OVER-ESTIMATION OF ATOMIC OXYGEN FLUENCES DUE TO UNDECOMPOSED OXYGEN MOLECULES INCLUDED IN HYPERTHERMAL BEAMS AND COMPARISON WITH FLIGHT DATA

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ABSTRACT

The role of undecomposed O_2 contained in ground-based atomic oxygen (AO) tests was evaluated quantitatively. The experiment was carried out by adding an Ar beam at the same collision energy as the O_2 component in the AO beam. The addition of the Ar beam was made by the one-nozzle two-beam laser detonation system developed in Kobe University. The experimental results clearly indicate that erosion of Kapton in the laser-detonation system was promoted by the presence of O_2 in the beam. This result suggests that Kapton-equivalent AO fluence measured in the "ordinary" laser-detonation system, which includes 30-50% O_2, is over-estimated 1.3 - 2 times due to the presence of undecomposed O_2 (AO-induced material risks evaluated based on ground-based AO tests have been under-estimated to be 1/2 to 2/3). The on-ground experimental results were compared with in-orbit AO measurements.

1. INTRODUCTION

Atomic oxygen (AO) beams formed by laser-detonation sources contains not only AO, but also undecomposed O_2. The effect of O_2 on the material degradation, which is exposed to sample surface simultaneously with AO, has never been considered. In our previous study using dual-beamline laser-detonation system, an acceleration effect of material degradation with simultaneous exposure of AO and Ar was clearly confirmed, i. e., erosion yield (Ey) of polyimide under simultaneous AO and Ar exposure is more than three times greater than AO exposure without Ar exposure [1]. This phenomenon was determined to be collision-induced desorption of oxidative reaction products by Ar collisions [2-4]. The AO+Ar simultaneous exposure condition simulates the sub-LEO space environment where AO and N_2 collide simultaneously on material surfaces. However, it is rather a "special" environment, and not the case as higher altitude LEO where many samples have been tested for their AO resistance on the International Space Station (ISS).

On the other hand, AO resistance has also been evaluated in ground-based experiments using laser-detonation AO sources. For many cases, material exposure missions aboard ISS includes ground-based AO exposures for comparison purposes. Both in-orbit and on-ground results have been normalized/compared with Kapton Ey of 3.0E-24 cm^3/atom [5]. Some AO research studies performed by laser-detonation systems with mass spectrometers indicate that an AO beam formed by laser-detonation sources contains undecomposed molecular oxygen as high as 30-50%. The undecomposed O_2 with collision velocity of 8 km/s may provide similar effect to N_2 in sub-LEO (or Ar in AO+Ar simultaneous exposure) which accelerates desorption of reaction products.

In this study, the role of undecomposed O_2 contained in ground-based AO tests was evaluated quantitatively. Moreover, the conclusions obtained in the ground-based experiment are compared with past flight experiments, particularly the Materials International Space Station Experiment (MISSE) series.

2. EXPERIMENTS

The experiment was carried out by adding Ar beam pulses at the same collision energy as the O_2 component in the AO beam. The addition of an Ar beam was made by the one-nozzle two-beam laser detonation system developed in our group (Figure 1). Detail of the facility is described in reference 6 [6]. Table 1 summarizes the

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Table 1 Experimental settings

	CH1	CH2
Target gas	O_2	Ar
Pressure (MPa)	0.7	0.3 - 0.7
Laser delay (ms)	0.35	0.35 - 0.43
Laser energy (J)	6.89	6.89
PSV voltage (V)	3.6	2.8 - 3.6
Repetition rate (Hz)	1.0 - 1.5	1.0

experimental conditions. The flux of AO was evaluated from the frequency shift of polyimide-coated QCMs, in contrast, those of O_2 and Ar were estimated from the areas of the flux-weighted TOF signals with known ionization probabilities of AO, O_2 and Ar [7]. The material targeted is PMDA-ODA polyimide which has the same repeating unit as Kapton-H. The erosion of polyimide was calculated from the frequency shift of the polyimide-coated QCMs located 52 cm away from the nozzle throat at room temperature.

3. RESULTS AND DISCUSSION

Figure 2 shows the TOF distributions of AO, undecomposed O_2 and Ar components in the beam. Average translational energies of AO, O_2 and Ar are 2.9, 4.0 and 4.0 eV, respectively. The average translational energy was set to a lower value as compared to the real space environment because the translational energy gives large effect on this phenomenon and the distribution of the AO beam pulses in the laser detonation source is much greater than that in LEO [8, 9]. Figure 3 indicates the relationship between fraction of high-energy molecules (O_2+Ar) and relative Ey of polyimide. The data point of 0.257 in the abscissa is the AO beam without adding Ar pulses. The ordinate is normalized by the erosion rate of ordinary AO+O_2 beam pulses without adding Ar pulses. It is obvious that the erosion rate of

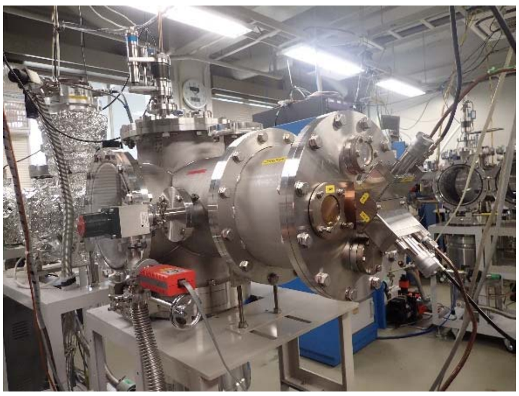

Figure 1 One-Nozzle two-beam laser detonation beam facility used in this study

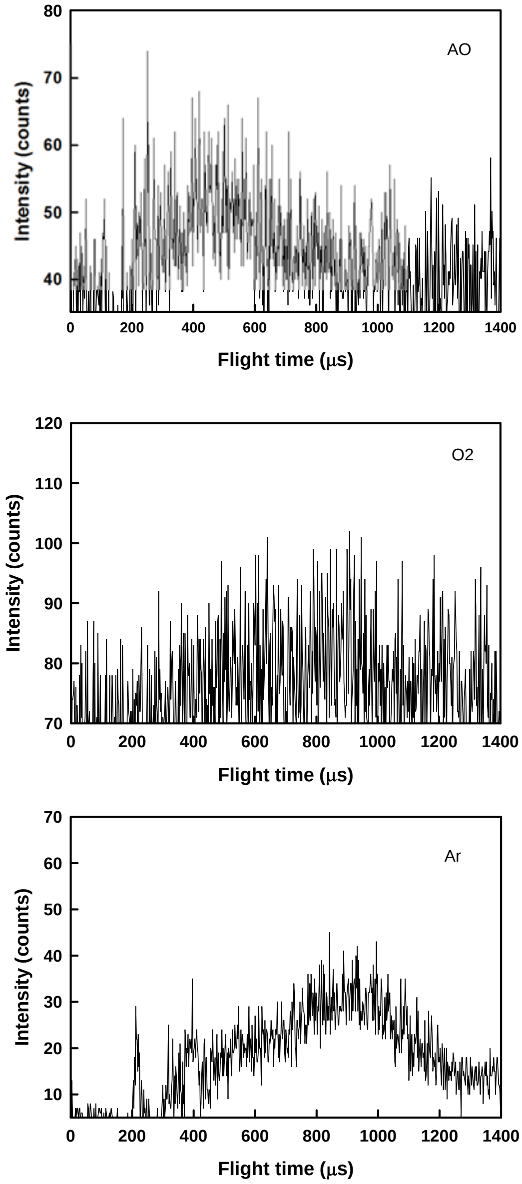

Figure 2 Time-of-flight spectra of AO, O_2 and Ar beams (From top to bottom). Average translational energies are 2.9, 4.0 and 4.0 eV, respectively.

polyimide linearly increases with increasing the fraction of high-energy molecules, i.e., O_2 +Ar. By extrapolating the linear fitting results, the net erosion rate of polyimide by AO component (without the help of O_2 collision) is 62% of the conventional AO beam used for the ground-based experiments. In other words, polyimide erosion in the laser detonation AO beam source is accelerated 1.6 times by the presence of the O_2 component in the beam. Since the AO beam formed by the laser-detonation system includes 30-50% O_2 depending on the condition, the mass-loss of Kapton witness samples exposed to the AO beam in the ground-based experiments is

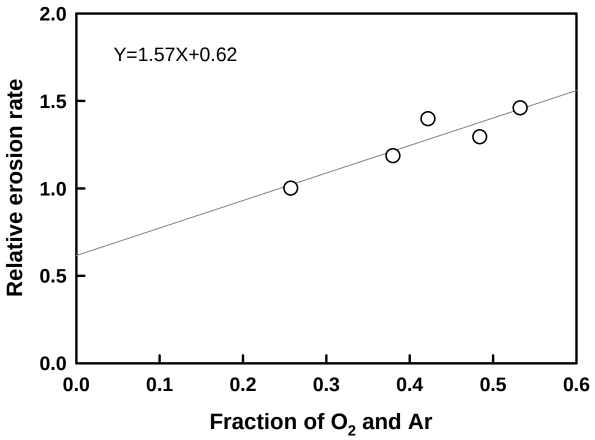

Figure 3 Relationship between Ar+O_2 fraction in the beam and the relative erosion rate of polyimide.

accelerated; i.e., fluence of AO is over-estimated 1.5 - 2 times. The over-estimation of AO fluence leads to under-estimation of the AO-induced material risks evaluated based on the ground-based AO tests to be 1/2 to 2/3.

On the other hand, this effect may be applied as a method to accelerate the AO-induced erosion of hydrocarbon polymers if the erosion mechanism is same as the polyimide.

4. KAPTON EROSION YIELD MEASUREMENTS

Kapton-H has been used for measuring the fluence of AO exposures for many years. The standard Ey of 3.0E-24 cm^3/atom is recommended for measuring the flux of AO in ASTM standard E-2089 [5]. This value has been applied both to ground-based experiments and to flight experiments. However, the experimental results in this study clearly indicated that the Ey of polyimide depends on the fraction of high-energy molecules. Difference in the exposure condition of simultaneous high-energy molecules has never been considered in the past exposure tests, i. e., AO beam in the laser-detonation source always contains 30-50% hyperthermal O_2 and AO environment in ISS orbit contains O_2 or N_2 as low as a few percent or less.

The value of 3.0E-24 cm^3/atom was first measured in the early space shuttle flights. The STS-8 mission (225 km) provided some of the first carefully characterized Ey values, with several PI's reporting Kapton Ey values of 3.0E-24 cm^3/atom including Banks [10] and Visentine [11]. Koontz then determined the Ey of Kapton to be 3.1E-24 cm^3/atom in his EOIM-III experiment (STS-46), which was also at a low altitude of 230 km [12]. Gregory reports the Kapton Ey from his leading edge (Row 9) A0114 experiment to be 2.89±0.06E-24 cm^3/atom [13]. LDEF's altitude ranged from ≈478 km down to 324 km (note that altitudes vary somewhat based on the reference). LDEF received 74% of the total AO fluence within the last year of the mission, and the altitude for the last year ranged from approximately 449 km to 345 km (altitudes used in AO fluence calculations by Bourassa [14]). So, one could state that Gregory's 2.89E-24 cm^3/atom was determined from a flight in the ≈449-345 km range. This is essentially the altitude for ISS (≈400 km). In addition, LDEF experiment A0134, also flown on the leading edge of LDEF, exposed samples to the space environment for the first 10-months of the LDEF mission, when it was at the higher altitudes (≈481-470 nm). The Kapton Ey for this experiment was also determined to be 2.9E-24 cm^3/atom [15]. Silverman summarizes Kapton Ey values and, he states that the Kapton Ey of 3.0E-24 cm^3/atom should be used for design considerations [16]. The Silverman guide is highly referenced, and the data is based on both lower altitude Shuttle missions and also higher altitude LDEF data. From the history described above, Kapton Ey has been measured during several flight missions at altitudes ranging from 225 km to 450 km. The Kapton Ey for the flight experiments were based on mass loss or recession depth measurements, but the AO fluence during the flight was calculated using the MSIS model. In the MSIS calculations the N_2 collision effect has not been considered even though the N_2 fraction at 225 km reaches as high as 33%.

5. COMPARISON OF E_Y ON ISS MISSIONS

We have searched the past flight experiment aboard STS and ISS, in order to compare the difference in predicted and measured AO fluence. Not many examples were found in literature, however, some examples are listed in Table 2. It was obvious that the AO fluences measured by Kapton-H and calculated by the MSIS model agrees well for EOIM-3 [17], however they are not consistent in the JEM/MPAC&SEED [18] and MEDET [19], i.e., Kapton-equivalent fluence is underestimating the MSIS-

Table 2 AO fluence of the orbital material tests

Mission	Year	Platform	Atomic oxygen fluence (atoms/cm^2)		
			MSIS prediction	Kapton-equiv.	ratio
EOIM-3	1986	STS-46	2.1E+20	2.4E+20	0.88
JEM/MPAC&SEED	2010	ISS	1.4E+21	5.9E+20*	2.4
MEDET	2008	ISS	2.3E+21	1.7E+21	1.4

*: Vespel-equivalent fluence

Table 3 Measured and calculated AO fluence on MISSE-2

Location	Atomic oxygen fluence (atoms/cm^2)		
	Calculated	Kapton-equiv.	ratio
Ram-side, near airlock	9.9E+21	6.5 - 6.8E+21	1.52 - 1.46
Ram-side, away from airlock	9.9E+21	8.5 - 9.1E+21	1.16 - 1.09
Wake-side	2.5E+19	1.67 - 1.99E+20	0.15 - 0.13

based AO fluence.

The results of detailed MSIS predicted AO fluences for the MISSE 2 mission is summarized in Table 3. Original MSIS calculation of MISSE-2 ram AO fluence was 1.2 E+22 atoms/cm^2. However, that is not the actual AO fluence received on the MISSE ram surfaces. Pippin provides a description of the environment exposure conditions experienced by the MISSE-2 hardware [20]. In his computations, the AO fluence was estimated using a detailed predictive model that accounted for altitude (≈350-400 km), ISS attitude changes, thermal velocity spreading in the ambient atmosphere, co-rotation of the atmosphere, and oxygen atom number density variation with solar activity. The calculated ram values also took into account shielding by the STS when docked to ISS, but did not take into account shielding of any other nearby structures. When the STS shielding and ISS attitude changes are taken into account the MISSE-1 and MISSE-2 calculated AO fluence values are significantly less. As shown in Table 3, the calculated AO fluence for MISSE-2 ram is 9.9E+21 atoms/cm^2 (82.5% of the original, non-adjusted, MSIS AO ram fluence). The measured Kapton-equivalent AO fluence on the "ram-facing" side of MISSE-2 ranged from 6.5E+21 to 9.1E+21 atoms/cm^2, depending on the specific location on the MISSE-2 tray. Pippin stated that the significant variation in the measured MISSE-2 ram fluence values is due to shielding effects due to the airlock structure. With his detailed analysis, the ratio of the model predicted (computed) to measured MISSE-2 AO fluence is 9.9E+21/9.1E+21 = 1.09.

As described above, an accurate prediction of the AO fluence for an ISS mission is not an easy task. Various factors should be considered, such as solar activities, ISS attitude and shielding effects by visiting vehicles and ISS components. The MSIS values of MEDET and JEM/SEED in Table 2 may not take into consideration on these factors. The fact that the wake-side AO fluence measured by Kapton is greater than the MSIS-based calculation (Table 3) may emphasize the complex nature of predicting shielding effect when modelling the AO fluence of the long-term ISS-mounted sample. To avoid these uncertainties, real-time measurement by a small satellite would be beneficial. Such measurement is currently carried out in the Atomic Oxygen Fluence Sensor (AOFS) mission aboard Superlow Altitude Test Satellite (SLATS) which will be expected to provide much clear evidence on this effect.

4. CONCLUSIONS

We have examined the effect of hyperthermal collisions of undecomposed O_2 on the polyimide erosion in ground-based AO tests. Collision energy of O_2 was simulated by the simultaneous Ar collisions formed by the one-nozzle two-beam laser detonation system developed in this study. The results clearly indicate that the erosion rate of polyimide linearly increase with increasing fraction of high-energy particles (O_2 and Ar). Since the AO beam formed by the laser detonation system always contains a hyperthermal O_2 component, the erosion of polyimide in ground-based simulations is accelerated by the presence of O_2. This effect leads to the over-estimation of AO fluence by the factor of 1.3 to 2 in the ground-based simulations. The simultaneous O_2 collision effect in material degradation in LEO, which was firstly explored by Minton and co-workers [8, 9], gave large effects on polyimide erosion not only by the collision energy but also by the O_2 fraction in the environment.

The experimental findings of this study also suggests the Kapton Ey varies with orbiting altitudes. This effect has not been clearly observed based on flight experiments conducted at varying altitudes, such as those flown on the shuttle, LDEF and ISS. SLATS/AOFS mission will be beneficial to provide much clear evidence on this effect.

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