ATOMIC OXYGEN EFFECTS ON COATED TETHER MATERIALS

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ABSTRACT

The University of Alabama in Huntsville's Propulsion Research Center has teamed with NASA's Marshall Space Flight Center (MSFC) to research the effects of atomic oxygen (AO) bombardment on coated tether materials. Tethers Unlimited Inc. has provided several candidate tether materials with various coatings for AO exposure in MSFC's Atomic Oxygen Beam Facility. Additional samples were exposed to ultraviolet (UV) radiation at MSFC. AO erodes most organic materials, and ultraviolet radiation embrittles polymers. This test series was performed to determine the effect of AO and UV on the mechanical integrity of tether materials that were treated with AO-protective coatings, such as Photosil or metallization. Both TUI's Multi-Application Survivable Tether (MAST) Experiment and Marshall Space Flight Center's Momentum Exchange Electrodynamic Reboost (MXER) programs will benefit from this research by helping to determine tether materials and coatings that give the longest life with the lowest mass penalty.

INTRODUCTION

A space tether is best described as a physical connection between two orbiting bodies that allows for the transfer of momentum and/or energy. To date, approximately sixteen tether missions have flown, beginning with the Gemini XI mission in 1966,[1] which used tethers for artificial gravity experiments to the Tether Physics and Survivability (TiPS) mission launched in 1996,[2] to study the long term dynamics and survivability of a 4 km non-conductive tether in low Earth orbit.

Currently, there are two space tether missions being planned, researched and evaluated. The first of these missions is the Multi-Application Survivable Tether (MAST) Experiment,[3] proposed by Tethers Unlimited Inc., (TUI). The MAST mission consists of three one-kilogram satellites along a one kilometer Hoytether™. The main goal of this mission is to gather data on the long-term survivability of a Hoytether™ in low Earth orbit. The second tether mission being planned is the Momentum eXchange and Electrodynamic Reboost (MXER) Mission by NASA's Marshall Space Flight Center. The MXER tether system itself can be likened to a 100-120 km bolo in a highly elliptical Earth orbit. The MXER mission employs a slingshot momentum exchange to launch payloads into higher orbits and then regains the momentum by passing a current through the conductive portion of its tether. Both of these missions are designed to remain in low Earth orbit for an extended period of time, subjecting them to various hazards, including atomic oxygen and ultraviolet radiation.

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Atomic oxygen is formed by the dissociation of oxygen molecules by solar ultraviolet (UV) radiation into free oxygen atoms. AO is the dominant species in low Earth orbit (LEO) from 200 to 700 km altitude and has a significant effect on most organic materials. This is due to the fact that polymeric materials contain many C-H and C-C bonds which require only 4.29 eV and 3.59 eV[5] respectively to break the bonds, and the spacecraft's orbital velocity of 7.8 km/s translates to being hit with AO with an energy level of approximately 5 eV[6]. Mass loss of polymers and composite materials due to AO erosion is well-documented[7-9]. Protective coatings are needed to maintain the mechanical integrity of tether materials, particularly if the mission is in low Earth orbit and is long duration.

There are several criteria that an AO resistant coating must meet in order to be used in orbit. These criteria include low weight penalty, high flexibility, abrasion resistance, UV radiation tolerance, and durability in thermal cycling. There are numerous possibilities for tether coating material, however, past experiments[7, 10-12] with polymeric material and new developments in coating technology have greatly assisted in narrowing the choices for the best tether material and coating combination.

TETHER MATERIALS AND COATINGS

Spectra 2000 from the Honeywell Corporation and Zylon PBO from Toyobo Co., Ltd. were chosen as candidate fibers for the materials testing. Spectra 2000 is composed of ultra-high molecular weight polyethylene (UHMWPE). Samples of Spectra 2000 were in the form of:

- 130 denier strand, coated with Photosil
- 3 x 1000 denier braid, coated with Photosil

Zylon is composed of poly(p-phenylene-2,6-benzobisoxazole)(PBO). Samples of Zylon were in the form of:

- 1000 denier strand, coated with Photosil
- 18.14 kg (40 lb.) test Spiderwire, coated with Photosil
- 250 denier strand, metallized with nickel

Photosil is a coating developed by Integration Testing Laboratories, Inc. which incorporates silicon-containing functional groups into the top micron of an organic material. This coating is applied in a three-step process such that a graded transition region is formed from the surface, allowing the material to survive the cracking caused by thermal cycling and handling of the material. It has been shown to reduce reactivity to AO with polyurethane- and epoxy-based thermal control coatings[13]. Originally the Photosil process was designed to mask flat materials such as thermal blankets and has just recently been applied to rougher, curved objects such as braids and strands of tether materials[14].

The nickel coating is deposited in a 1μm thick layer onto each Zylon fiber through a multi-step process developed by Tethers Unlimited. Whereas nickel does have the ability to withstand AO attack, there are some concerns that thermal cycling may cause some cracking in the coating as the nickel may expand or contract at different rates than the Zylon.

To prepare the samples for testing, they were knotted twice before cutting to prevent loss of any of the strands. Samples ranged from fifteen to twenty centimeters in length, depending on how much material was available. To ensure that none of the materials were hydroscopic, each was placed into a vacuum chamber and brought to 50 millitorr and then weighed with readings being taken every minute for five minutes. Regression analysis to time zero is then used to eliminate any water weight gain. The samples were also photographed before exposure to simulated space environment.

SPACE ENVIRONMENT SIMULATION

AO and UV radiation tests were performed at MSFC. The Atomic Oxygen Beam Facility (AOBF) (fig. 1) generates a neutral beam of AO of 5 eV energy, closely approximating low Earth orbit AO. Samples exposed to AO are also exposed to vacuum UV radiation of 130 nm wavelength in the AOBF. An AO flux of approximately $5x10^{15}$ atoms/cm^2/s is produced by the AOBF in a pulsed fashion. A calibration run of all Kapton samples was performed first. There is variation of the AO beam across the sample holder, so this is precisely measured before each test and change in configuration. A Kapton witness sample is always placed in the center of the test fixture, and the ratio of AO flux of the witness sample to each sample slot is measured. Kapton was used as a witness material because its AO reactivity is a well known value.

Tether samples were loaded onto the AO test fixture (fig. 3) and placed into the AOBF with a Kapton witness sample for varying lengths of time up to a maximum exposure of approximately 3.61×10^{21} atoms/cm^2. After each exposure, the materials were photographed, removed from the testing fixture and weighed. The Kapton witness sample was first vacuum dehydrated because of its highly hydroscopic nature and then weighed over a period of five minutes. From the AOBF beam current, time of exposure, and Kapton mass loss, a value for the fluence in the AOBF can be found. The AO fluence was calculated using the following formula:

$$F = \frac{\Delta m}{\rho * R_e * A} \qquad (1)$$

where Δm is the change in mass in grams, ρ is the density of Kapton, R_e is the AO reactivity of Kapton, and A is the area exposed to the AO.

Tether samples were also exposed in one of MSFC's Ultraviolet Radiation Test Chambers (fig. 2) for 500 equivalent sun-hours (ESH) of UV radiation of 250 to 400 nm wavelength. The samples were exposed to UV in a vacuum of 10^{-6} torr or better, and a water filter is used to minimize infrared heating. More details of the AO and UV facilities may be found in reference 16.

After simulated space exposure, the samples were taken to the Mechanical Properties Test Lab where an Instron mechanical test machine was used to determine tensile strength. To prepare for the testing, the ends of each sample were doped with Socketfast Blue to allow the machine to better grab and pull the tether sample.

RESULTS

A. Spectra- Photosil

While the intent was to expose all of the materials to AO for the full fluence of 3.61×10^{21} atoms/cm^2, it was decided to end testing ahead of schedule for the Spectra-Photosil strand. After receiving only 9.82×10^{20} atoms/cm^2 of AO, the Spectra-Photosil strand (fig. 4) had completely eroded. Another Spectra-Photosil strand which received 7.24×10^{20} atoms/cm^2 only had a few strands intact. The braided Spectra-Photosil (fig. 5) had better results, surviving the entire test regime. This is not surprising given the greater amount of material and better sample integrity of the braid form.

Table 1. Test Results for Spectra-Photosil Strand

Sample	AO Fluence (atoms/cm^2)	% Mass Loss	Maximum Tensile Strength (N)
Control	0	0	
AO-A	2.58E+20	12.15%	
AO-B	7.24E+20	28.74%	
AO-E	9.82E+20	29.62%	Eroded Through
UV	0		

Table 2. Test Results for Spectra-Photosil Braid

Sample	AO Fluence (atoms/cm^2)	% Mass Loss	Maximum Tensile Strength (N)
Control	0	0	
AO-A	2.80E+20	1.41%	
AO-B	6.06E+20	3.48%	
AO-C	1.07E+21	3.69%	
AO-D	3.83E+20	1.14%	
AO-E	2.33E+21	9.66%	
UV	0		

Because the exact density of the Spectra-Photosil is not known, the AO reactivity can only be approximated. It is possible, however to estimate the AO reactivity by using the following equation:

$$R_e = \frac{\Delta m}{\rho * F * A} \quad (2)$$

where ρ, in this case, is the density of untreated Spectra. By performing these calculations and comparing the reactivity data to that for untreated Spectra it was found that the Photosil was able to lower the AO reactivity but only by a factor of 4. The AO reactivity for untreated Spectra[7] is 4.8×10^{-24} cm^3/atom whereas the reactivity for braided Spectra treated with the Photosil was found to be only 0.93×10^{-24} cm^3/atom and the AO reactivity for Spectra-Photosil strand was found to be 1.2×10^{-24} cm^3/atom. While the Photosil offered some AO protection, a decrease of at least an order of magnitude in the AO reactivity is desired for a long duration tether mission such as MXER.

B. Zylon-Photosil

Based on mass loss and appearance, the Zylon strands had uneven Photosil coating. A sample receiving 9.83×10^{20} atoms/cm^2 of AO eroded completely through, while a sample receiving the same amount was intact. This latter sample was further exposed to a total of 2.04×10^{21} atoms/cm^2 and still had a few strands holding together (fig. 6). AO reactivity calculations for the Zylon strand samples ranged from 3.0 to 9.4×10^{-24} atoms/cm^2.

The Zylon -Photosil braids (fig. 7) fared better and were more consistent in AO reactivity. These were similar to the Spectra-Photosil braids in structural integrity and surviving the entire test regime. AO reactivity for the Zylon-Photosil braids was calculated to be 1.7×10^{-24} cm^3/atom.

Table 3. Test Results for Zylon-Photosil Strand

Sample	AO Fluence (atoms/cm^2)	% Mass Loss	Maximum Tensile Strength (N)
Control	0	0	
AO-A	3.15E+20	3.41%	
AO-B	7.41E+20	24.61%	
AO-C	9.83E+20	32.58%	Eroded Through
AO-E	2.04E+21	31.42%	
UV	0		

Table 4. Test Results for Zylon-Photosil Braid

Sample	AO Fluence (atoms/cm^2)	% Mass Loss	Maximum Tensile Strength (N)
Control	0	0	
AO-A	3.17E+20	0.82%	
AO-B	5.58E+20	1.55%	
AO-C	1.00E+21	2.28%	
AO-D	4.58E+20	0.75%	
AO-E	2.33E+21	4.73%	
UV	0		

C. Zylon-Nickel

After the failure of the Spectra strand with Photosil coating, Zylon strands with nickel coating were included in the AOBF exposures. These samples had only small changes in mass, with one sample gaining weight. For the samples that lost weight, the AO reactivity was calculated to be 0.31 x 10^{-24} cm^3/atom.

Table 5. Test Results for Zylon-Nickel Strand

Sample	AO Fluence (atoms/cm^2)	% Mass Loss	Maximum Tensile Strength (N)
Control	0	0	
AO-A			
AO-B			
AO-C	1.27E+21	1.62%	
AO-D	4.68E+20	0.64%	
AO-E	1.74E+21	Slight Mass Gain	
UV	0		

CONCLUSIONS

It appears that the Photosil coating is more effective on a coherent, tightly woven tether sample rather than the loose fibers of the strand samples. Given the past success of Photosil in protecting organic materials, it is hoped that the process can be tailored for better AO reactivity. The nickel coating appeared to adequately protect the Zylon strand samples.

Future activities in this area include AO and UV testing of polyhedral oligomeric silsequioxane (POSS) to determine its resistance to simulated space environmental effects.

Fig. 1. AOBF
Fig. 2. UV chamber
Fig. 3. Sample holder
Fig. 4. Spectra-Photosil strand after AO
Fig. 5. Spectra-Photosil braid after AO
Fig. 6. Zylon-Photosil strand
Fig. 7. Zylon-Photosil braid
Fig. 8. Zylon-nickel strand

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