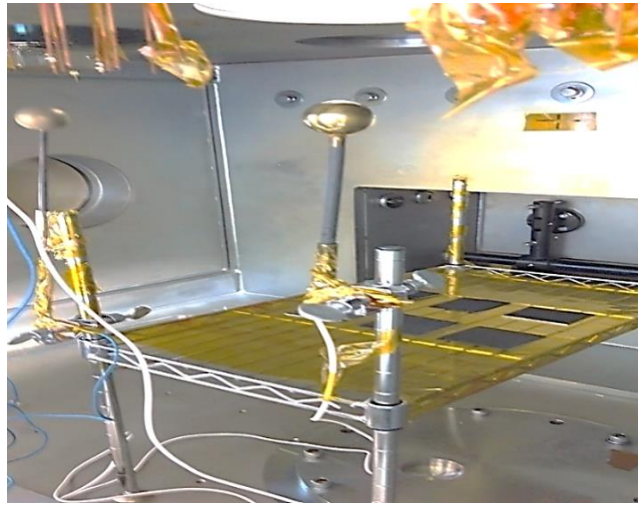


Figure 3. Langmuir probe and samples inside the chamber

4. RESULTS AND DISCUSSION

This section presents the experimental results of investigating the impact of LEO plasma on the anodic aluminum alloy Al6061-T6. The analysis thoroughly examined the structural and physical characteristics before and after plasma exposure. A total of four samples with oxide layer thicknesses of 20, 25, 35, and 45 μm were initially prepared. Among them, two thicknesses (20 and 35 μm) were selected for detailed plasma exposure and optical property analysis. These two samples were chosen based on preliminary characterization, which showed that the 20- μm layer represents the thinnest uniform oxide coating achievable with the selected anodization conditions, while the 35- μm sample represents a medium thick coating with stable morphology. This selection was made to cover a meaningful range of thickness variations and avoid redundancy in measurements. The 25- and 45- μm samples were excluded from plasma

exposure testing due to equipment time constraints and because their characteristics fell within the expected interpolation range between the tested samples. This approach ensured that the analysis remains focused and is scientifically representative without compromising reliability. For each selected sample, three repeated measurements were performed under every testing condition to ensure consistency. The results presented in this study are the averaged values. The standard deviation was calculated to represent measurement uncertainty. Systematic and random errors were considered, including instrument resolution, positioning of the sample relative to the plasma source, and environmental fluctuations during the measurements.

4.1. Arc current and potential waveform

To study the charging and discharging process resulting from plasma exposure, the samples were exposed to two different durations: 1 and 2 h. Initially, the experimental procedures were performed on all four samples exposed to simulated plasma within a vacuum chamber connected to the discharge unit. Once the pressure of the discharge unit reached approximately 1.5×10^{-4} Pa, the gas path was opened up to 50 cm, resulting in the pressure reaching around 1.9×10^{-2} Pa. The biasing circuit for the samples operated with a negative voltage of up to -450 V, and the circuit resistance was $64.4 \text{ k}\Omega$. The discharge unit operated under specific conditions and a negatively biased voltage for 1 h. The typical current traces and potentials during the discharge and arc event were captured using an oscilloscope and digitized by a computer program for recording, as shown in Figures 4 and 5, respectively.

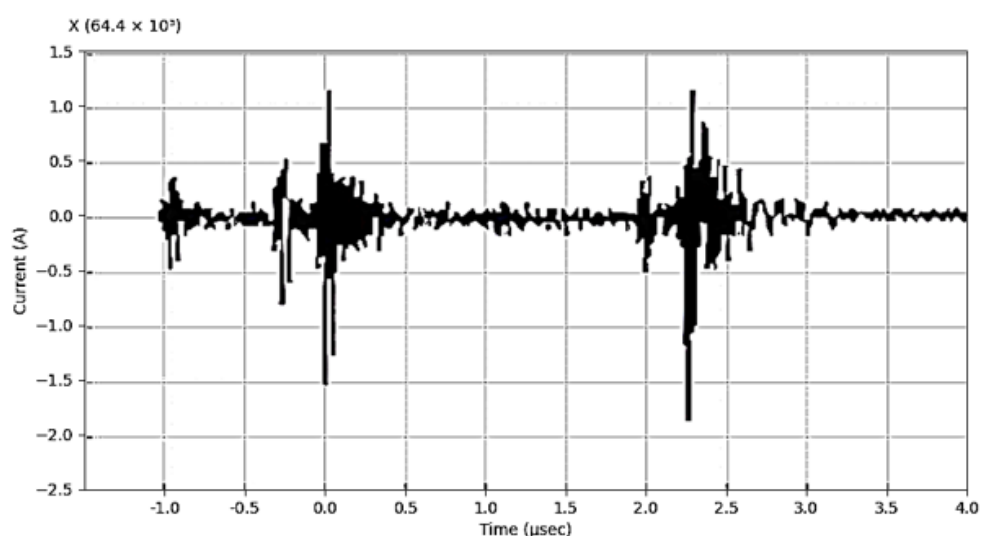


Figure 4. The behavior of arc current in samples subjected to a 1-h biasing voltage

The observed slight negative pulse is due to the surface that collected a substantial electron current from the plasma. Multiple peaks are observed in the current waveform.

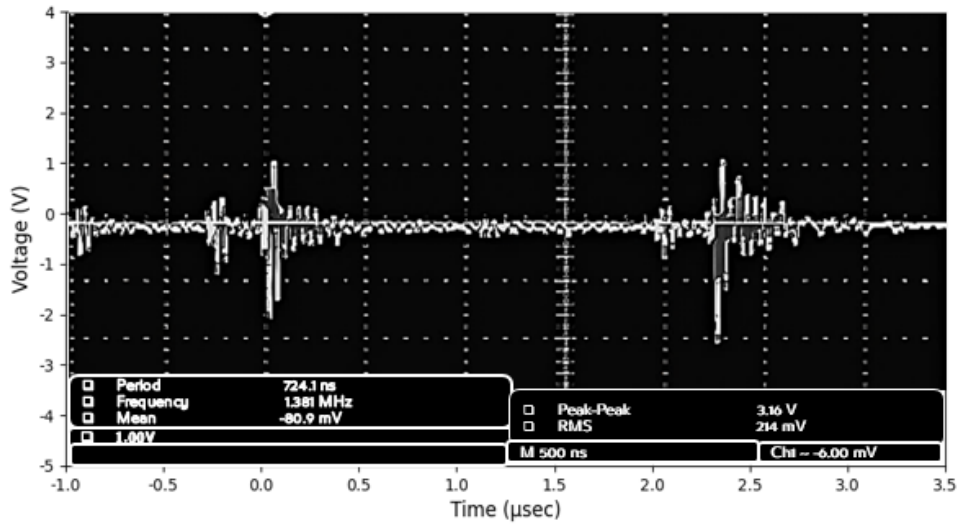


Figure 5. Behavior of the potential waveform in samples subjected to a biasing voltage for 1 h

In the second experiment, a negatively biased voltage of -450 V was applied to another set of four samples and exposed to simulated plasma for 2 h. When the pressure of the discharge unit reached approximately 1.8×10^{-4} Pa, the gas path was opened up to a value of 60 SCCM (μsec), resulting in the pressure of the discharge unit reaching approximately 2.3×10^{-2} Pa. The same resistance of 64.4 k Ω was applied to the circuit. Under these conditions, the samples were exposed to plasma for 2 h. The current traces and potential waveform during a discharge event are shown in Figures 6 and 7, respectively.

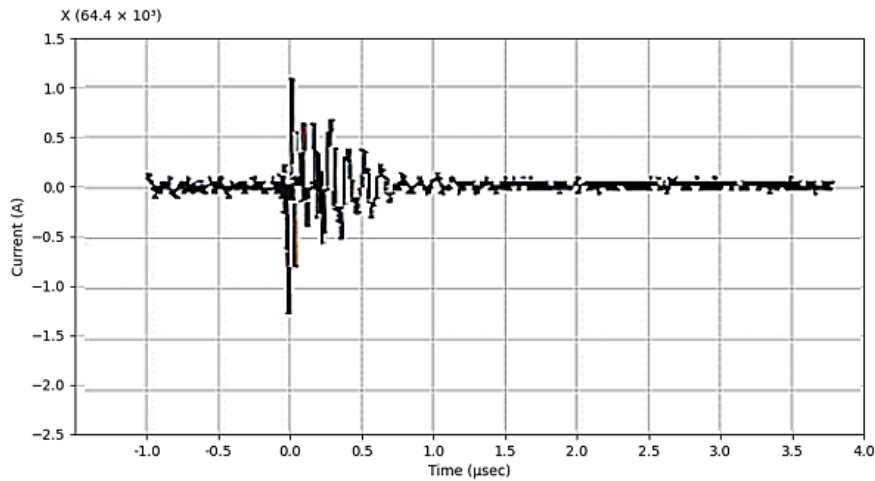


Figure 6. Arc current behavior in samples subjected to a 2-h biasing voltage

Figures 4–7 confirm that the current behavior depends on the duration of the discharge event. A typical discharging sequence reveals that the current increases to a peak value, which is dependent on the capacitance of the arc site. After a short time, the current decreases with roughly exponential decay. From Figures 6 and 7, it is noticeable that with the increase in the time of plasma exposure, several factors, such as the current trace, the decay in the discharge current waveform, and the duration of arc events, all take longer time to be repeated (more than 4 μsec).

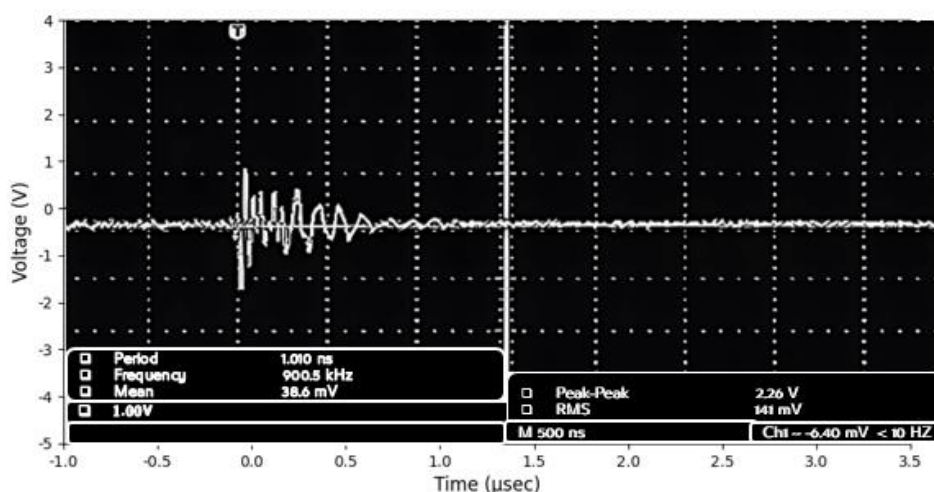


Figure 7. The behavior of the potential waveform in samples exposed to a biasing voltage for 2 h

With a short duration of plasma exposure, as shown in Figures 4 and 5, the discharge and arc events are continuously repeated, with multiple peaks of the current occurring after a short time, approximately around 2 μsec . This can be interpreted as the increase in exposure time may cause the rearrangement and redistribution of particles on the surface to be less porous. Consequently, the oxide-coated film on the surface becomes more homogeneous and uniform, resulting in a surface with fewer defects. This can lead to an improvement in the coated surface and enhance its resistance. As a result, there is a delay in the discharging sequences and arc events. The results confirm that surfaces with oxide coatings can mitigate the occurrence of discharging and arc events due to plasma exposure.

4.2. Structural analyses and physical characteristics

To confirm the plasma effects on the alloy characteristics, the analysis was focused on two samples with two different oxide film coating thicknesses, that is, 25 and 45 μm . The examination aims to clarify the variations in physical characteristics under the influence of simulated LEO-plasma. These two thickness values were selected to represent the lower and upper range of oxide film thicknesses considered in this study, enabling a comparative analysis of plasma effects on different coating levels. The analyses have shown that the results showed similar trends in optical absorbance and structural response; thus, the detailed discussion was limited to the two representative thicknesses. So, there is no need to repeat the analyses with other two coated thickness values.

4.2.1. Ultraviolet/Vis/NIR absorption spectral analysis

The Cary 5000 ultraviolet (UV)/visible (Vis)/NIR spectrophotometer is a high-performance instrument capable of superb photometric performance in the 175–3300 nm range. This instrument is used to check and analyze the optical characteristics of samples. Figure 8 illustrates the optical properties of an Al6061 alloy sample with an anodic film thickness of 25 μm . The absorption spectra of this sample were examined before and after plasma exposure. The figure is plotted for three different cases: the black line refers to the sample without plasma exposure, the red line represents the sample after 1 h of plasma exposure, and the green line indicates the sample after 2 h of plasma exposure. It is clear from the figure that significant absorption values are observed in the UV/Vis region, with higher peak absorbance compared to other regions. The peak values shift toward shorter wavelengths, indicating a narrow particle size distribution. As the wavelength increases, the absorbance sharply decreases to lower values toward the NIR region. It is also noted that the plasma is more effective, particularly at shorter

wavelengths, and this effect increases with the duration of plasma exposure. The same relationships are plotted for the sample with a thickness of 45 μm , as shown in Figure 9. The figure illustrates the same behavior observed in Figure 8. However, it is noted that the values of the peaks vary due to the differences in thickness.

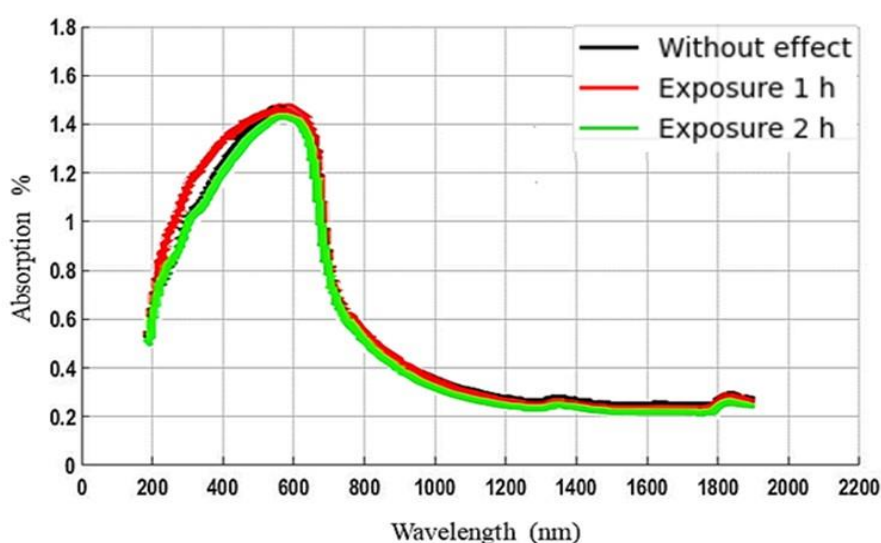


Figure 8. UV/Vis absorption spectra for a sample with a coating thickness of 25 μm

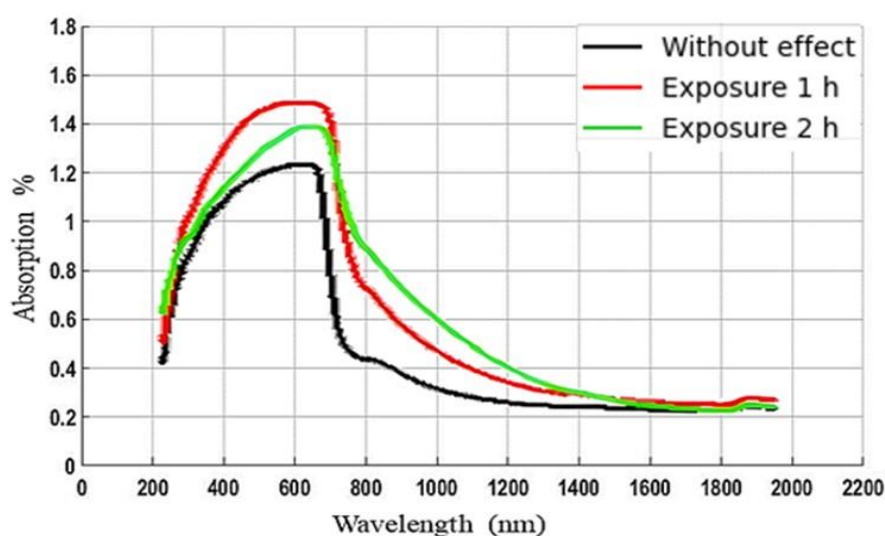


Figure 9. UV/Vis absorption spectra for a sample with a coating thickness of 45 μm

4.2.2. UV/Vis/NIR reflectance spectral analysis

The anodized samples were colored using an organic dye, which influenced the measured absorbance and reflectance spectra. The presence of the dye was considered during the interpretation of the optical results, as it contributes to the absorption behavior of the surface. However, the effect of the dye was not isolated in a separate control experiment. The primary objective of this study was to assess the effect of plasma interaction on anodized aluminum surfaces, including those subjected to standard surface treatment procedures. Further investigation is required to differentiate the optical contributions of the oxide layer and the dye independently. The variations in the reflectance spectra were examined for the same two samples under the same plasma exposure conditions. This is shown in Figures 10 and 11, which are plotted for the samples with coating thicknesses of 25 and 45 μm , respectively. For the

sample with a thickness of 25 μm (Figure 10), it is clear that in the UV/Vis region, the reflectance gradually decreases to lower values and tends to gradually increase near the infrared (IR) region. The figures also shows the variation in the level of reflectance values with the duration of plasma exposure.

For the sample with a thickness of 45 μm , the same relationship is plotted and shown in Figure 11. The reflectance behavior shown in Figure 11 differs from that in Figure 10. While the 2-h exposure sample demonstrated the highest reflectance across most wavelengths in Figure 10, the untreated sample showed the highest reflectance in Figure 11. This discrepancy may be attributed to differences in surface morphology, localized roughness, or thickness-related interference effects between the two samples. In particular, the higher reflectance of the untreated sample in Figure 11 may result from a more compact or smoother surface structure, leading to reduced light trapping. In addition, the partial overlap between the 1- and 2-h exposed samples suggests that the interaction between plasma and oxide structure is not linear and may involve competing effects such as surface reorganization and defect generation. Further investigations are needed to isolate the mechanisms responsible for this behavior. Absorbance values in Table 2 are presented with high numerical precision. Each value represents the average of three repeated measurements. The standard deviation for the majority of readings was within ± 0.002 , indicating good measurement repeatability. Sources of systematic error included alignment accuracy, instrument calibration, and surface uniformity. These were minimized through consistent measurement conditions. While the absorbance values for untreated Al6061 alloy were not included in this study, we acknowledge their relevance and intend to address this in future work to better quantify the effect of the surface treatment process. To determine the optimal thickness for the anodic oxide surface, we plotted the peak values provided in Table 2 in Figures 12 and 13. The resulting data indicated that the samples with an anodic film thickness of 25 μm exhibited the highest reflection.

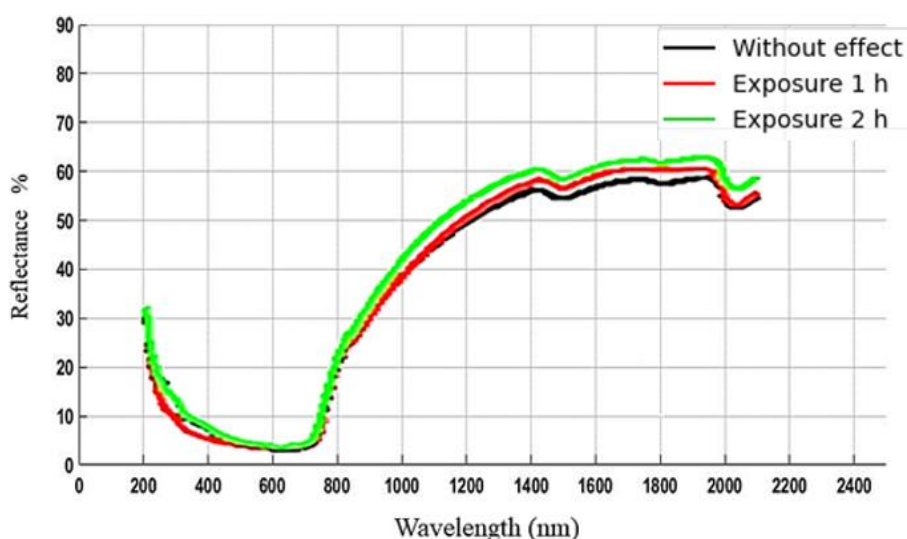


Figure 10. Reflectance of the 25- μm -thick sample

Table 2. Maximum absorbance and reflectance values for the two samples

Condition	45 μm		25 μm	
	Abs (max)	Ref (max)	Abs (max)	Ref (max)
Without the plasma effect	1.18935	50.4173	1.451	66.9496
Plasma exposure (1 h)	1.4533	51.9398	1.532	67.1468
Plasma exposure (2 h)	1.35128	51.962	1.486	71.105

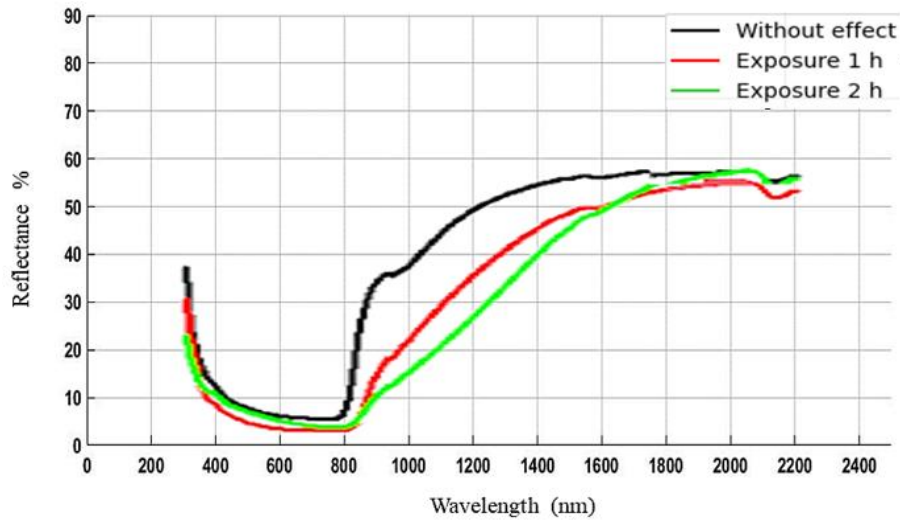


Figure 11. Reflectance of the 25- μm -thick sample

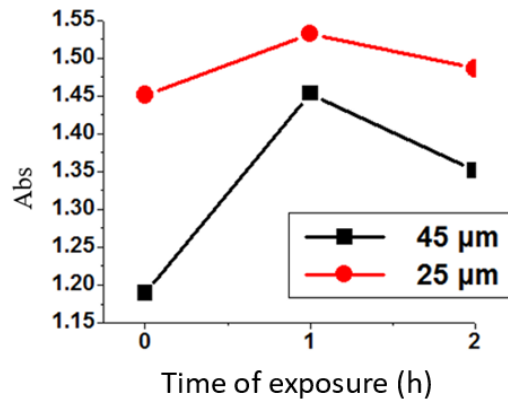


Figure 12. Peak values for the two samples at various times of plasma exposure in the absorption case

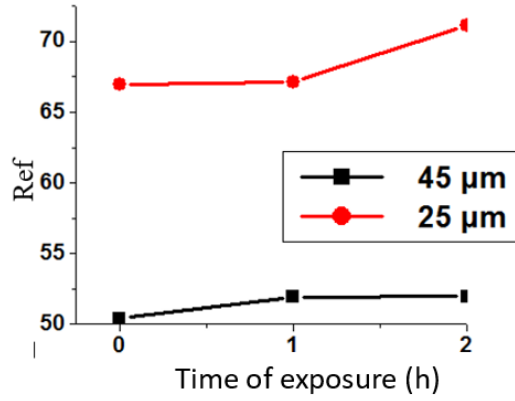


Figure 13. Peak values for the two samples at various plasma exposure times in the reflectance case

The absorbance of the sample with lower thickness was higher compared to the thicker sample. The absorption spectra results confirm that the absorbance in the UV/Vis region increases with plasma exposure time, both at 1 and 2 h, compared to the absence of plasma effect. This may be attributed to reduced porosity and particle redistribution; however, this interpretation is based solely on optical results. Therefore, the surface becomes rougher, and the absorbance is reduced with increasing exposure time. This can be interpreted as the plasma causing collisions of surface particles, leading to rearrangement and redistribution of particles on the surface, resulting in denser particulates and reduced porosity. In addition, changes in the mass of the coated thickness occur due to the removal of impurities, resulting in an enhancement of the coating morphology. This leads to the surface becoming smoother, with fewer contaminants, resembling a polished surface. The results indicate that plasma exposure modifies the reflectance properties of the oxide layer; however, the trend is not strictly monotonic with exposure time. In particular, the 1-h exposure sample shows higher reflectance than the 2-h sample in the wavelength range of approximately 850–1600 nm, suggesting a nonlinear relationship between plasma duration and optical response. This trend is consistent with the optical behavior reported in Keçebaş and Şendur (2018), where similar plasma-induced effects were observed. The analysis of absorbance and reflectance results suggested possible changes in the surface structure and roughness of the oxide layer due to plasma interaction. However, these interpretations are based on optical measurements alone and do not include direct structural or topographical evidence such as Scanning Electron Microscopy (SEM) or atomic force microscopy (AFM) analysis. As a result, the conclusions regarding changes in structure and roughness remain indicative and not definitive. Since this study relies solely on optical measurements, further morphological characterization, such as SEM or AFM analysis, is necessary to validate the proposed interpretations.

4.3. EDX analysis

The EDX technique is employed to analyze the variation in atomic concentrations for the elements in the alloy sample under the effect of plasma exposure. EDX analyses are performed on a sample with a coated thickness of 45 μm to ensure the effects of the denser oxide layer on the sample characteristics. Figure 14 and Table 3 present the EDX analysis of the sample without plasma exposure. Figure 15 and Table 4 show the EDX analysis of the sample exposed to plasma for 1 h, and Figure 16 and Table 5 display the EDX analysis of the sample exposed to plasma for 2 h. The images in Figures 14–16 show regions with surface charging effects, visible as bright areas likely resulting from electron accumulation on dielectric features. These effects may influence the accuracy of localized elemental analysis. To reduce this impact, multiple measurement points were analyzed, and consistent compositional trends were

confirmed across different regions of the sample. The analyses show the total percentage of the elemental composition for the surface of the sample. The figures and data table clarify the variation in the concentration of the alloy elements due to plasma exposure. SEM images of the sample surface are shown in the figures. The observed different elements have different surface binding energies, and the differences have a significant effect on propagation of the collision cascade. The elements carbon (C) and sulfur (S), shown in the figures, are considered impurities and contaminants embedded in the alloy during manufacturing. Plasma exposure reduces the concentration of these elements by approximately 10% of their total initial concentration. This indicates the removal of these impurities. In addition, after plasma exposure, the concentration of oxygen (O) in the oxide layer decreases slightly, by around 9%, compared to the values before plasma exposure. This reduction is evident from the atomic concentration values of "OK." The results in the data tables show that the oxide layer is not completely removed and it retains a significant value, approximately 45% of the total Al_2O_3 compound. These substantial OK values confirm that the oxide layer still influences the optical characteristics of the sample. These results align with the findings from the UV/Vis/NIR analyses and confirm that a thinner oxide coating on the sample yields the best properties. Moreover, the SEM images reveal that only a small portion of the oxide layer is removed after plasma exposure. This removal likely results from sputtering and etching of particulates on the sample surface, effectively eliminating impurities and enhancing surface cleanliness. This can lead to more homogeneity and arrangement occurring on the grain and particle concentrations, and then the surface becomes more polished and glossier. The results shown in Tables 3–5 are presented as whole number approximations, reflecting the inherent accuracy limits of the SEM–EDX technique. In particular, the quantification of carbon content remains subject to significant uncertainty due to potential contamination in the SEM chamber and from the vacuum system. These effects are well documented in literature and are often mitigated by using high-purity reference samples and chamber cleaning protocols, which were not available in the current setup. Therefore, the presented carbon values are considered qualitative rather than absolute. The interpretation of the data has been adapted accordingly.

Table 3. Quantitative analysis of the sample excluding plasma effects

Element	Weight %	Atomic %
CK	16.73	19.98
OK	45.72	50.16
Al K	32.27	27.78
Si K	0.51	0.23
S K	4.77	1.85
Total	100	100

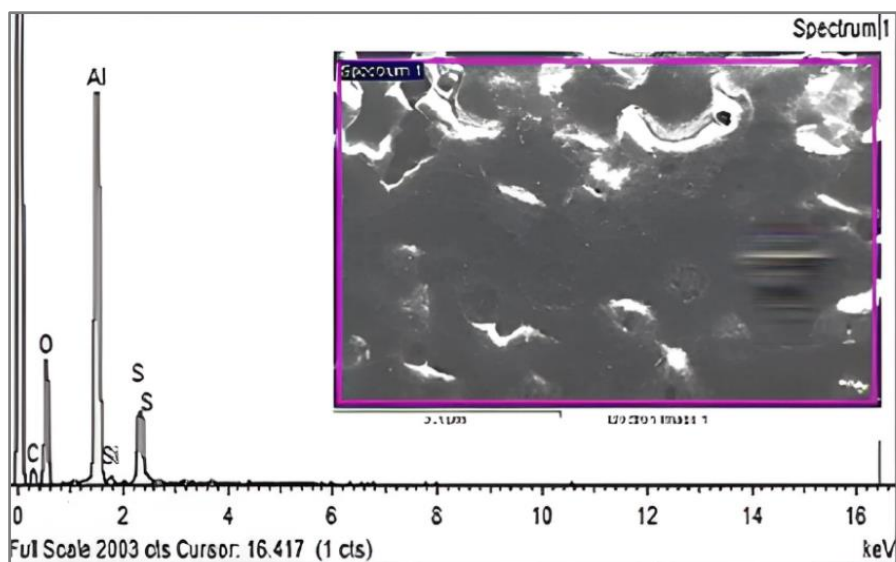


Figure 14. EDX analysis of the 45- μ m-thick sample before plasma exposure

Table 4. Quantitative analysis of the sample after 1 h of plasma exposure

Element	Weight %	Atomic %
CK	13.23	16.28
OK	42.63	46.06
Al K	39.39	36.16
Si K	0.33	0.15
S K	4.42	1.35
Total	100	100

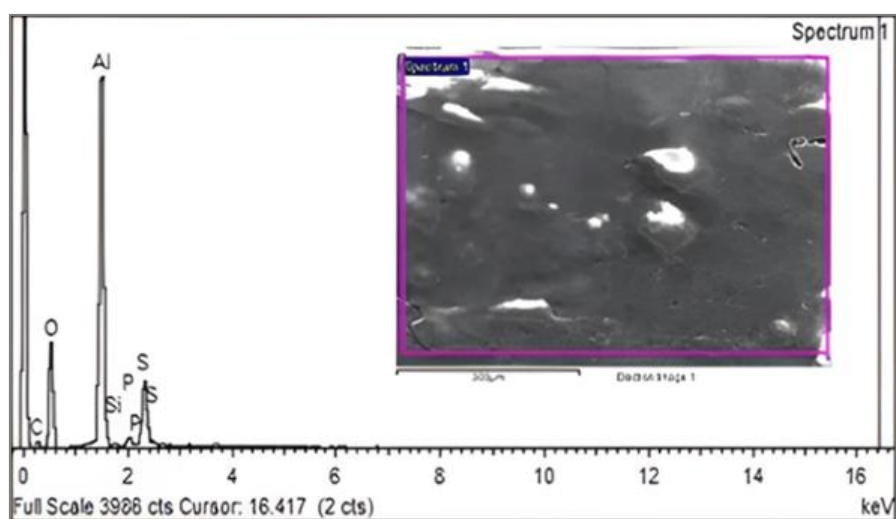
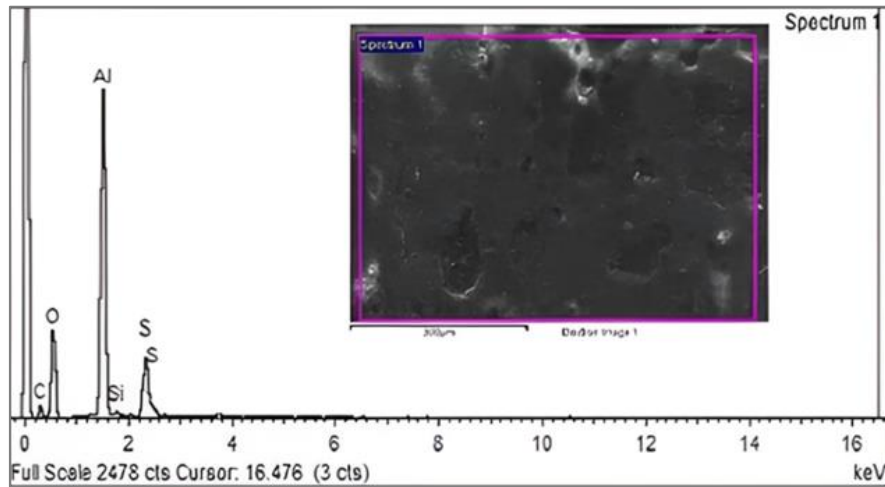


Figure 15. EDX analysis of the 45- μ m-thick sample after 1 h of plasma exposure

Table 5. Quantitative analysis of the sample with 2 h of plasma exposure

Element	Weight %	Atomic %
CK	12.86	15.81
OK	40.79	44.09
Al K	41.63	38.57
Si K	0.48	0.22
S K	4.24	1.31
Total	100	100

**Figure 16.** EDX analysis of the 45-μm-thick sample after 2 h of plasma exposure

4.4. Surface roughness testing

Surface roughness tests were conducted to assess the changes in the formation and surface structure resulting from plasma exposure. The analyses are performed on the same two samples mentioned earlier, both before and after 2 h of plasma exposure. Test conditions and the resulting data of the average roughness for the two samples are presented in Table 6.

Table 6. Average surface roughness values for the two samples

Condition	Surface roughness (μm)	
	Sample with a thickness of 45 μm	Sample with a thickness of 25 μm
Without plasma effect	1.8178	1.831
With plasma exposure (2 h)	1.2291	1.5157

The data in Table 6 show that before plasma exposure, increasing the coating thickness resulted in a decrease in surface roughness. This suggests that higher coating thickness leads to reduced grain sizes and porosity, resulting in decreased surface distortion and deformation. On the contrary, the data shows a reduction in surface roughness after plasma exposure, indicating a smoother surface due to processes like sputtering, etching, and the removal of impurities. Both coating thickness and plasma exposure time significantly affect the surface porosity. The

roughness values presented in this section were derived from linear profile measurements and are shown with adjusted precision to reflect the instrumental resolution. No statistical or systematic error analysis was performed for these values. As such, the results should be considered approximate. It is important to note that surface roughness alone cannot provide definitive conclusions regarding the structure or phase composition of the oxide layer. For a more complete understanding, future studies should incorporate detailed surface imaging and phase identification methods, such as XRD or AFM, to validate the observed morphological changes.

5. CONCLUSIONS

This research focused on analyzing the effects of LEO-plasma exposure on anodized aluminum alloy samples Al6061-T6. The experiments were conducted at the Laboratory of Lean Satellite Enterprises and In-Orbit Experiments, Kyushu Institute of Technology, Japan. The study thoroughly investigated the characteristics of argon (Ar) plasma and its impact on the anodized aluminum alloy. Samples with anodic coating thicknesses of 20, 25, 35, and 45 μm were tested to determine the optimal surface characteristics for space applications. In addition, a negatively biased voltage of -450 V was applied to the samples to study charging/discharging phenomena. The results indicate a delay in the initiation of discharging and arc events, likely due to prolonged plasma exposure. This observed delay suggests a possible improvement in surface uniformity and electrical insulation characteristics, although no direct structural or compositional verification has been provided. As a result, there was a reduction in porosity, leading to a more uniform surface. These findings support the idea that oxide-coated surfaces can alleviate discharging and arc processes induced by plasma exposure. The study examined the physical characteristics of two samples with thicknesses of 25 and 45 μm , representing low and high anodic oxide coatings, respectively. The analysis focused on the morphological structure, optical properties, and surface roughness to assess how these characteristics vary with the duration of plasma exposure. The UV/Vis/NIR absorption and reflection spectra were analyzed, which showed that absorption peaks occurred at shorter wavelengths and decreased as the wavelength increased. Conversely, the reflectance spectra exhibited an opposite trend. The analyses confirmed that plasma exposure duration impacted the peak values of both absorbance and reflectance. In addition, EDX analyses demonstrated changes in atomic concentrations and the total percentage of each element in the alloy due to plasma exposure. The roughness test results confirm that the surface morphology and microstructures of the alloy vary due to plasma effects. The analyses show that plasma exposure influences the physical characteristics of the alloy. In the context of our project to design the surface structure of the LEO orbital TEDD-CubeSat, selection of 25 μm as an optimal thickness is based on a balance between optical performance and discharge mitigation, in line with TEDD-sat's mass and surface constraints. The increased thickness values can add weight and mass to the surface. However, this thickness is compatible with operational subsystems and minimally affects system performance, thereby aiding in achieving the necessary mission life. The findings of this study will aid satellite and aerospace designers in selecting optimal oxide film coatings for CubeSat structures. In our forthcoming research, we will investigate the thermal stability and conduct thermal vacuum cycling tests on surface samples coated with different thicknesses of oxide coatings. These experiments will simulate space-relevant temperature cycles to assess coating stability and degradation patterns.

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