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ATOMIC OXYGEN INTERACTION WITH SOLAR ARRAY BLANKETS AT PROTECTIVE COATING DEFECT SITES

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ABSTRACT

Atomic oxygen in the low-earth-orbital environment will oxidize SiOx protected polyimide Kapton solar array blankets at sites which are not protected such as pin windows or scratches in the protective coatings. The magnitude and shape of the atomic oxygen undercutting which occurs at these sites is dependent upon the exposure environment details such as arrival direction and reaction probability. The geometry of atomic oxygen undercutting at defect sites exposed to atomic oxygen in plasma ashers was used to develop a Monte Carlo model to simulate atomic oxygen erosion processes at defect sites in protected Kapton. Comparisons of Monte Carlo predictions and experimental results are presented for plasma asher atomic oxygen exposures for large and small defects as well as for protective coatings on one or both sides of Kapton. The model is used to predict in-space exposure results at defect sites for both directed and sweeping atomic oxygen exposure. A comparison of surface textures predicted by the Monte Carlo model and those experimentally observed from both directed space ram and laboratory plasma asher atomic oxygen exposure indicate substantial agreement.

INTRODUCTION

The prime material being considered for construction of the Space Station Freedom solar array blanket is polyimide Kapton (ref. 1). This material has been shown to be vulnerable to oxidation by low-earth-orbital atomic oxygen thus indicating a need for its protection or replacement with a suitable alternative material (ref. 2). Because atomic oxygen durable substitutes for Kapton have not yet been demonstrated to be fully acceptable, 1300Å thick SiOx (where x = 1.9-2.0) sputter deposited coatings are to be used to protect a two-layer polyimide blanket with coatings on either side of each sheet of each one-mil (0.025 millimeter) thick Kapton H polyimide blanket as shown in figure 1. The mechanical ability of the array blanket to provide support for the solar cells and the flexible printed circuitry is highly dependent upon the atomic oxygen durability of the SiOx protected Kapton. Defects in the protective coatings can exist because of particulate contaminates, surface irregularities, abrasion during handling and processing, and micrometeoroid and debris impacts. Portions of the solar facing side of the array blanket (between the cells) and all of the anti-solar side of the array blanket are exposed to sweeping atomic oxygen attack. Recent atomic oxygen durability evaluations of 1300Å thick SiOx sputter deposited coatings on each side of Kapton H blankets indicate that scratch defects as opposed to pin windows represent the most serious threat to high fluence solar array blanket durability. Figure 2 is a photograph of a sample of such a material after exposure to an effective fluence of 1.28 x 10^{22} atoms per cm^2 on each side of the SiOx coated 1 mil (0.025 millimeter) thick Kapton H. As can be seen by Figure 2, significant oxidation has occurred along scratched defect sites.

Efforts to model the atomic oxygen undercutting which occurs at scratched defect sites have resulted in a Monte Carlo model which is capable of simulating the effects of plasma asher, directed space ram, and sweeping space ram attack at scratch defect sites (ref. 3). The Monte Carlo model predicts undercutting shapes at defect sites by statistical ray tracing techniques. The model operates on the following assumptions:

- o Two dimensional scratch or crack defects.
- o Atomic oxygen reaction probability with Kapton H is proportional to $E^{.68}$ where E is the impact energy.
- o Reaction probabilities:
  - a) 0.138 for space (for first impact).
  - b) 0.0098 for space (for

second and subsequent impacts).
  c) 0.0098 for plasma ashers.
- o Reaction probability decreases for grazing incidence and is proportional $(\cos\theta)^{1/2}$ where θ is the angle between the surface normal and the impact direction.
- o Atomic oxygen thermally accommodates with surfaces impacted.
- o Atomic oxygen remains atomic after impacting protective coatings.
- o Unreacted atomic oxygen leaves surfaces in a cosine distribution.

This technique was used to predict the shape of atomic oxygen undercutting geometries which are presented in reference 3. Recent scanning electron microscopy investigations at defect sites indicate that the undercut profiles experimentally observed from plasma asher exposures are not as accurately predicted by the Monte Carlo model as is desired. This paper more closely examines the details of the undercut sites and utilizes that information to refine the Monte Carlo model and predict laboratory and space atomic oxygen undercutting profiles.

APPARATUS AND PROCEDURE

Atomic oxygen exposure at defect sites is accomplished by use of 13.56 MHz RF plasma ashers operated on air and a directed atomic oxygen ion beam using a gridless (end Hall) ion source operated on oxygen. Details of the atomic oxygen exposure apparatus are given in references 1, 4, and 5. The directed oxygen ion beam was capable of directed ram oxygen attack as well as sweeping ram attack.

Samples exposed in the plasma asher were examined by scanning electron microscopy to document the shape and size of scratch and pin window defects. Aluminum adhesive tape used for scanning microscopy sample grounding was applied to the surface of the sample. This tape was then peeled off which removed the SiOx coatings from the underlying Kapton where undercutting had occurred. As a result, a clear view of the undercut patterns was observed in subsequent scanning microscopy inspections. The shape of these undercut profiles was used as a guide to modify the Monte Carlo assumptions to allow a better match between theory and experiment.

Alterations to the assumptions of the Monte Carlo calculation were evaluated and compared with experimentally observed plasma asher results as well as knowledge of directed and sweeping beam results to produce a predictive model which more accurately agrees with observed experimental results. Modifications to the initial assumptions included consideration of the following items:

- o Higher atomic oxygen reaction probability at the SiOx Kapton interface than in the bulk.
- o A finite probability of recombination of atomic oxygen upon each impact.
- o Specular as opposed to diffused scattering off the SiOx surfaces.
- o A higher initial impact reaction probability than subsequent impact reaction probabilities for Kapton in plasma ashers.

RESULTS AND DISCUSSION

Although previous examination of the shape of atomic oxygen undercutting of Kapton at defect sites was greatly limited because remnants of the protective coating blocked inspection of the undercut cavity below the protective coatings, tape peeling allowed full inspection of defect sites. Figure 3a and 3b compare plasma ashed SiOx coated Kapton prior to and after tape peeling. Many atomic oxygen defect sites can be clearly identified after tape peeling which are marginally or not at all evident prior to tape peeling. Figure 4a and 4b compare the more microscopic details of a defected area prior to and after tape peeling. As can be seen in figure 4a, the defect on the left has a central pin window approximately 1.5 micrometers in diameter. The SiOx coating has spontaneously peeled away from the defect after the conclusion of plasma ashing. This observation can be concluded by a comparison of the resulting axisymmetric undercut profile and the unpeeled defect protective coating geometry. The defect on the right in figure 4a and 4b has a diameter that must be substantially less than one micron in diameter. By comparison of these two defects and numerous others, a conclusion was drawn that defects whose width-to-coating-thickness ratio greatly exceed one, produce double dimpled cavities as shown on the left in figure 4b; whereas those whose width-to-coating-thickness ratio is less than or equal to one, produce a single dimpled cavity which is rather conical in shape. These results appeared to be consistent whether the defect is a pin window, a crack, or a scratch. In addition, the angle between the polyimide Kapton and the oxidized surface plane at the perimeter of the defect was not 90° as was previously predicted by the Monte Carlo model. Alterations in the Monte Carlo assumptions were evaluated to see if different modeling assumptions would produce either the double dimpled defect cavity shape or the more conical cavity as opposed to a hemispherical cavity. Alteration of the Monte Carlo model to assume specular scattering of atomic oxygen off the bottom of the protective coating was found not to cause any measurable change in the profile of the undercut defect. A model alteration which included a finite probability of atomic oxygen recombination upon each impact, similarly did not yield undercut profiles which agreed with experimental results. However, if one assumes that the probability of atomic oxygen reaction with the Kapton at the SiOx interface is greater than that of the bulk Kapton, then a more conical undercut cavity is predicted at its outer edges. Figure 5 is a plot of the undercut angle resulting from various interface reaction probabilities. Assuming that the bulk reaction probability is 0.0098, based on experimental plasma asher observation, an interface reaction probability of 0.049 (5 x bulk reaction probability) was selected for the Monte Carlo model improving assumption. The double dimple feature observed for large width-to-coating-thickness defects was found to be produced if one assumed the initial impact reaction probability for plasma ashers was larger than the subsequent thermally accommodated impact reaction probabilities. Based on trials of various initial impact reaction probabilities, an initial impact reaction probability of 0.0392 (4 x reaction probability for the second and subsequent impacts) for plasma ashers was selected to produce erosion predictions which were in reasonable agreement with experimentally observed results in plasma ashers.

Rationale for the reasonableness of these two model change assumptions have not been fully developed. However, it is quite conceivable that the atomic oxygen reaction probability at the polyimide SiOx interface is in fact different than the bulk due to details of the interface chemistry either resulting from the Kapton fabrication or the sputter deposition of the SiOx coating. The higher initial impact reaction probability for plasma ashers is quite possible because of the mix of many stable states and ions at higher than thermal temperatures in the plasma asher discharge. This may produce reaction probabilities which exceed those which would be projected based on the room temperature energy alone. The higher initial impact reaction probability was assumed only for the plasma asher environment and not for the more energetic 4.5 ev space atomic oxygen. A summary of the revised Monte Carlo assumptions is given in table 1.

Figure 6 compares the predicted Monte Carlo undercutting profiles for large crack-width-to-coating-thickness defects and small crack-width-to-coating-thickness defects. As can be seen from figure 4b, the experimentally observed undercutting profile of the wide defect is in reasonable agreement with the Monte Carlo predicted profile. Figure 7 is a scanning electron photomicrograph of a plasma ashed undercut defect site for a narrow width-to-coating-thickness ratio defect. As can be seen, it also compares favorably with the predicted results shown in figure 6. A comparison of the Monte Carlo predicted and experimentally observed undercutting profile for plasma ashed polyimide Kapton which has protective coatings on both surfaces and a defect on the top surface only is shown in figure 8. As can be seen by comparing figures 8a and 8b, the predicted camphored walls of the undercut polyimide Kapton is in reasonable agreement with experimentally observed results. Based on comparisons between pin window and scratch defects from plasma asher experiments, the undercut profiles of each appear to have the same general shape. Thus the two-dimensional results of the Monte Carlo prediction are relevant to the three-dimensional pin window defect profiles.

The higher initial impact reaction probability of space ram atomic oxygen interaction causes a considerable drilling effect as shown in figure 9 for normal incident atomic oxygen because of the higher interface reaction probability. There is also a small but noticeable flaring to the undercut profile at the SiOx interface. Figure 10 compares the results of a wide defect exposed to fluence levels which produce the same depth of erosion for both plasma asher and normal incident space ram atomic oxygen attack. As can be seen, the surface morphology of a plasma asher is rather smooth compared to the space ram exposed surfaces. These results are very consistent with experimentally observed plasma asher and space exposure results. The predicted undercut Kapton profile for scratch or crack defects exposed to space sweeping ram atomic oxygen exposure as would occur on Space Station Freedom photovoltaic arrays is shown in figure 11 for polyimide Kapton protected on one surface and figure 12 for polyimide Kapton protected on two surfaces. As can be seen in figure 12, scattered atomic oxygen widens the undercut region well beyond the defect site.

SUMMARY

Tape peeling of plasma ashed SiOx coated polyimide Kapton provides a clear view of defect undercutting profiles by scanning electron microscopy. The undercutting profiles have a conical shape for defects whose width-to-coating-thickness ratio is less than or equal to one, and have a double dimple shape for defects whose width-to-coating-thickness ratio greatly exceeds one. The undercutting profile experimentally observed is more conical than the hemispherical undercutting that previous Monte Carlo modeling had predicted. Monte Carlo modeling provides a good fit to experimental results if the initial impact reaction probability in plasma ashers is 4 times the subsequent impact reaction probability and the probability of interface reaction for plasma ashers in space is 5 times the bulk reaction probability. Observed surface textures produced by plasma ashers and normal incident space ram are in good agreement with resulting Monte Carlo predictions. Sweeping ram exposure to polyimide Kapton protected on the top and bottom surfaces is expected to produce wide undercutting due to scattered atomic oxygen.

REFERENCES

1. S.K. Rutledge and J.A. Mihelcic, "Undercutting of Defects in Thin Film Protective Coatings on Polymer Surfaces Exposed to Atomic Oxygen," (NASA TM #101986), paper presented at the 16th International Conference on Metallurgical Coatings sponsored by the American Vacuum Society, San Diego, California, April 17-21, 1989.

2. B.A. Banks et.al., "Ion Beam Sputter-Deposited Thin Film Coatings for Protection of Spacecraft Polymers in low earth orbit," (NASA TM #87051), paper presented at the 23rd Aerospace Sciences Meeting sponsored by the American Institute of Aeronautics and Astronautics, Reno, Nevada, January 14-17, 1985.

3. B.A. Banks, S.K. Rutledge, B.A. Auer, and F. DiFilippo, "Atomic Oxygen Undercutting of Defects on SiOx Protected Polyimide Solar Array Blankets," paper presented at the Materials Degradation in Low Earth Orbit Symposium of the 119th TMS Annual Meeting and Exhibit, Anaheim, California, February 18-22, 1990.

4. B.A. Banks, et.al., "The NASA Atomic Oxygen Effects Test Program," paper presented at the 15th Space Simulation Conference, Williamsburg, Virginia, October 31-November 3, 1988.

5. B.A. Banks, et.al., "Simulation of the Low Earth Orbital Atomic Oxygen Interaction with Materials by Means of an Oxygen Ion Beam." (NASA TM #101971), paper presented at the 18th Annual Symposium on Applied Vacuum Science and Technology conducted by the American Vacuum Society, Clearwater Beach, Florida, February 6-8, 1989.

TABLES

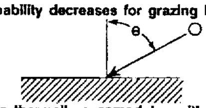
Table I - Monte Carlo Model Assumptions with Modification to Produce Agreement with Plasma Asher Results.

ASSUMPTIONS:

- 2D model simulates scratch or crack defect
- Reaction probability α (energy)$^{1/2}$

  0.138 for space (1st impact)
  0.0098 for space (≥ 2nd impact)
  0.0392 for plasma ashers (1st impact)
  0.0098 for plasma asher (≥ 2nd impact)
  0.0490 for plasma asher and space at Kapton/protective coating interface

- Reaction probability decreases for grazing incidence $\propto (\cos \Theta)^{1/2}$



- Atomic oxygen thermally accomodates with surfaces impacted
- Atomic oxygen remains atomic after impacting protective coating
- Unreacted atomic oxygen leaves surfaces in a cosine distribution

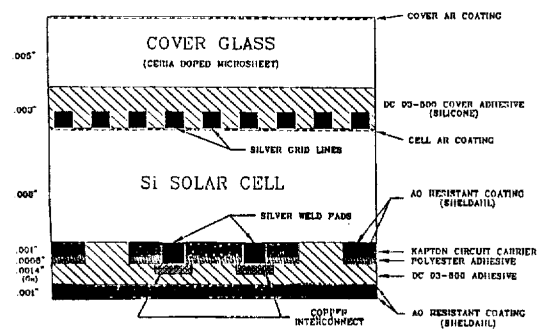


Figure 1 - Cross Section of Space Station Freedom Photovoltaic Array.

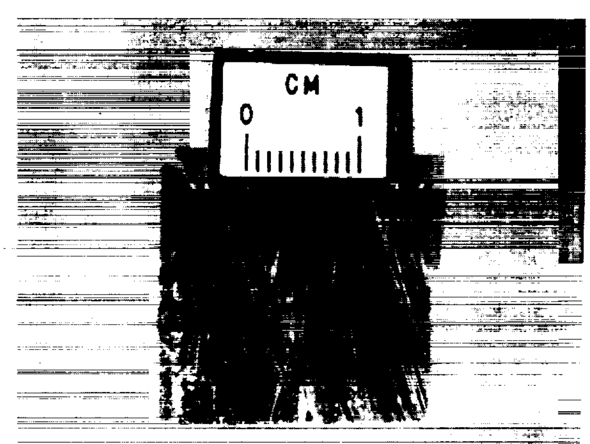
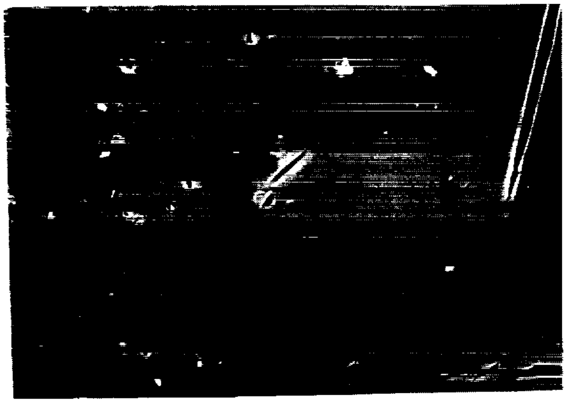
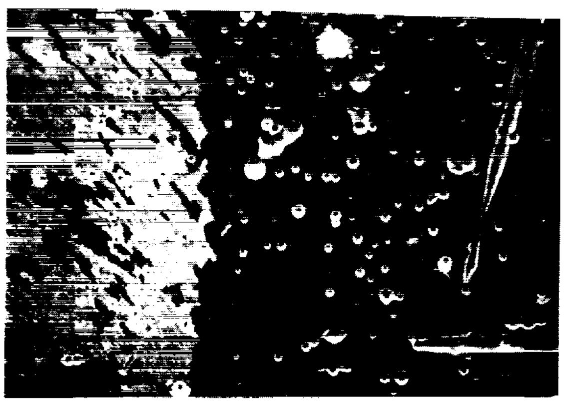


Figure 2 - Kapton H Protected on Both Sides with 1300Å Thick SiOx coatings After Plasma Ashing to a Fluence of 1.28 x 10^{22} atoms per cm^2 on each side.



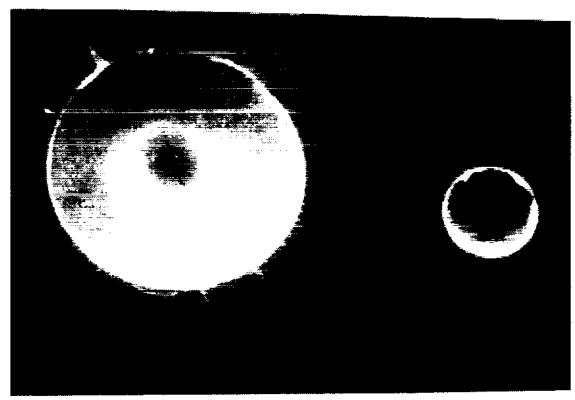
(a) Before Tape Peeling.



(b) After Tape Peeling.

Figure 3 - SiOx Coated Kapton H after Plasma Asher Exposure to a Fluence of 4.45 x 10^{20} atoms per cm^2.

(a) Before Tape Peeling.



(b) After Tape Peeling.

Figure 4 - Comparison of Two Defects in Protected Kapton after Plasma Asher Exposure to a Fluence of 4.45 x 10^{20} atoms per cm^2.

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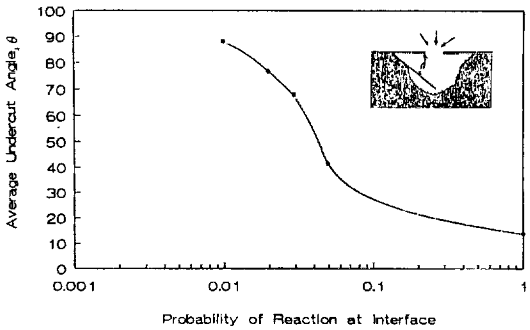


Figure 5 - Atomic Oxygen Undercut Angle at Kapton Interface Dependence Upon Interface Reaction Probability.

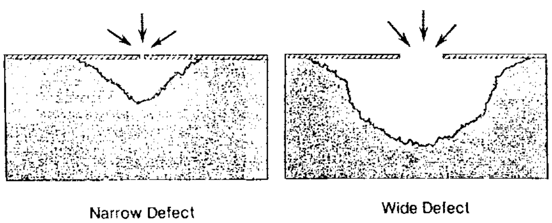


Figure 6 - Monte Carlo Plasma Asher Undercutting Defect Profiles Comparing Large and Small Defect Width-to-Coating-Thickness Ratios.

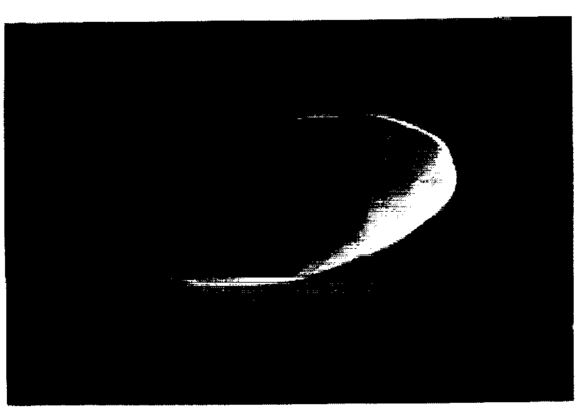
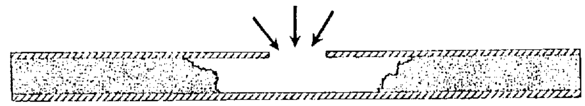


Figure 7 - Scanning Electron Photomicrograph of Plasma Ashed (to a fluence of 1.28 x 10^{22} atoms/cm^2) and Tape Peeled Defects on 1300Å SiOx Coated Kapton with a Small Defect-Width-to-Coating Thickness Ratio.



(a) Monte Carlo Prediction for Crack in Top Surface Defect.

(b) Plasma Asher Experimentally Observed Results for Pin Window Defect.

Figure 8 - Comparison of Monte Carlo Predicted and Experimentally Observed (after plasma ashing to a fluence of 1.28 x 10^{22} atoms/cm^2) Atomic Oxygen Undercutting Profiles for Polyimide Kapton Protected (1300Å SiOx) on Both Top and Bottom Surface with a Defect in the Top Surface Only.

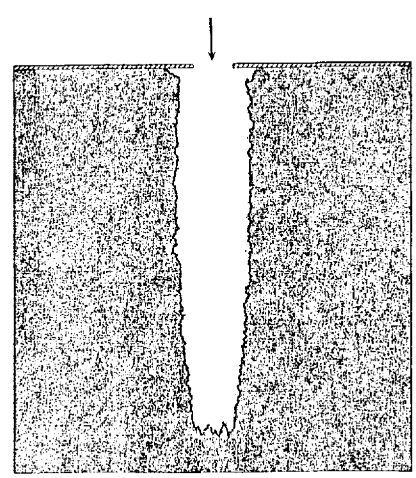


Figure 9 - Normal Incident Space Ram Atomic Oxygen Monte Carlo Prediction for Defect on Kapton Protected on One Surface.

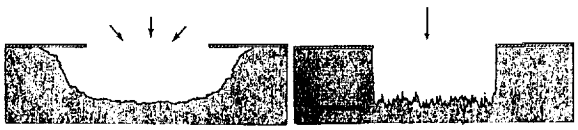


Figure 10 - Comparison of Monte Carlo Predicted Surface Profile for Equal Depth Erosion Plasma Asher and Normal Incidence Space Ram Atomic Oxygen Exposure of a Wide Defect.

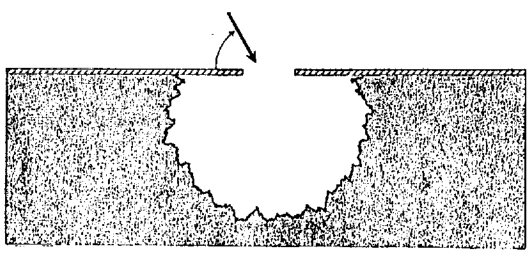


Figure 11 - Sweeping Ram Atomic Oxygen Monte Carlo Prediction for Defect on Kapton Protected on One Surface.

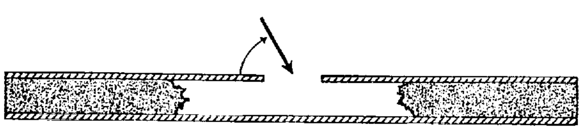


Figure 12 - Sweeping Ram Atomic Oxygen Monte Carlo Prediction for Defect on Kapton Protected on Top and Bottom Surfaces.