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Physical simulation of the long-term dynamic action of a plasma beam on a space debris object

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ABSTRACT

A methodology is developed for physical (laboratory) simulation of the long-term dynamic action of plasma beam high-energy ions on a space debris object with the aim of removing it to a lower orbit followed by its burning in the Earth's atmosphere. The methodology is based on the use of a criterion for the equivalence of two plasma beam exposure regimes (in the Earth' ionosphere and in laboratory conditions) and an accelerated test procedure in what concerns space debris object material sputtering and space debris object erosion by a plasma beam in the Earth's ionosphere. The space debris coating material (blanket thermal insulation) sputtering yield and normal and tangential momentum transfer coefficients are determined experimentally as a function of the ion energy and the ion beam incidence angle.

1. Introduction

Recently, the problem of spacecraft safety in near-Earth orbits has become quite pressing. This is due to the contamination of near-Earth space with fragments of space hardware, or space debris objects (SDOs): spent rocket stages, fuel tanks, old satellites, etc. A large number of projects aimed at "cleaning" near-Earth space by the removal of SDOs to lower orbits followed by their burning in the Earth's dense atmosphere have been proposed. In the LEOSWEEP project funded by the European Commission, it is intended to push an SDO to a lower orbit by acting thereon with a plasma beam produced by an ion thruster onboard a dedicated spacecraft (ion beam shepherd). A schematic of the LEOSWEEP concept is shown in Fig. 1[1,2]. The efficiency of implementation of such a project is largely determined by the transfer of the momentum of Xe^+ ions with energy $E_i \approx 3.5$ keV to the SDO surface.

The processes of sputtering and force (momentum) transfer are crucial in the dynamic interaction of plasma beam high-velocity ions with a solid surface.

At bombarding particle energy $E_i >> 10^2$ eV, the surface material mass loss is mainly governed by the sputtering of the bombarded material. The contribution of the scattered particles is accounted for via the momentum and energy transfer coefficients (accommodation coefficients).

For the majority of SDOs (for example, the third stage of the Cyclone-3 launch vehicle), the outer coating material is blanket thermal insulation (BTI), which has a complex multilayered structure.

According to preliminary estimates, for an SDO to be removed from a 650 km orbit to an altitude of 300 km, the duration of its exposure to plasma beam high-energy Xe^+ ions may have to be as long as 100 days and more [3].

The effects and consequences of the exposure of the SDO coating material to a plasma beam can only be predicted by physical simulation of the long-term dynamic interaction of high-energy ($E_i > 1$ keV) Xe^+ ions with BTI on a dedicated setup. Up to now, there have been no experimental studies on the features of dynamic interaction of Xe^+ ions with BTI at energies $E_i \geq 10^2$ eV. Because of the complexity of the BTI composition and structure, numerical simulation of this interaction is hardly possible, if at all.

The aim of this work is the development of a methodology for physical (laboratory) simulation of long-term dynamic interaction in the plasma beam high-energy ions – SDO coating material system in the Earth's ionosphere in terms of sputtering and momentum transfer.

2. SDO coating material sputtering

2.1. Experimental facilities and procedures

The experiments described in this paper were conducted on the ITM plasmadynamic setup. The setup is a plasma gas-dynamic tunnel, and it serves to study spacecraft – Earth ionosphere interaction by simulating the following processes [4–6]: momentum and energy transfer from rarefied plasma beams to a spacecraft surface and spacecraft systems (aerodynamics and heat exchange), the electrora-

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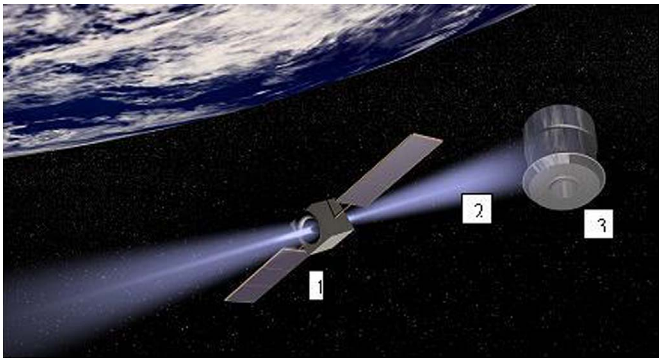

Fig. 1. Schematic of the LEQSWEEP concept: the removal ("pushing") of a space debris object to a lower orbit by a plasma beam in the Earth's ionosphere, 1 – ion beam shepherd; 2 – plasma beam; 3 – space debris object.

diative differential charging and neutralization of spacecraft in geostationary orbits and in the polar ionosphere, and the physicochemical degradation of spacecraft surface materials.

The vacuum chamber of the setup (a cylinder of diameter 1.2 m and length 3.5 m) is made of nonmagnetic stainless steel. The evacuation system of the setup (mechanical pumps of capacity up to 2.5 m^3/s, diffusion pumps of capacity about 50 m^3/s, and an oil-free evacuation system of air capacity about 50 m^3/s, which consists of a discharge vacuum unit and a turbomolecular pump) and LN_2-cooled cryopanels in the vacuum chamber provide a static vacuum of about 10^{-5} N/m^2 and a pressure of 10^{-3} N/m^2 with gas inflow [6].

Targets (test material samples and spacecraft structural elements and instruments) and diagnostic instruments are mounted on movable platforms (an upper one and a lower one) with four degrees of freedom (DOFs) each, which can move in a lengthwise and a transverse direction in a horizontal plane, move in a vertical direction, and rotate about a vertical axis. The positioning accuracy is 0.5 mm for linear displacements and 0.5° for angular ones. During an experiment, the targets and diagnostic probes can be moved to nearly any point of the plasma beam and the interior of the vacuum chamber. The plasma beam parameters are measured using a system of electric probes and a 5.45 GHz microwave interferometer [6]. The following probes are used: cylindrical probes made of tungsten (radius r_p=2×10^{-2} cm and length l_p≈1.0 cm) and molybdenum (r_p=4.5×10^{-3} cm and l_p=0.45 cm), a spherical molybdenum probe of diameter 2r_p=0.40 cm, a plane molybdenum probe of diameter 2r_p=1. 0 cm, and a molybdenum Faraday cup of diameter 2r_p≈1.0 cm and height l_p≈1.0 cm.

The directional ion energy E_i is measured with a multielectrode energy analyzer, the spread of measured values being within ±4.5%. Rarefied plasma beams with high-energy ions were produced using a gas-discharge accelerator with electron impact ionization and electron oscillation in an external magnetic field. The accelerator can produce supersonic rarefied plasma beams using such working gases as H_2, He, Ne, N_2, O_2, Ar, Kr, and Xe. The Xe^+ ion energy is 0.1–0.3 keV in the standard regime and 0.75–1.8 keV with the use of a multielectrode ion after-acceleration system.

Current–voltage characteristics are recorded automatically, the current measurement error being within ±2%. The plasma potential was determined from the point where the characteristics of a cold and a hot thermoprobe diverge, the plasma potential spread being within ±4%. The targets were oriented with respect to the incident flow velocity using a single cylindrical probe of radius r_p≈4.5×10^{-3} cm and length l_p≈0.45 cm. When rotating the probe about a vertical axis, the peak of the ion current detected by the probe corresponds to the probe orientation along the flow, and the ion current peak half-width is proportional to the degree of nonisothermality of the rarefied plasma. The composition of the residual gas in the vacuum chamber was checked using a mass-spectrometer [6,7].

In the sputtering experiments, a target made of the SDO coating material (BTI) was used (hereinafter referred to as the BTI target). The components of the BTI target are as follows:

- BTI mat, which consists of ten layers of 5×10^{-4} cm perforated aluminized polymer film and fiberglass fabric, with which the polymer film layers are interleaved to prevent them from clinging together;
- envelope bag made of glass cloth (continuous alumina-borosilicate fiber of thickness about 2.5×10^{-2} cm), into which the BTI mat is put.

The envelope bag with the BTI mat is fastened to a 1 mm Al-Mg alloy plate.

The outer coating of the BTI mat is a glass cloth net. The glass cloth is made of continuous alumina-borosilicate fiber. The predominant components of the fiber are SiO_2 (54%), B_2O_3 (5%), Al_2O_3 (14%), CaO (23%), MgO (2.5%), and Na_2O (0.5%). The percentage of each of the other components is less than 0.3%. The volume density of the glass cloth fiber is ρ_W≈2,54 g/cm^3, and its average molecular weight is m_W≈65.5 amu. Up to now, there have been no studies on the interaction of Xe^+ ions of energies $E_i >> 10^2$ eV with BTI. Because of this, to verify the data measured for the BTI target in a Xe^+ ion beam with $E_i >> 10^2$ eV, use was also made of a reference steel target (type 12Kh18N10T stainless steel) with a bombarded area equal to that of the BTI target. The predominant components of type 12Kh18N10T steel are Fe (68%), Cr (18%), Ni (10%), Mn (2%), Si (0.8%), and C (0.12%). The percentage of each of the other components is less than 0.1%. The volume density of the steel is ρ_W=7.9 g/cm^3, and its molecular weight is adopted to be m_W≈55.2 amu. The targets used in the sputtering experiments have the form of disks of outer diameter d_1=41×10^{-1} cm with a bombarded surface of diameter d_W=33.5×10^{-1} cm. The BTI target and the steel target were mounted on the 4 DOF lower movable platform in Xe plasma beams with a Xe^+ ion energy of 0.2–1.8 keV.

The gas-discharge plasma accelerator makes it possible to produce plasma beams of concentration 10^8 to 10^{10} cm^{-3} at electron temperatures T_e from 2.5 to 3.0 eV and ion temperatures T_i from 0.4 to 0.7 eV. The tests were conducted in plasma beams with Xe^+ ion concentration n_i≈3.1×10^8 cm^{-3}. The total exposure time was 2 days. The BTI target and the steel target mounted on the lower movable platform in a Xe plasma beam are shown in Fig. 2. The measurements were made at a beam cross-section with a uniform core (with a constant ion concentration and a constant ion velocity) of diameter about 20 cm. The beam divergence angle was ±7.5^0.

To weight the targets outside the vacuum chamber (about one hour before and one hour after the vacuum and plasma exposure), an analytical microbalance with an error within 10^{-4} g was used. Weighting outside the vacuum chamber about one hour before and

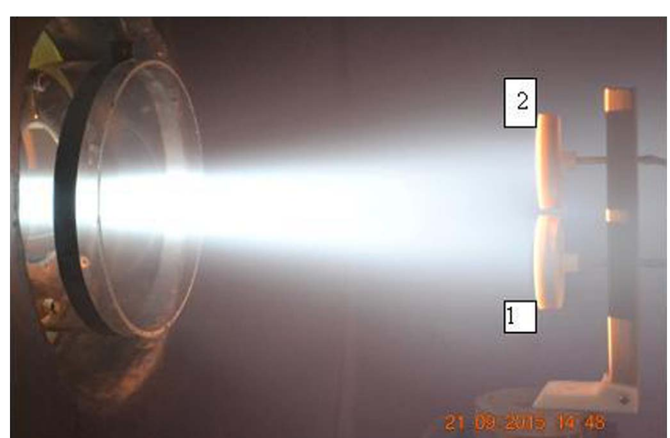

Fig. 2. Targets in a rarefied Xe plasma beam, 1 – steel target; 2 – BTI target.