THE USE OF PHOTOVOLTAIC CELLS FOR IN-ORBIT ATOMIC OXYGEN MEASUREMENTS

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ABSTRACT

Atomic Oxygen (AO) is the predominant neutral specie in the Low Earth Orbit (LEO) environment and considered as an important hazard to spacecraft materials. Measuring AO flux in-orbit and obtaining an accurate data may contribute to the design of the next generation spacecraft, mainly in terms of reduction of AO protection coatings.

Currently, AO flux can be measured by a variety of techniques including witness sample mass loss, quartz crystal microbalance (QCM), mass spectrometry, actinometers, and catalytic probes. These methods are either extremely expensive, require a retrieve of the samples, or complicated to implement on board of a spacecraft. In this study a new approach is proposed in which photovoltaic cells, an existing component onboard of any satellite, are utilized for In-Orbit Materials Degradation (IOMAD) measurements.

The IOMAD sensor's principle of operation is based on a change of the photovoltaic cell output as a function of AO fluence. The photovoltaic cell is pre-coated by a thin layer of AO sensitive material, such as Kapton or amorphous carbon (a:C). The photovoltaic cell output depends on the optical transmittance of the coating. AO erosion affects the coating optical transmission and, accordingly, the photovoltaic cell output.

The experimental work was performed using two Si-based photovoltaic cells. The first photovoltaic cell was coated with a thin layer of either Kapton or a:C. The second photovoltaic cell was left uncoated and used as a reference. The thickness of the coated layer was measured using an Atomic Force Microscope (AFM). A conventional RF plasma reactor was used to simulate the effect of AO in the LEO environment and a Xe lamp was used to simulate the solar spectrum. The cell’s output, measured in terms of $V_{oc}$ and $I_{sc}$, changed as a function of coating thickness and reached a plateau upon complete coating erosion. AO equivalent fluence was obtained based on a known coating thickness and erosion yield.

The proposed IOMAD sensor reveals a large dynamical range; carbon coating can be used for AO equivalent fluences at the order of $10^{18}$-$10^{19}$ O-atom/cm$^2$, while Kapton extends its use to the order of $10^{20}$-$10^{21}$ O-atom/cm$^2$.

1. INTRODUCTION

Satellites, launched into low Earth orbit (LEO) altitudes, from 200 to 1000 km, are exposed to an environment which possesses many obstacles to a successful spacecraft mission. The degrading LEO environment includes atomic oxygen (AO), ultraviolet (UV) and ionizing radiations, ultrahigh vacuum (UHV), thermal cycles, micrometeoroids and orbital debris [1]. A constituent of particular concern for materials in the LEO environment is AO which can oxidize and erode many materials and especially polymers which are used in thermal control blankets [2]. AO is formed when short wavelength ultraviolet radiation (>5.12 eV, <243 nm) from the Sun dissociates molecular oxygen in the upper atmosphere [3]. Due to separate, combined or synergistic interactions with these space hazards, polymers in particular suffer a relatively rapid erosion, structure modification and surface roughening [4, 5].

The durability of materials to the LEO environment in general, and their response to AO in particular, is in a focus of both technological and scientific communities for the last three decades. During the past years different methods were developed for AO flux measurements. Most of these methods are indirect and are based on material response to AO erosion. The first method which was used for AO flux and fluence measurements is based on the exposure of witness samples in LEO and retrieval of the samples to Earth for post flight assessment. The need to retrieve the samples makes this method of no use for most of the space projects [6].

Quartz crystal microbalances (QCMs) have been used to measure erosion of polymers and AO fluence by coating the exposed face of the crystal with hydrocarbon polymers or carbon films. As the material erodes, the beat frequency of the QCM changes, thereby measuring the AO erosion rate. The use of QCM requires special infrastructure and for high fluence missions unacceptably thick coatings are needed. However, for low fluence missions very sensitive measurements can be achieved [7].

Mass spectrometers have been widely used for AO fluence measurements and for detection of AO/polymer reaction products. However, the usage of such devices is not applicable in small scale satellites due to their large size, mass and power consumption [2, 8].
Another technique that was applied to satellite missions is based on thin film actinometry. In this method, thin films of materials which are reactive with AO and electrically-conductive are deposited onto an inert and electrically-insulating substrate. AO equivalent flux and fluence measurements are obtained from the resistance change of the film as it is eroded. Carbon, silver and osmium have been used to measure AO equivalent fluence in this method [9, 10].

A new technique based on the optical transmission of semitransparent materials was recently developed in NASA for the measurement of AO equivalent flux and fluence. In this method, an optical sensor, for example a photodiode, is covered with a material sample. As the sample thickness decreases due to AO erosion, the optical transmission of the material increases. Sunlight is used as the source in this method [11].

The purpose of this work is to present a new In-Orbit Material Degradation (IOMAD) sensor. The IOMAD sensor is based on photovoltaic cells, devices which exist in any satellite. The IOMAD sensor’s principle of operation is also based on optical transmission changes due to AO erosion. However, it depends on the erosion mechanism of the covering material and especially on the developed surface morphology. The IOMAD is a cheap and reliable sensor which can be used for either AO equivalent fluence measurements or for real time in-orbit material degradation evaluation.

2. EXPERIMENTAL

2.1 Experimental setup

Fig. 1 shows a schematic presentation of the IOMAD sensor’s principle of operation. The IOMAD sensor uses two Si-based photovoltaic cells manufactured by EADS, Astrium. The first cell is covered by a semitransparent film which erodes under AO irradiation. The second cell serves as a reference.

Two parameters $V_{oc}$, the open-circuit voltage and $I_{sc}$, the short-circuit current generated by each cell are measured separately. In order to consider both parameters in each measurement, $P$, the theoretical maximum power was defined and calculated according to Eq. 1:

$$ P = V_{oc} \times I_{sc} $$

(1)

In order to avoid illumination power and temperature variation effects, the normalized maximum power ratio $P_n$ of both photovoltaic cells was defined as:

$$ P_n = \frac{P_c}{P_r} $$

(2)

Where $P_c$ is the coated cell’s theoretical maximum power and $P_r$ is the reference cell’s theoretical maximum power. The two cells, which form the IOMAD sensor, were exposed simultaneously to ground simulated solar spectrum and AO under vacuum conditions. The cells were illuminated by a Xe lamp (1000 W, Model 6269 from Newport) through a Quartz window at an intensity of 1366 W/m$^2$, which equals to one Solar Constant (SC) at zero Air Mass (AM), as per ASTM E 490-00A standard [12].

Exposure to AO was performed using a conventional RF plasma reactor (3000 W, 1.7-3 MHz, Model Litmas RPS 3001 from Advanced Energy), operating at 170 mTorr of oxygen. Samples were located downstream from the reactor, in the afterglow region where they were exposed to a mixture of atomic and molecular oxygen, excited species and vacuum UV (VUV) radiation [13]. Comparison of the covered cell theoretical maximum power to the uncovered reference cell theoretical maximum power provide real time data regarding AO fluence.

2.2 Materials

The optical semitransparent materials which were used in the IOMAD sensor were films of Amorphous Carbon (a:C) and Kapton. A 200 nm-thick a:C film was prepared by a graphite sputter coater (Model CA7652 Carbon Accessory from Quorum Technologies). The Kapton HN Polyimide was a 125 µm-thick film from DuPont, Inc..

The in-space erosion yield of Kapton HN is well documented as $3.0 \times 10^{-23}$ cm$^3$/O-atom [14]. In order to find the erosion yield of the a:C under the experimental conditions of this work, Polyimide and a:C coated QCM crystals were exposed to AO. Based on these experiments the erosion yield of the a:C was found to be $0.8 \times 10^{-24}$ cm$^3$/O-atom. This value is within the range of
graphite (sp²) and graphite-like films’ erosion yield, reported previously [15].

2.3 Characterization techniques

Optical transmission measurements of a:C films were measured using a UV-VIS spectrophotometer (Model V-570 from Jasco), at wavelengths from 200 to 900 nm. The roughness of RF plasma-exposed samples was studied using an atomic force microscope (AFM) (MultiMode, Nanoscope IV from Veeco). For each of the images the root mean square (RMS) roughness, \( R_q \), is given and defined as follows:

\[
R_q = \sqrt{\frac{\sum (Z_i - Z_{ave})^2}{N}}
\]  

(3)

where \( Z_{ave} \) is the average Z height value within a given area, \( Z_i \) is the current Z value and \( N \) is the number of points within the given area.

LEO equivalent AO fluence was determined gravimetrically, based on Kapton mass loss, using an analytical balance (Model UM3 from Mettler) with an accuracy of ±1 µg.

3. RESULTS

The main principle of operation of the IOMAD sensor is the effect of reduction in thickness of a semitransparent material on the output of a photovoltaic cell. The semitransparent material is placed on top of the photovoltaic cell and its thickness is reduced due to AO attack. In order to verify this simple idea, a set of glass slides were coated with a:C films having different thicknesses. Fig. 2 shows both experimental and theoretical results of the effect of the a:C film thickness on its optical transmission. The theoretical results were calculated according to Beer-Lambert law of absorption, i.e. the intensity \( I \) of radiant energy passing through a homogeneous absorbing medium decreases exponentially as the medium thickens according to the equation:

\[
I = I_0 \exp(-\alpha_a x)
\]  

(4)

where \( I_0 \) is the incident intensity, \( \alpha_a \) the absorption coefficient, and \( x \) the thickness of the medium [16]. The absorption coefficient of a:C was taken as \( 1 \times 10^{-4} \text{ cm}^{-1} \) [17, 18].

The results presented in Fig. 2 show qualitatively the correlation between the experimental and calculated data. According to these results, when AO erodes the a:C film, its optical transmission is expected to increase exponentially.

Fig. 3 presents experimental results of the normalized power, \( P_{Rv} \), of a 200 nm-thick a:C coated IOMAD sensor as a function of AO erosion time. The IOMAD sensor was exposed to an intensity which equals one SC at zero AM. As a result of this irradiation the photovoltaic cell's temperature increased from room-temperature to 55ºC.

\[
F_k = \frac{\Delta x_k}{E_s}
\]  

(5)

\[
f_k = \frac{F_k}{t}
\]  

(6)

Where \( F_k \) is the fluence, \( \Delta x_k \) is the thickness loss of the coating, \( E_s \) is the erosion yield, \( f_k \) is the effective flux and \( t \) is the time of erosion. According to Eq. 5, the AO equivalent fluence needed for the erosion of a 200 nm thick a:C is \( 2.5 \times 10^{19} \text{ O-} \).
atom/cm². According to Eq. 6 and the results of Fig. 3, the flux which was measured by the IOMAD sensor during this experiment was calculated as $2.3 \times 10^{14}$ O-atom/cm²·s.

Fig. 4 shows images of the a:C coated IOMAD sensor before (Fig. 4a) and after (Fig. 4b) exposure to the RF plasma environment. The upper photovoltaic cell in each image is the a:C coated cell, while the lower one is the reference cell.

Fig. 4b shows an uneven erosion of the a:C coating. At the center the 200 nm a:C coating was totally eroded with much less erosion at the peripheral regions. According to Fig. 3, after 1800 min. of exposure to the RF plasma environment, the normalized maximum power ratio, $P_{R}$, remained constant at a value of 94%. According to these results the AO flux at the center of the vacuum chamber was significant, as calculated earlier, while at the circumference of the chamber only negligible AO flux was present.

Fig. 4. Images showing the a:C coated IOMAD sensor before (a) and after (b) exposure to the RF-plasma environment.

Unlike the a:C erosion experiment presented in Fig. 3, in which $P_{R}$ increased as a result of the exposure to the AO equivalent flux, the results presented in Fig. 5 show an opposite behavior. As the LEO equivalent AO fluence increased, $P_{R}$ decreased. The decrease in $P_{R}$ can be divided into two parts: slow decrease up to a fluence of $1.1 \times 10^{21}$ O-atom/cm² followed by fast decrease up to a fluence of $1.7 \times 10^{21}$ O-atom/cm², where the experiment was stopped. The reduction in $P_{R}$ represents a decrease in the Kapton's optical transmission although the film thickness decreased with the AO fluence, in contrast with Beer-Lambert law. The unexpected response of the Kapton's optical transmittance to AO erosion required a deeper insight into this issue, which eventually revealed an additional application for the IOMAD sensor, as will be further discussed.

Fig. 5. IOMAD sensor normalized power change due to erosion of 125 µm-thick Kapton by RF-plasma, using the IOMAD sensor.

Fig. 5 presents the change in $P_{R}$ as a function of the LEO equivalent AO fluence. In order to achieve independent fluence measurements during this experiment, the Kapton mass loss was periodically measured. Unlike the a:C erosion experiment presented in Fig. 3, the reduction in $P_{R}$ represents a decrease in the Kapton's optical transmission although the film thickness decreased with the AO fluence, in contrast with Beer-Lambert law. The unexpected response of the Kapton's optical transmittance to AO erosion required a deeper insight into this issue, which eventually revealed an additional application for the IOMAD sensor, as will be further discussed.

Fig. 6 shows images of the Kapton covered IOMAD sensor before (Fig. 6a) and after (Fig. 6b) exposure to the RF-plasma environment. The pristine Kapton on Fig. 6a appears glossy, while the Kapton exposed in the RF plasma to AO equivalent fluence of $1.7 \times 10^{21}$ O-atom/cm² (Fig. 6b) appears matt and opaque. Exposure to an AO fluence of $1.7 \times 10^{21}$ O-atom/cm² results in thickness loss of about 50 µm [14]. According to Beer-Lambert law, in a homogeneous absorbing medium the decrease in thickness is related exponentially to an increase in optical transmission. The decrease in the Kapton's optical transmission is therefore related to another mechanism, in which the decrease in its thickness and Beer-Lambert law are less significant.
Fig. 6. Images of the Kapton coated IOMAD sensor before (a) and after (b) exposure to the RF plasma environment.

Fig. 7 shows Kapton's surface roughness and its optical transmission as a function of AO fluence. The optical transmission measurements of Fig. 7 were performed using a conventional spectrometer and not with the IOMAD sensor. The results show a reversed dependence between Kapton's surface roughness and its optical transmission as the AO fluence increased. As was presented in Fig. 5, the decrease in optical transmission can be divided into two parts: (i) slow decrease from 100 to 80 % up to an AO equivalent fluence of $1.1 \times 10^{21}$ O-atom/cm$^2$ and (ii) fast decrease in the Kapton's optical transmission from 80 to 0 % up to an AO equivalent fluence of $1.7 \times 10^{21}$ O-atom/cm$^2$. The Kapton's roughness measurements show a reversed behavior. A slow increase in surface roughness from 10 to about 130 nm was observed up to an AO fluence of $1.1 \times 10^{21}$ O-atom/cm$^2$ and a fast increase in the Kapton's surface roughness from 130 to 800 nm was observed up to an AO equivalent fluence of $1.7 \times 10^{21}$ O-atom/cm$^2$. These results are in agreement with previous works in which morphology and light scattering from polymeric surfaces were investigated and correlated [19, 20].

4. DISCUSSION

The results show the potential of the IOMAD sensor to serve both as an AO detector and to correlate its output to surface morphology and roughness buildup in semi-crystalline polymers.

In general, AO exposure to amorphous materials such as a:C, results in a uniform erosion of the surface and the optical transmission is expected to increase exponentially. This exponential increase is demonstrated in Fig. 2, in accordance with the Ber-Lambert law. However, during the IOMAD sensor experiment as shown in Fig. 3, the optical transmission, expressed in terms of normalized output power, $P_R$, increased logarithmically and not exponentially. The image of the IOMAD sensor at the end of the experiment (Fig. 4b) showed an uneven erosion of the a:C coating. The coating at the center was totally eroded while at the circumference the coating appears almost unchanged. As a result of the uneven erosion, different areas of the IOMAD sensor may be exposed to different light intensities from the Xe lamp.

In order to understand whether the logarithmical increase in optical transmission is associated with the uneven erosion and non-uniform light intensity, the following experiment was conducted. A photovoltaic cell was exposed to one SC light intensity while its irradiated area was changed, ranging from 1 to 8 cm$^2$. The results of this experiment are presented in Fig. 8, showing a logarithmical increase in the photovoltaic cell's output power as a function of the irradiated area.
These results demonstrate that the logarithmic increase in $P_R$ during the $a$:C erosion experiment is the result of an uneven erosion. Using a source with a large uniform AO flux, such as in LEO, will result in an exponential increase in $P_R$.

Unlike the $a$:C erosion experiment in which $P_R$ increased as a result of the exposure to the RF plasma environment, the results of Kapton erosion showed an opposite behavior, $P_R$ decreased as the AO fluence increased. The decrease in $P_R$ can be divided into two linear parts, slow decrease up to an AO equivalent fluence of $1.1 \times 10^{21}$ O-atom/cm$^2$ followed by fast decrease up to a fluence of $1.7 \times 10^{22}$ O-atom/cm$^2$. The results show a reversed dependency between Kapton's surface roughness and its optical transmission as the AO fluence increased. Within the sensitivity of our measurements, the curve inflection in the decrease of $P_R$ took place at Kapton's RMS roughness of about 130 nm, as shown in Figs. 5 and 7. The reason for this curve inflection at 130 nm RMS roughness may be considered in terms of geometrical optics [21], by electromagnetic wave scattering from the roughened surface. That is, at this point the spectrum of the Xe lamp, which starts at 185 nm resembles the surface RMS roughness height. It is assumed that when the roughness exceeds the Xe spectrum minimum wavelength of 185 nm, light scattering becomes more dominant and optical transmission decreases dramatically. The proposed IOMAD sensor reveals a large dynamical range; $a$:C coating can be used for AO equivalent fluences at the order of $10^{18}$-$10^{19}$ O-atom/cm$^2$, while Kapton extends its use to the order of $10^{20}$-$10^{21}$ O-atom/cm$^2$.

5. SUMMARY AND CONCLUSIONS

A new in-orbit material degradation and AO flux and fluence measuring sensor was presented. The IOMAD sensor is based on two photovoltaic cells, devices which exist on any satellite. One of the cells is covered by a semitransparent film which erodes under AO irradiation, while the other serves as a reference. The semitransparent materials used for testing the IOMAD sensor were $a$:C and Kapton films. With the right material choice, the IOMAD sensor can be sensitive to either AO fluence measurements and for material degradation evaluation. The $a$:C coated IOMAD sensor exposed to RF plasma environment showed monotonic increase in its output until a plateau was reached as the coating was eroded to its full depth. The increase in the IOMAD sensor output is attributed to uniform erosion of the $a$:C coating. Kapton covered IOMAD sensor exposed to RF plasma environment showed opposite behavior; as the AO fluence increased, the sensor's output decreased. The decrease can be divided into two linear parts, a slow decrease at the first stage, followed by a fast decrease at higher AO fluences. Due to the AO exposure, Kapton appeared matt and opaque, an indication of rough surface formation. Further investigation revealed a reversed dependency between Kapton's surface roughness, which increased with the AO fluence, and its optical transmission. It is assumed that when the roughness exceeds the Xe spectrum minimum wavelength of 185 nm, light scattering becomes more dominant and optical transmission decreases dramatically. The proposed IOMAD sensor reveals a large dynamical range; $a$:C coating can be used for AO equivalent fluences at the order of $10^{18}$-$10^{19}$ O-atom/cm$^2$, while Kapton extends its use to the order of $10^{20}$-$10^{21}$ O-atom/cm$^2$.

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6. REFERENCES


