ATOMIC OXYGEN-INDUCED EROSION OF SPACECRAFT MATERIALS –POTENTIAL HAZARDS FOR SPACECRAFT SYSTEMS–

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Abstract

In low Earth orbit (LEO) where 200-500 km in altitude, highly reactive atomic oxygen, which is the dominant species in the upper atmosphere of the Earth, bombards the polyimide surface which is widely used as a passive thermal control material at the exterior of spacecraft. Erosion of polyimide by atomic oxygen is very severe, research efforts have been intensively paid in the last two decades. Since polyimide has also been widely used in electrical systems of satellites, this paper provides an overview of the erosion properties of polyimide materials in an LEO space environment through ground-based simulation. The ground-based simulation technique and recent research results regarding hyperthermal atomic oxygen reaction with polyimide are described, including changes in surface composition due to air exposure, non-linear mass loss phenomenon, impingement angle and sample temperature dependences on gasification reaction. The synergistic effect on polyimide erosion with ultraviolet exposure in LEO and surface charging are also discussed.

1. Introduction

A number of spacecraft and satellites are operated in the altitude range between 200-700 km from sea level, which is called low Earth orbit (LEO). In LEO, the dominant atmospheric species is ground-state atomic oxygen ($O(^3P)$), which is produced by photodissociation of O_2:

$$O_2 + h\nu \ (<250nm) \Rightarrow O(^3P) + O(^3P) \quad\quad\quad (1).$$

Although, the density of atomic oxygen in LEO is low (10^7 -10^9 atoms/cm^3), but the orbital velocity of spacecraft is as high as 7800 m/s, resulting in a high atomic oxygen flux (10^{13} - 10^{15} atoms/cm^2/s) [1]. Since the orbital velocity of the spacecraft is greater than the thermal velocity of atomic oxygen in LEO, spacecraft surfaces directed to the velocity vector of spacecraft were suffered by the bombardment of atomic oxygen with an average impact velocity of 7800 m/s. This relative impact velocity corresponds to the impinging energy of atomic oxygen beam in a ground-based facility as high as 5 eV. Such a high-energy collision with chemically active atomic oxygen induces surface reactions with exterior surfaces of the spacecraft. Satellites are usually covered by a multilayer thermal insulation (MLI) whose outermost surface is made of polyimide or fluorinated polymers like ethylene propylene (FEP) Teflon. The degradation of polymeric materials due to high-energy collisions with atomic oxygen is so severe, a few micrometers in thickness is lost within a few tens of hours of atomic oxygen exposure in LEO [2]. Figures 1 shows scanning electron microscopy (SEM) images of a polyimide surface exposed to atomic oxygen with fluence of 3 x 10^{20} atoms/cm^2. The exposed surface becomes rough and many sharp peaks are obvious. This surface structure is called "shag carpet-like structure" and is characteristics of a surface that has suffered high-energy atomic oxygen collisions. The surface in Figure 1 was etched 8.9 µm by atomic oxygen-induced etching. It has been reported that after 25 years of operation, the International Space Station (ISS) will lose thickness of 2.5 mm of polymers due to atomic oxygen-induced erosion [3].

Polyimide has also been used as an insulating material in electronic circuits due to its superior electric insulating properties. In many satellites, electronic systems use polyimide as flexible substrates or insulators for solar cells. Erosion of polyimide may lead to unexpected change in its chemical/physical properties, and could be potential hazards for spacecraft systems. However, published research results about the fundamental reaction of 5 eV atomic oxygen with polyimide are limited. This is due probably by the following two reasons: (1) opportunity for flight tests in LEO is
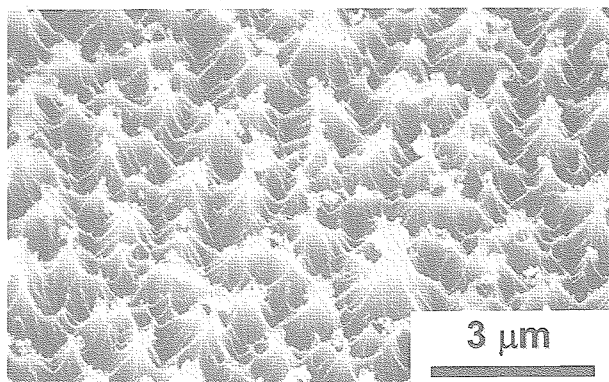

Figure 1 SEM images of an atomic oxygen-exposed PMDA-ODA polyimide at atomic oxygen fluence of 3.0 x 10^{20} atoms/cm^2.

limited and experimental data are sometimes not consistent, and (2) acceleration of electrically neutral atomic oxygen up to 5 eV has been difficult in ground-based facilities. However, recent development of a laser detonation-type hyperthermal atomic oxygen source enables ground-based simulation of polyimide erosion in LEO environment by forming an atomic oxygen beam with translational energy of 5 eV.

In this paper, recent research results regarding 5 eV atomic oxygen beam interaction with polyimide in the simulated LEO space environment are presented. The erosion properties of polyimide in various conditions are surveyed; i.e., non-linear mass loss, impingement angle, temperature dependence, effect of ambient air, wettability, synergistic effects of simultaneous exposure with ultraviolet and of charging. Polyimide surface exposed to an LEO space environment, i.e., an extremely oxidative environment, is analyzed and discussed based on the ground-based experimental results.

2. Laser detonation atomic oxygen beam facility

In ground-based facilities, it has been difficult to create 5 eV atomic oxygen beam with flux greater than 10^{13} atoms/cm^2/s, which is corresponding to the atomic oxygen flux in LEO. A conventional plasma asher or radio-frequency (RF) plasma system can create high flux atomic oxygen [4, 5], but the translational energy of atomic oxygen with these experimental facility is less than 0.1 eV. It does not simulate the reaction mechanism of hyperthermal atomic oxygen with solid surfaces in LEO. Acceleration of electrically neutral atomic oxygen to 5 eV is not an easy task. The translational energy of 5 eV is too high for supersonic molecular beam methods and too low for ion beam methods. A laser detonation-type atomic oxygen source is the only practical way to accelerate neutral species to translational energy as high as 5 eV with a flux higher 10^{15} atoms/cm^2/s [6]. Figure 2 shows a photograph of the laser detonation atomic oxygen beam source used in this study. This type of atomic beam source uses a pulsed valve and pulsed CO$_2$ laser to generate high-energy intense atomic oxygen beam. In the laser detonation beam source, an incoming laser pulse is focused on the molecular oxygen introduced at a nozzle throat. The detonation wave is initiated by a high-power laser-induced breakdown phenomenon. With a laser pulse, the detonation wave quickly becomes a blast wave, which propagates to the nozzle exit plane with converting the high-pressure of the gas behind into a propelling force. The energy of the laser-produced plasma is converted effectively to velocity of the exhaust gases. The laser detonation atomic oxygen source can generate atomic oxygen with translational energies ranging from 2 to 20 eV. Moreover, it was also identified that the atomic oxygen created by the laser detonation source was a ground-state neutral oxygen atom (O(^{3}P)) [7]. Detailed configuration of the atomic beam facility used in this study is reported elsewhere [8, 9].

3. Experiments

All experiments reported here were carried out with the laser detonation atomic oxygen beam facility at Kobe University, which is explained in the previous section. The polyimide sample was PMDA-ODA polyimide which is chemically equivalent to Kapton-H (Semicofine SP-510, Toray). A polyimide amide acid was spin-coated on a sensor crystal of quartz crystal microbalance (QCM) at 12,000 rpm for 10 s, and the curing treatments at 423 K for 1 hr. and 573 K for 1 hr. were carried out in order to form polyimide structure with a thickness of approximately 0.1 μm. The spin-coated polyimide film, thus formed, and Kapton-H film has the same repeating unit of polymer. The temperature of the QCM sensor was controlled by the water recirculation unit with accuracy of 0.1 K during the experiments. Reaction efficiency (Re) of the spin-coated polyimide film was calculated from the frequency shift of the polyimide-coated QCM with an equation below:

$$\Delta f / f_0 = - \Delta m / (\rho A d) \qquad (1)$$

where f_0 is the resonant frequency, d the thickness of quartz, Δm mass change equivalent to thickness change, ρ and A the density and area of quartz, respectively. For the AT-cut QCM sensor crystals ($f_0 = 5$ MHz) used in this study, the change in resonant frequency is expressed by the following equation:

$$\Delta f = -2.26 \times 10^{-6} (f_0^2 \Delta m) / A \qquad (2)$$

where Δf and f_0 in Hz, Δm in g, and A in cm^2. Thus, for the QCM with a resonant frequency of 5 MHz, 0.1 Hz of Δf corresponds to 2 ng. It is clear from equation 2 that the detection of atomic oxygen-induced mass loss of polyimide can be achieved with a mass

Figure 2 Photograph of the laser detonation atomic oxygen source used in this study.
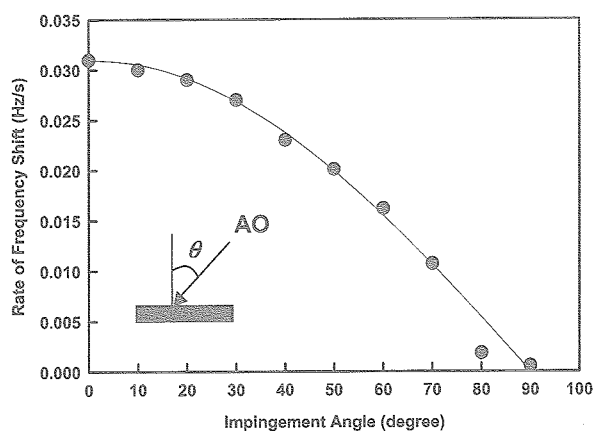
Figure 3 Impinging angle dependence of atomic oxygen on the erosion rate of polyimide. Translational energy 4.6 eV and flux 3.0 x 10^{14} atoms/cm²/s. Mass loss of the polyimide film follows cosine distribution.
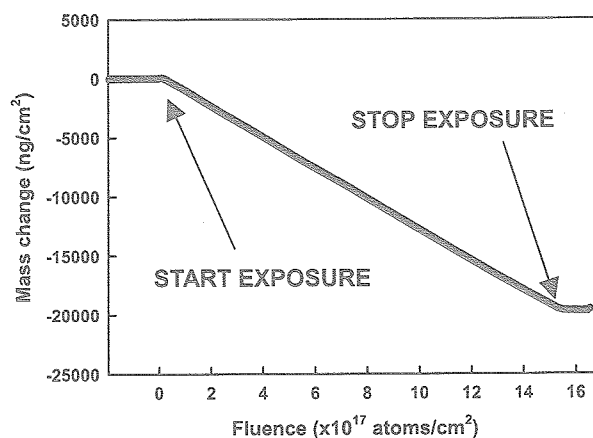
Figure 4 Mass change of the polyimide-coated QCM during atomic oxygen exposure; the translational energy 4.7 eV and flux 3.1 x 10^{14} atoms/cm²/s. Change in mass of the polyimide film is proportional to the atomic oxygen fluence.

resolution of nanogram level by using QCM. The QCM used in this study was specially designed so as to apply bias voltages to the sample surface.

4. Properties of atomic oxygen-induced erosion of polyimide
4.1 Impingement angle dependence

Effect of impingement angle of atomic oxygen on polyimide erosion was investigated with the atomic oxygen beam (translational energy: 4.6 eV, flux: 3 x 10^{14} atoms/cm²/s) at 311 K [10]. The frequency shift of the QCM during atomic oxygen beam exposures were recorded at impingement angles from 0 to 90 degrees. The impingement angle was taken with respect to the surface normal. A good linear relationship between the frequency shift and exposure time, i.e., mass loss and atomic oxygen fluence, was observed at all impingement angles. The slope of the mass loss rate at every impingement angle was calculated by a least squares fit, and plotted against the impingement angle. The results are presented in Figure 3. It is clear that the rate of frequency shift, or erosion rate, of polyimide depends on the impingement angle and the dependence obeys cosine law almost perfectly as indicated by the solid line in Figure 3. The fact that the impingement angle dependence of the erosion rate follows a cosine law clearly indicates that the erosion rate is proportional to the effective flux of atomic oxygen; i. e., the reaction yield of oxygen atom is independent of the impingement angle.

4.2 Non-linear mass loss

Figure 4 shows the results from the *in-situ* measurements of mass change of the spin-coated polyimide film under 4.7 eV atomic oxygen beam exposure at sample temperature of 311 K [9]. As can be seen in Figure 4, the mass of the film decreases in proportion to the atomic oxygen fluence. It was confirmed that the mass loss of the polyimide film was due to the formation of volatile reaction products such as CO or CO_2 [2, 7]. However, not only the steady-state mass loss, but also the mass gain at the beginning of the reaction was observed. A mass increase of the spin-coated polyimide was observed at the beginning of the exposure to a virgin polyimide (induction time of mass loss). In contrast, the surface that had been prior oxidized by atomic oxygen exposure of 3.2 x 10^{18} atoms/cm² does not show the mass gain phenomenon, i.e., the rate of mass loss immediately became steady-state. The surface, thus prepared, was confirmed to be already oxidized by the atomic oxygen exposure. Therefore, it is concluded that the non-linear mass increase phenomenon is observed only when atomic oxygen attacks virgin polyimide surface. The X-ray photoelectron spectroscopy (XPS) results showing the increase of surface oxygen content with atomic oxygen exposure suggest that the mass gain is due to the oxygen adsorption (or oxidation) at the polyimide surface. The computational modeling and analysis of the non-linear mass loss phenomenon indicated that the major reaction path of carrying the mass away from the surface (99.8 %) occurs at the oxidized polyimide surface [9]. This computational result suggested that the gasification of polyimide by hyperthermal atomic oxygen was governed by the two-stage reaction; oxidation and following gasification reactions.

4.3 Temperature dependence

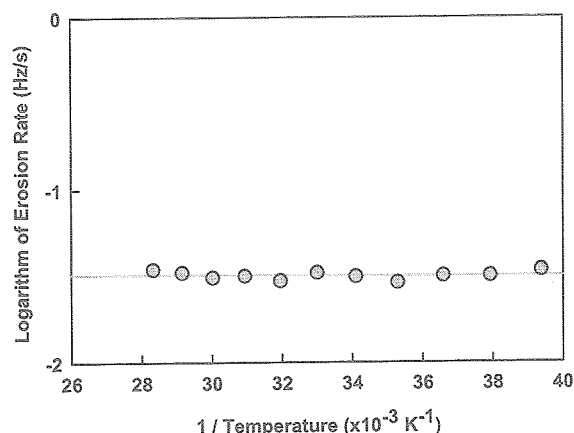Temperature dependence of the erosion rate of polyimide was examined using an atomic oxygen beam with a

Figure 5 Arrhenius plot of the erosion rate with atomic oxygen beam with translational energy of 5.0 eV. The sample temperature was controlled from 253 K to 353 K. The activation energy of the gasification reaction was estimated to be 5.7×10^{-4} eV.

Table 1 Effect of ambient air exposure on the surface composition of atomic oxygen-exposed polyimide.

Days for air exposure	Atomic concentration (%)		
	C	O	N
Pristine*	74.9	16.9	8.2
0**	61.7	29.8	8.5
10**	68.7	25.1	6.2

*Without atomic oxygen exposure
**After atomic oxygen exposure at 7.6×10^{17} atoms/cm^2

translational energy of 5.0 eV [11]. The flux of the beam was 2.6×10^{14} atom/cm^2/s. Linear relationships between the frequency shift (mass loss) and exposure time are identified at all sample temperatures tested (253 K to 353 K). The slope of the frequency shift (erosion rate) was calculated by the least-squares fit. The relationship between $1/T$ and the logarithm of erosion rate is plotted in Figure 5 (Arrhenius plot). From the slope of the Arrhenius plot, the activation energy of the mass loss reaction was calculated to be 5.7×10^{-4} eV. The same experiment was carried out with an atomic oxygen beam with translational energy of 1.1 eV and flux of 2.1×10^{15} atom/cm^2/s. The activation energy of 4.5×10^{-2} eV was calculated for the 1.1 eV atomic oxygen beam. The activation energy of gasification reaction with 5.0 eV atomic oxygen beam was two orders smaller than that with 1.1 eV beam. It was also observed that the erosion rate by the 5 eV atomic oxygen beam was 300 % higher than that by the 1.1 eV beam even though atomic oxygen flux was only one eighth [11]. This finding suggested that the reaction yield of atomic oxygen with polyimide depended strongly on the translational energy of the atomic oxygen. The activation energies measured in this study agree with those obtained by flight experiments [12] and by ground-based experiments [13] reported previously.

Minton et al recently reported the temperature dependence of atomic oxygen-induced polyimide erosion at higher temperatures up to 573 K [14]. They reported the Arrhenius-like temperature dependence with apparent activation energy of 0.31 eV above 373 K. The activation energy of 0.31 eV measured by Minton et al., is almost same value of that obtained by atomic oxygen with thermal energies, even though they used 5 eV atomic oxygen beam. This observation suggested that the effect of hyperthermal impinging energy of atomic oxygen does not influence the erosion mechanism of polyimide at the sample temperature above 373K.

4.4 Effect of ambient air exposure

The atomic oxygen-exposed polyimide film with an atomic oxygen fluence of 7.6×10^{17} atoms/cm^2 was stored in a Teflon container under a class 10,000 clean air environment. XPS measurements were periodically performed in order to identify the stability of the surface chemistry of the atomic oxygen-exposed polyimide. The results are shown in Table 1 [15]. It was observed that N was decreased slightly, whereas the atomic concentration of C increased and that of O decreased with air exposure. Namely, the carbon and oxygen concentrations before air exposure were 62 % and 30 %, respectively, but, with an air exposure of 10 days, the carbon and oxygen concentrations changed to 69 % and 25 %. These values are close to the analytical results of STS-8 and STS-46 flight samples. These spectral changes are obvious on C1s high-resolution spectra of atomic oxygen samples. It is obvious from the comparison of C1s high-resolution spectra that the atomic oxygen-exposed surface before ambient air exposure contains larger amounts of carbonyl (287.7 eV) and ketone (288.9 eV) groups at the surface, i.e., a highly oxidized surface. However, they decreased with ambient air exposures. These results indicate that the recoveries of C and O were due to the decrease of carbonyl and ketone groups at the polyimide surface. It was thus suggested that the highly oxidized surface due to atomic oxygen beam exposure was gradually deoxidized by surface relaxation processes in ambient air environment, and the influence of atomic oxygen exposure was lost with time. The deoxidation process may involve gasification of volatile products, the decomposition of unsaturated bonds between carbon and oxygen and movement of surface moiety of oxidized polymer into the bulk [12].
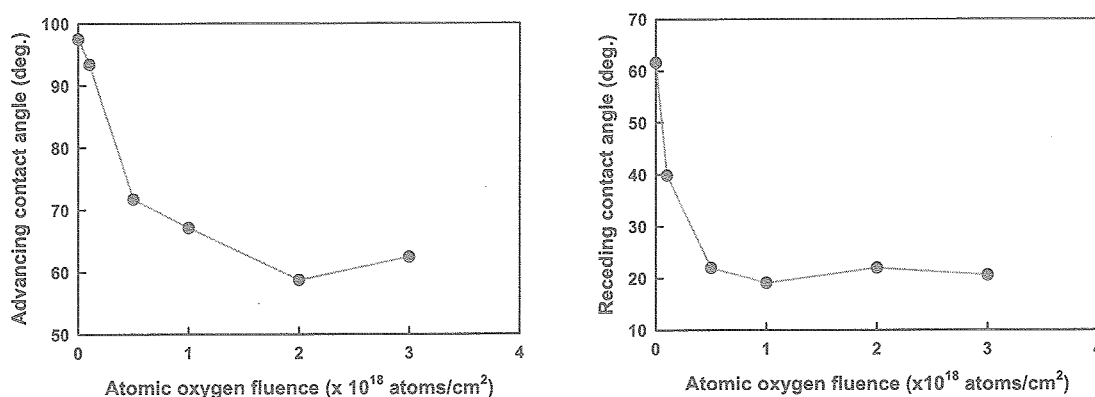
Figure 6   Contact angles of water on the atomic oxygen-exposed polyimide as a function of atomic oxygen fluence. (Left): advancing contact angle and (Right): receding contact angle.

4.5 Wettability

Oxidation of polymer surface leads to change in wettability of polymers.   Figure 6 shows the contact angles of water as a function of atomic oxygen fluence [16].   With increasing atomic oxygen fluence, both advancing and receding contact angles decreased, i.e., the wettability increased.   The oxygen concentration at the polyimide surfaces as measured by XPS also increased with atomic oxygen fluence.   The contact angles were replotted against the oxygen concentration, and the results are shown in Figure 7; both advancing and receding contact angles decreased with increasing oxygen concentration.   The Lifshitz-van der Waals component and Lewis acid and base components of the surface free energy of polyimide films were analyzed.   It was confirmed that the base component increased with increasing oxygen concentration whereas the other two components remained constant [16].   These results were explained by the introduction of surface functional groups due to atomic oxygen bombardment.   The presence of carbonyl and carboxyl groups at the atomic oxygen-exposed polyimide surface was clearly detected by XPS.   These surface functional groups are expected to play a role for electron donors.   It is, then, concluded that the increase in wettability of polyimide in LEO would be mainly caused by the increase in the base component of the surface free energy due to the formation of carbonyl and/or carboxyl groups.   The increase in wettability (or surface free energy) may affect the reactivity of the surface in LEO.   In fact, relationship between surface free energy and erosion yield by atomic oxygen was reported [17].   Lowering the surface free energy would be beneficial for future material development of polyimide.

4.6 Synergistic effect with ultraviolet exposure

The erosion rate of polyimide with simultaneous exposure to ultraviolet and atomic oxygen beam is examined.   An excimer lamp with a wavelength of 172 nm was used as the ultraviolet source.   The results are shown in Figure 8 [18].   The abscissa indicates the relative intensity of ultraviolet (ultraviolet flux divided by atomic oxygen flux) and the ordinate represents the normalized erosion rate (erosion rate in simultaneous exposure of atomic oxygen and ultraviolet divided by that in atomic oxygen exposure alone).   It is clear that the erosion rate of polyimide almost linearly increases with increasing relative ultraviolet intensity.   In the range of $\sim 1 \times 10^{-14}$ mJ/atom, an increase in erosion rate of $30 \sim 40$ % was confirmed.   This result validates the ground-based synergistic experiments reported previously [19].   In the intense ultraviolet environment at 4×10^{-14} to 8×10^{-14} mJ/atom, the erosion rate increased by as much as 400 % than that for atomic oxygen exposure alone.   These results suggest that in high altitude, where the atomic oxygen flux is relatively small compared to that in
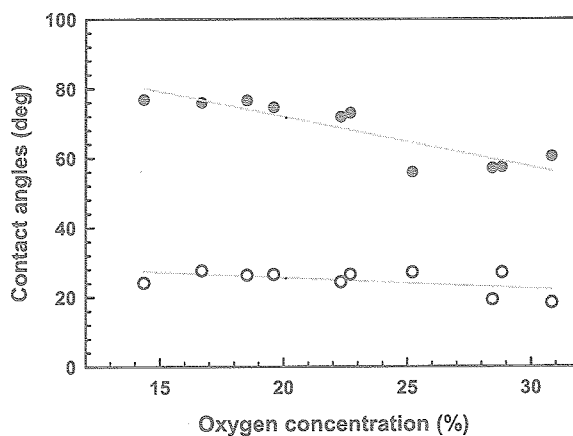

Figure 7   Advancing (◉) and receding (○) contact angles of water at the atomic oxygen-exposed polyimide surfaces as a function of surface oxygen concentration.

low altitude, the effect of simultaneous ultraviolet exposure in polymer degradation might be enhanced.

The role of ultraviolet in the simultaneous exposure of atomic oxygen and ultraviolet is to increase the role of gasification reaction. A 172 nm ultraviolet exposure does not influence the erosion rate of pristine polyimide, however, desorption of embedded CO and CO_2 is promoted by ultraviolet exposure. The decomposition of the surface functional groups due to ultraviolet is known as the Norrish type II reaction; one of the mechanisms for automatic oxidation of polymers in the presence of oxygen [20]. However, the contribution of this photochemical reaction would not be important in the overall degradation of polyimide if gasification due to collision-induced production process by atomic oxygen were the major reaction. The effect of ultraviolet becomes obvious when relative ultraviolet intensity becomes greater compared to the atomic oxygen flux. In fact, it was confirmed in this experiment that the erosion rate of polyimide increased significantly (up to 400 %) by ultraviolet exposure. Difference in relative intensity of atomic oxygen and ultraviolet is probably a key to explaining the inconsistency in synergistic effects of atomic oxygen and ultraviolet reported previously [2, 19].
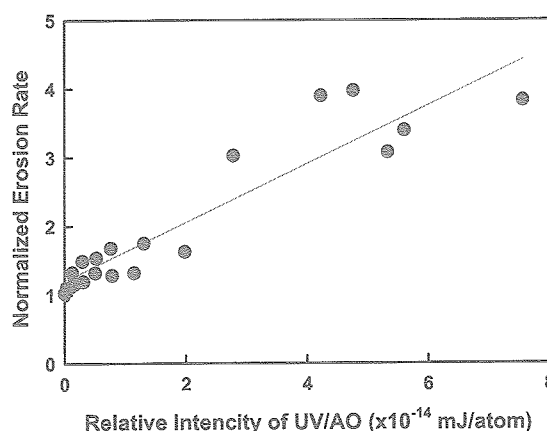

Figure 8 Normalized erosion rate of polyimide as a function of relative intensity of ultraviolet against atomic oxygen flux. It was made clear that the gasification reaction was promoted by the simultaneous 172 nm ultraviolet exposure.

4.7 Synergistic effect with charging

Surface charging is sometimes critical to spacecraft operation. Natural plasma environment and photoemission by solar ultraviolet arise surface charging of spacecraft. Much attention has been paid for arcing by charging which may cause electrical failure of solar cells. However, surface charging may also affect the atomic oxygen-induced erosion of polymers. King et al, reported that the signal of volatile products from atomic oxygen exposing polysulfone was enhanced when the polysulfone surface was biased [21]. Tagawa and co-workers recently examined the charging effect under atomic oxygen-induced erosion of polyimide and polysulfone [22]. They found that erosion rate of polyimide and polysulfone was hardly affected by surface charging. These two reports did not provide contradicted results, since these conclusions were based on the different signals, i.e., King detected reactive product with quadrupole mass spectrometer and Tagawa did mass change of the film with QCM. Both experimental results may be explained simultaneously when effect of charging on the surface ionization of the reactive products is considered. The effect of charging on the surface ionization cross section is currently studied in atomic oxygen-polymer systems.

4.8 Reaction mechanisms of atomic oxygen with polyimide

From a series of experiments reported previously, we have concluded that the mass loss phenomenon of polyimide due to atomic oxygen exposure is basically a two-stage reaction: gasification reaction following oxidation reaction [9]. When a pristine polyimide surface is exposed to atomic oxygen, oxidation reaction occurs as the first stage of reaction. The impinging atomic oxygen is chemically adsorbed on the surface and forms oxides, i.e., carbonyl and carboxyl groups. XPS analysis of atomic oxygen-exposed polyimide suggested that chemical bonds between C and N atoms in PMDA were predominantly broken. Minton [23] reported a correlation study between crossed molecular beam experiment and the theoretical calculation of hyperthermal atomic oxygen interaction with gas phase hydrocarbons. The study found three major reaction pathways of hyperthermal atomic oxygen: H-atom abstraction, H-atom elimination, and C-C bond breakage. The C-N bond breakage would preferentially occur in polyimide because its bond strength is lower than that of C-C bond. H-atom elimination reaction at the polyimide surface oxidizes the polyimide structure. The H-atom abstraction would be important to decompose the benzene structure in ODA. Once the surface is oxidized by these reactions, further attack by energetic atomic oxygen provides collision-induced production of CO and CO_2 which originated from carbonyl and carboxyl groups, respectively. The translational energy of the impinging atomic oxygen plays a key role in the later gasification reaction stage and the chemical nature of oxygen atom may not be important. This conclusion is based on experimental results that show hyperthermal argon atoms give almost identical results to atomic oxygen once the target surface is fully oxidized [24]. In LEO environment, it is considered that the rate of oxidation is greater than that of gasification because flight samples showed higher concentration of oxygen even though they had suffered ambient air exposure effect [15]. Thus, the gasification reaction might be a rate-limiting step in mass loss reaction in LEO.

5. Effect of atomic oxygen to spacecraft solar cells

Beside the direct reaction with polyimide, atomic oxygen may react to other key materials in photovoltaic systems aboard spacecraft. Quartz glass at the solar cell surface is stable with atomic oxygen bombardment. However, organic materials adsorbed on the quartz surface will be removed by oxidation by atomic oxygen. This oxidation reaction makes the quartz surface clean, which means the quartz surface becomes hydrophilic (high-energy) surface. Such high-energy surface would promote contamination attachment and may lead to a decrease in transmittance of solar light.

Scattering of atomic oxygen at the non-reactive solid surface also influence the material erosion. Banks and co-workers reported that the ISS solar photovoltaic array showed severe atomic oxygen-induced erosion even though it was double aluminized for protection [25]. The Monte Carlo simulation showed the following mechanism for the promotion of erosion: an oxygen atom enters the cavity from a pinhole in the front aluminized layer and reacts with the polyimide. When the oxygen atom reaches the aluminized layer at the backside of the film, atomic oxygen is reflected at the aluminium surface and reacts with the polyimide between the protective layers. The reaction yield of atomic oxygen with double aluminised polyimide is close to 1.0. This is because the atomic oxygen still reacts with polyimide even though a part of the translational energy is lost by the scattering events. It is, thus, demonstrated that pinholes in the protective overlayer on polyimide may be problematic in actual LEO environment.

Reaction of atomic oxygen with silver is also important to electrical systems of satellites. Silver-covered connector and electrical lines are severely oxidized by atomic oxygen, if it suffered atomic oxygen attack. Unlike the other metals, silver oxide is not terminated in atomic oxygen-induced oxidation; i.e., even for sliver bulk, it will be oxidized completely [26]. Moreover, due to the volume expansion of silver by oxidation, silver oxide may easily delaminated by the intrinsic stress which means complete loss of the electricity.

Electrical loss is the major causes for loss of a whole satellite system as well as mechanical problems. It is, thus, essential to protect environment-sensitive satellite materials from the atomic oxygen exposures in a LEO space environment.

6. Conclusions

Polyimide in LEO space environment is subjected to an extremely oxidative environment, i.e., hyperthermal atomic oxygen bombardment. Recent research results on the interaction between hyperthermal atomic oxygen and polyimide that is used for photovoltaic system in LEO satellites are summarized. The mass loss phenomenon of polyimide due to atomic oxygen exposure is basically a two-stage reaction: gasification reaction following oxidation reaction. The contact angles of water on the atomic oxygen-exposed polyimide film decrease with increasing oxygen concentration at the polyimide surfaces in LEO. It was also made clear that the decrease in the contact angle was due to the increase in the base component of the surface free energy. These phenomena are related to the formation of surface functional groups due to atomic oxygen-induced oxidation reaction. In contrast, the rate-limiting step of the steady-state mass loss phenomenon in LEO would be the gasification reaction. In simultaneous atomic oxygen and ultraviolet exposure conditions, ultraviolet-enhanced polyimide erosion up to 400 % could be observed. This is due to the fact that the ultraviolet exposure boosts the desorption of oxide species embedded in the polyimide surface. Impingement energy of atomic oxygen as high as 5 eV, which corresponds to the orbital velocity of spacecraft, gave activation energy for gasification reaction of polyimide as low as 5.7×10^{-4} eV and almost no temperature dependence below 373 K. From the research results reported here it was concluded that the survivability of ordinary PMDA-ODA polyimide in LEO space environment was not very high. Also non-reactive anti-atomic oxygen protective coatings of polyimide may induce further erosion of polyimide between the coatings. The fundamental research of atomic oxygen reaction with materials is important for future low-risk, long-term LEO missions.

For convenience of readers, some recent references regarding atomic oxygen reaction with materials from the author's research group are listed in the end of references including synergistic effect with UV [27-29], temperature and impingement angle dependences [30-31], surface energy [32-34], energy transfer [35], silicon oxidation [36], HOPG degradation [37], and lubricant degradation [38-39].

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