On the degradation of structural polymers exposed to high-energy atomic oxygen ions

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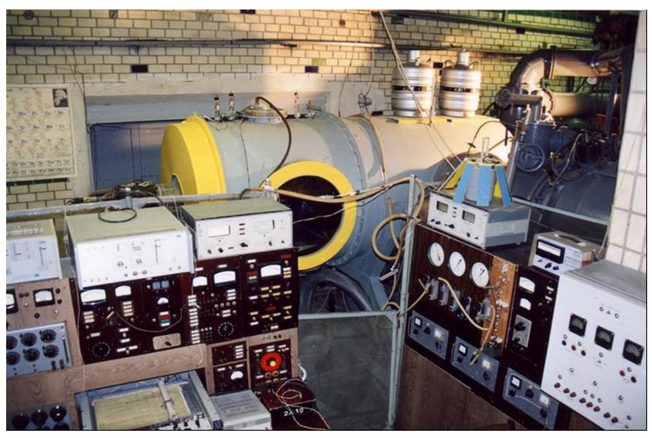
Introduction

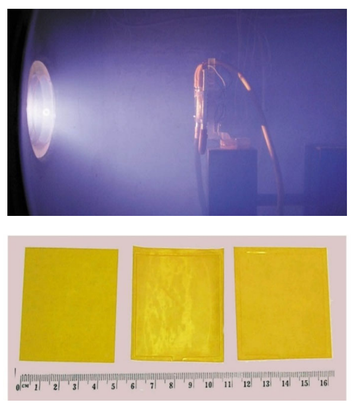
Polymers are widely used in spacecrafts as structural materials for outer coatings, solar array coverings, components of blanket thermal insulation, etc. The near-satellite environment at altitudes of 200–700 km attacks spacecraft polymers by exposure to the partially ionized ionospheric plasma of atomic and molecular oxygen. This leads to significant changes of physical, chemical, thermo-optical, and mechanical material properties.

This publication presents the results of experimental studies on the degradation of properties of polymer structural materials employed in space rocket hardware (among which are polyimide Kapton-H and teflon FEP-100A) exposed to high-energy atomic oxygen ions. It is found that at oxygen ion energies ~ 5…200 eV polymer surface sputtering, mass loss, destruction, and erosion are governed by chemical etching.

Experimental Setup

Experimental studies were carried out on a plasma-electrodynamic bench of the Institute of Technical Mechanics. To generate flows of atomic-molecular oxygen ions, a gas-discharge accelerator was used with ionization of the working fluid by electron impact and electron oscillation in an external magnetic field. The plasma accelerator can produce plasma beams with ion density 10^8…10^{10} cm^{-3} and energy 5 …100 eV in the beam working zone. The systems and devices of the setup allow one to physically simulate processes and phenomena that take place in the interaction of spacecraft's materials and structural elements with gas, plasma, and high-energy charged particle flows and electromagnetic radiation of wide frequency range in the Earth's upper atmosphere and ionosphere.





Polymer samples after exposure to plasma flow

Results and discussion

The polymer erosion yield, erosion depth, mass loss, solar absorptance, and emittance are determined as a function of the AO ion energy and flux. The experimental values and relationships are approximated by a power function.

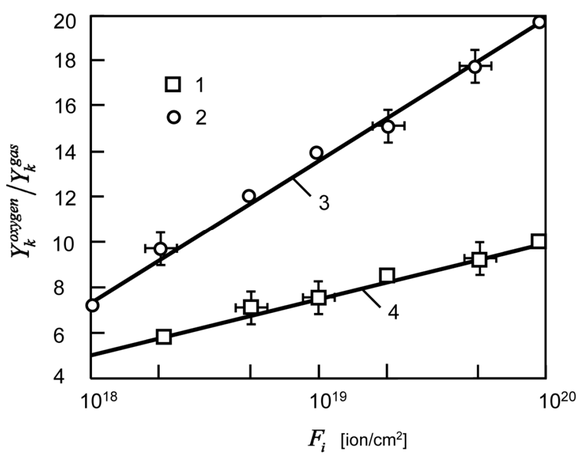
The results obtained on the ITM plasma-electrodynamic setup are in agreement with those obtained in the Earth's ionosphere onboard the Mir orbital station, the International Space Station, the Space Shuttle, the Spot-1, 2, 4, etc.

Polyimide sputtering yield

The sputtering yield Y is defined as the number of particles ejected from the target material per incident ion

Sputtering yield ratio Y^{oxygen} / Y^{gas} for polymers (especially polyimide Kapton-H) bombarded by high-energy ions of oxygen plasma ("*oxygen*") and plasma with chemically neutral ions Ne, N ("*gas*") versus the bombarding particle fluence F_i with different ion energy in wide range.

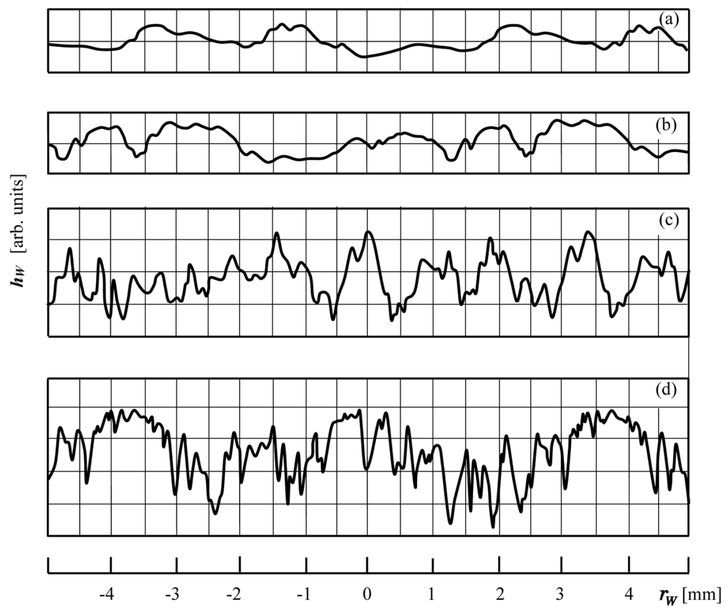
For bombardment by oxygen ions chemical sputtering (chemical etching) is predominant.

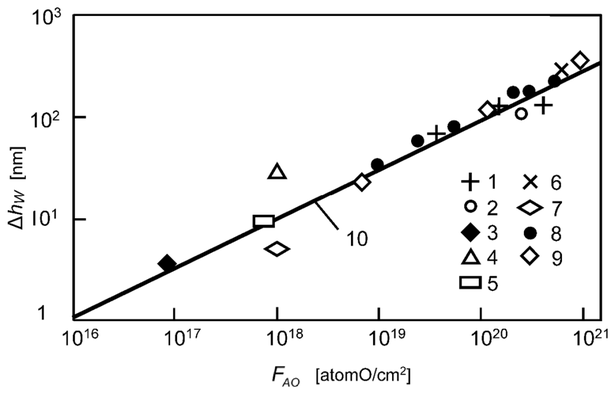


Polymer surface destruction (roughness)

Polymer exposure to oxygen ions flow causes surface destruction and changes the relief and the surface roughness.

Profilograms of the polyimide surface after oxygen ion irradiation (ion energy 6.9 eV, fluense from 6.7×10^{18} ion/cm^2 to 1×10^{21} ion/cm^2)

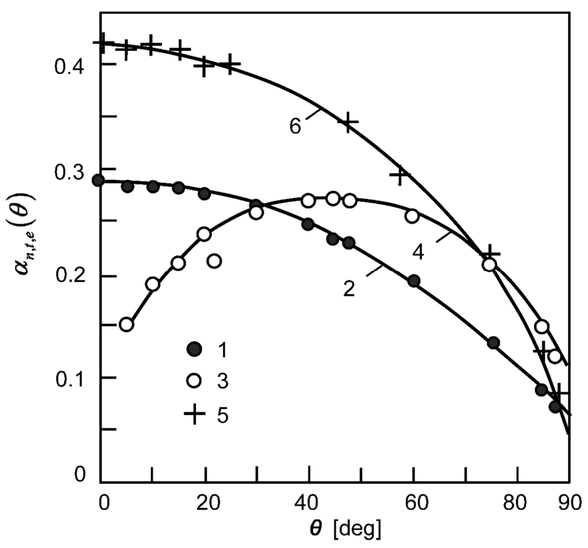




The dependence of roughness Δh on fluence F for polyimide Kapton-H exposure to atomic oxygen plasma flow with ion energy in range 4.6…7.5 eV

Atomic oxygen-to-polyimide momentum and energy transfercoefficients

With the help of a high-sensitivity microbalance, parameters of dynamic interaction in the atomic oxygen ion – polymer system are determined: the drag force and the lift force acting on a flat plate. The normal (n, line 2) and tangential (t, line 4) momentum and energy (e, line 6) transfer coefficients are found as a function of the angle of attack (θ) on a flat surface. We identified the effect of the surface roughness degree on the ion momentum and energy transfer coefficients as a function of the angle of attack of a flat plate.



The relationships for the momentum and energy accommodation coefficients may be used in the calculation of the aerodynamic characteristics and surface heat fluxes of arbitrarily shaped bodies.

Conclusions

The results of experimental studies and developed procedures for accelerated endurance tests of polymers for resistance to long-term exposure (3…7 years) to hypersonic AO flows in very low-Earth orbits (150…3000 km).

The parameters that characterize the dynamic interaction of polymers surfaces with flows of fast atomic oxygen ions (with energy above 4.5 eV) are determined. The obtained dependencies allow one to predict the behavior of the polyimide parameters during a long lifetime at altitudes ~150–700 km in the Earth's ionosphere and may be used as reference values in tests of structural polymer materials.

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