EXPERIMENTAL DETERMINATION OF SPUTTERING COEFFICIENTS ISP SOFTWARE : NUMERICAL CALCULATION OF MATERIAL EROSION

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Abstract

ISP (Interaction Software Propulsion) is a software dedicated to the calculation of the plume effects occurring in electrical propulsion. The interactions between spacecraft surfaces and SPT plasmic jet lead notably to a phenomenon of surface degradation (material erosion and sputtered particles re-deposition). The numerical calculation of these degradation effects can be achieved with ISP through sputtering coefficients. The sputtering coefficients depend particularly on the impinged surface material, incident angle and ions energy.

Experimental measurements of material erosion is the only way to determine the sputtering coefficients. A test campaign has been carried out for several materials which are the main constituents of telecommunication satellites devices. The objective of the tests was to determine the sputtering coefficients S (mm3/C) or S' (atom/ion) as a function of energy level, impact angle and radiation dose for the following materials : silver, coverglass, Tefzel, kapton, paste, and paint. The results show the differences between materials behaviours when submitted to plasma jet.

The results of this campaign allow to update the ISP material data base. An example of realistic calculation on a telecommunication satellite solar array is presented through graphical visualisations of material sputtering. The evaluation of the materials erosion can lead to an estimation of optical or electrical performance degradation.

Introduction

The use of electric propulsion system is an attractive solution to the fuel mass saving, payload extension and lifetime increasing problems for the future telecommunication satellites. In order to assess the innocuousness of this type of propulsion, it is necessary to evaluate the influence of the plasma jet on the satellites regarding surfaces. The presence of charged particles with very high velocities due to the gas ionisation (plasma) results also in new types of interactions : surfaces degradation (material erosion and sputtered particles re-deposition) and electrical effects (modelisation of surface potential). I.S.P. (Interaction Software Propulsion) offers the capability to compute the phenomenon of sputtering + re-deposition and possibly cleaning (sputtering of re-deposited particles). The sputtering rate is calculated through several parameters, including the sputtering coefficients. These coefficients can only be obtained by the mean of ground experiments.

Experimental measurements

A test campaign has been performed for several materials in order to characterise their behaviour in term of erosion when exposed to a plasma jet. These tests were ordered by Alcatel Space Industries and were achieved in the Moscow Aviation Institute.

Tests objective

The objective of these tests was the determination of the sputtering coefficients as a function of ion energy level, impact angle, and impinged materials. The measured data will be used to fulfill the ISP software data base.

Selection of materials to be tested

Two main criteria guided the choice of materials to be tested : the criticity of their on-board possible erosion, and the need to quantify the erosion rate.

The major subsystems concerned by these tests were the thermal control subsystem and the solar array subsystem. Indeed, the electrical thrusters are located on spacecraft in front of the solar array and close to a lot of thermal control devices.

The selected materials were : silver, Tefzel, kapton, paste, paint, and coverglass.

Test facilities

The aim was to determine erosion coefficients as a function of incidence angle, energy level and radiation dose. The radiation dose D is defined as :

$$D = j \times \tau \qquad (1)$$

with j the incident ion density and τ the exposure time.

The distance between thruster and material sample was decided to be as small as possible, so that a great radiation dose in a short exposure time can be

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obtained. The plasma source was controlled in order to reach the foreseen ion density at the sample location. Probes were installed in the chamber to measure current density, ions energy, residual pressure and nature of residual gases.

Samples were located on the thruster axis with a variable incidence angle (see figure 1). A diaphragm was used to avoid disturbances due to the deposition of the chamber sputtered materials.

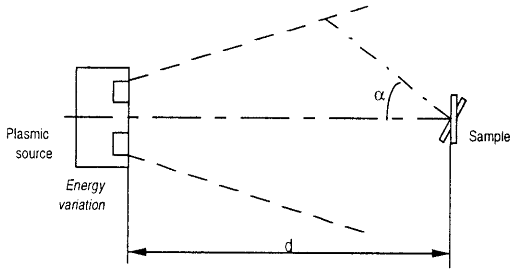


Figure 1. : tests configuration

As mono-layers materials were tested, a small vacuum chamber with a quite simple vacuum pump has been used. A preliminary test was performed to check the compatibility between the materials outgassing rate and the vacuum pump capacity.

Results

The paste was tested with success and we determined its sputtering rate. The paste is mainly composed of silver and silicone.

We noticed that the erosion rate decreases when the radiation dose increases. The asymptotic erosion rate seems to be the silver erosion rate. Furthermore, the paste conductivity increases with exposure time. These two statements access that silver proportion in the paste increases with the radiation time. Thus, silicone is more eroded than silver.

Concerning the evolution of sputtering coefficient as a function of the other parameters:
- versus energy level : the evolution is nearly linear and increases with energy level.
- versus incidence angle : a maximum is obtained for incidence angle around 50°.

For white paint, the sputtering coefficient is nearly the same whatever the radiation dose is. At the beginning of these tests, we noticed sometimes a higher value of erosion rate, which corresponds to a polishing of the impacted surface.
The maximum erosion rate is obtained for an incidence angle of around 45°, but the evolution is slight.

For silver, the sputtering rate increases linearly with radiation dose. And the evolution versus incidence angle is very slight, and very similar with paste and paint.

The coverglass has a very low sputtering rate compared with the previous ones. It also increases linearly versus ions energy level. The sputtering rate of coverglass highly depends on the incidence angle. The maximum sputtering rate is obtained for an angle between 50° and 55 ; the maximum sputtering rate is four times higher than the value at 0°. The coverglass test exhibits high degradation of its optical properties : we can see that coverglass is frosted after testing.

The sputtering rates are close for paste, paint, and silver. Their evolutions versus energy level and incident angle are also very close. Their sputtering rate decreases with energy level (see figure 2).

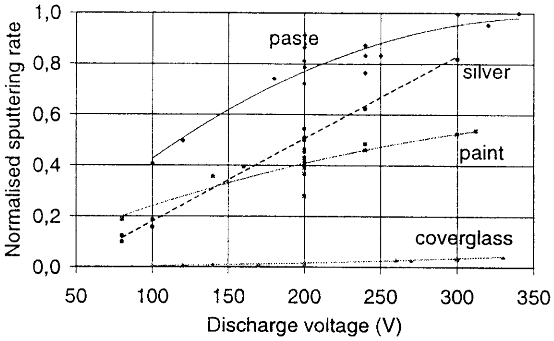


Figure 2. : Normalised sputtering rate versus discharge voltage at angle 0°

The maximum sputtering rate occurs for a 50° incidence angle. For the three materials, the maximum value is 1.5 times higher than value at 0° incidence angle (see figure 3).

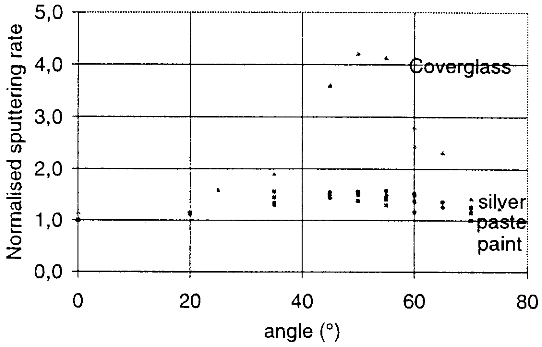


Figure 3. : Normalised sputtering rate versus incidence angle

For coverglass, the sputtering rate is low but is highly dependent on incidence angle. The maximum sputtering rate (for a 50° or 55° incidence angle) is four times higher than the value at 0° (see figure 3).

Notes

To keep the dose D constant (between the test and the reality), it is necessary to increase the ion current density to reduce the test duration, as exposed in equation (1). That is why the distance between samples and plasma source was lowered, in order to have the same radiation dose in a shorter exposure time. This is a realistic hypothesis only if the sample surface is not destroyed by a thermal phenomena. This trouble was encountered for Tefzel and kapton. The maximum allowable temperature for these two materials is around 200°C which was very low for our chosen tests conditions. For a non thermal conductive material, the temperature calculated at the sample location on the thruster axis, may reach 600°C ! Thus the tests of kapton and Tefzel were unsuccessful.

In order to check these assumptions, another test was conducted for kapton : it was exposed to the plasma source at a longer distance from the thruster, during times corresponding to 250, 500, 750 and 1000 flight hours. No visible change in surface properties was observed : the kapton surface, exposed to the jet, exhibits no difference with the witness-sample. So we concluded that kapton will withstand the plasma jet without great change in surface properties.

Example of realistic calculation

I.S.P. Interaction Spacecraft Propulsion Software

In order to describe the sputtering in the ion energy range of interest, several methods are available. For most of the materials, the sputtering theories based on collisionnal models of the surface atoms give the more suitable results.

The sputtering coefficients S can be defined as :

$$S = \frac{Nb\ of\ sputtered\ atoms}{Nb\ of\ incident\ ions} \qquad (2)$$

These coefficients were extracted from the experimental measurements described in the previous chapter. They were tabulated for various ion energies and angles of incidence. Interpolation formula are then used to modelise all the satellite geometric configurations.

In ISP software, for the SPT modelisation, plasma plume is represented with a multi-fraction model, based on the following : the Xe ions amount is divided into two groups depending on their charge (Xe+ and Xe++) and in each group, the particles are separated into monovelocity (monoenergy) classes called fractions. The dispersion of each fraction is examined separately. With appropriate assumptions, the model of the point source with varying intensity on jet divergence angle is taken as model to describe the spatial distribution of particles concentration for each fraction.

The total sputtering rate is then calculated using the following relationship :

$$\lambda(d,\varphi) = \frac{m_s}{\rho_s}\sum_f n_f(d,\varphi)u_f S(\varepsilon_f,\theta) \qquad (3)$$

Where $n_f(d,\varphi)$ is the particles concentration for the f-fraction on the φ-ray at a distance d from the thruster outlet.

Sputtered particles coming from exposed surfaces degradation can deposit on other parts of the satellite. The mathematical model used in ISP allows to calculate flow density of the different particles which come from every sputtered surface and arrive on contamined surfaces. Those particles densities widely depend on geometric parameters such as emission angle of sputtered particles θ_{AB} and viewing angle in the direction θ_{BA} (see figure 4).

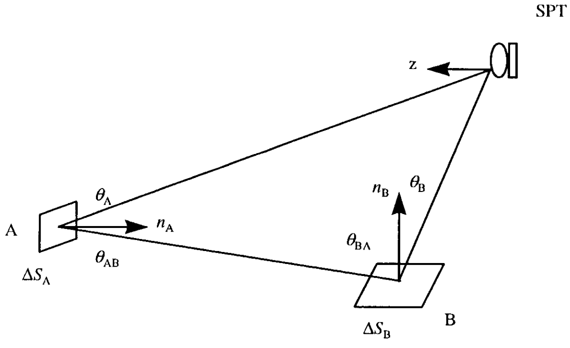


Figure 4

Application to a realistic configuration

The results of the tests allow to update the ISP materials database, for several materials : coverglass, silver, paste and white paint. The sputtering coefficients for aluminium had been already obtained in a previous experimental campaign.

For a western telecommunication satellite, the main subsystem exposed to the SPT plasma jet is the solar array.

The main materials constitutive of the solar array are coverglass for the solar cells, silver and paste for the electrical connectors, aluminium for the lateral sides of the panels and white paint for the yoke. The rear face of the solar array is constituted with a carbon skin. At present, due to the lack of information concerning the carbon erosion, and especially sputtering coefficients, the modelisation of this surface erosion is not possible.

The geometric configuration is shown hereafter.

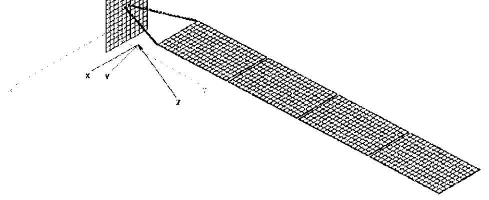


Figure 5 : Geometric configuration

ISP is able to take into account the solar array rotation during one orbit day through the creation of geometrical models for each hour (discretisation chosen for the solar array rotation step).

The simulation is divided in two parts :

- On one hand, calculation of the erosion rate on the solar array, summation and integration of these rates for the satellite lifetime in order to obtain the erosion depths and to estimate the criticity of the phenomenon.
- On the other hand, calculation of the re-deposition rates for each sputtered particle on the surfaces located in a direct visibility range from the sputtered surfaces. As in the previous part, summation and integration of these rates are done.

The results of erosion are represented on figure 6 for all materials and are normalized with the maximum value.

The figure 7 displays the re-deposition of all the solar array sputtered materials on the south lateral side of the satellite. The depths are also normalized with the maximum value of this phenomenon.

Conclusion

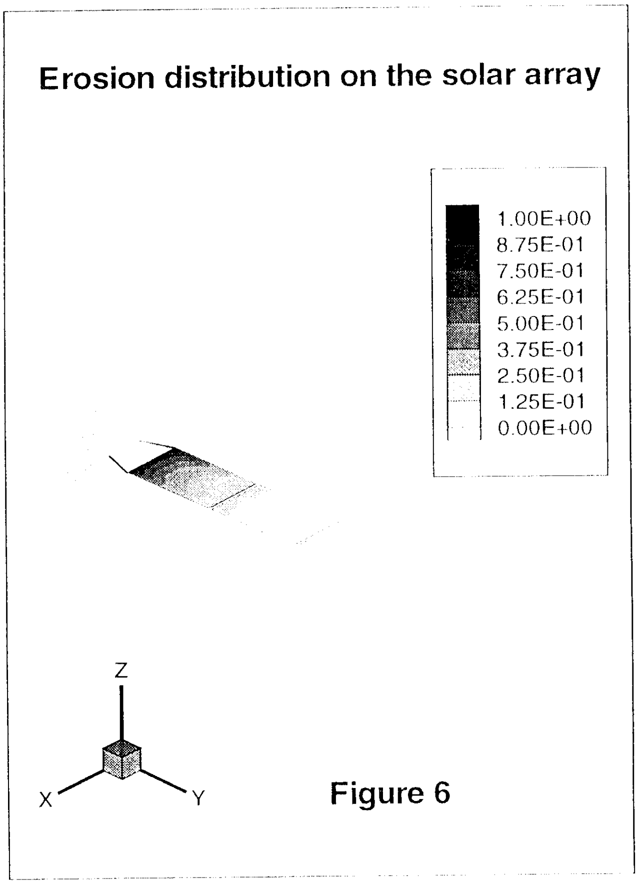
The test campaign has partially reached its goal by providing Alcatel with a new materials sputtering data base for ISP, which permits to calculate the erosion and re-deposition depths on the whole satellite. The erosion criticity on satellites can now widely be evaluated with ISP software.

Regarding re-deposition calculation, the database for carbonaceous components have to be completed, and tests have to be refined to obtain more suitable measurements on materials such as kapton, MLI, Tefzel...

Nevertheless, ISP is an efficient way to compute, even partially, the complex phenomenon of sputtering + re-deposition + cleaning. It allows to quantify the impact of the electrical propulsion use, on the solar array performances (erosion calculation) and on the pollution of passive thermal control devices (deposition calculation).

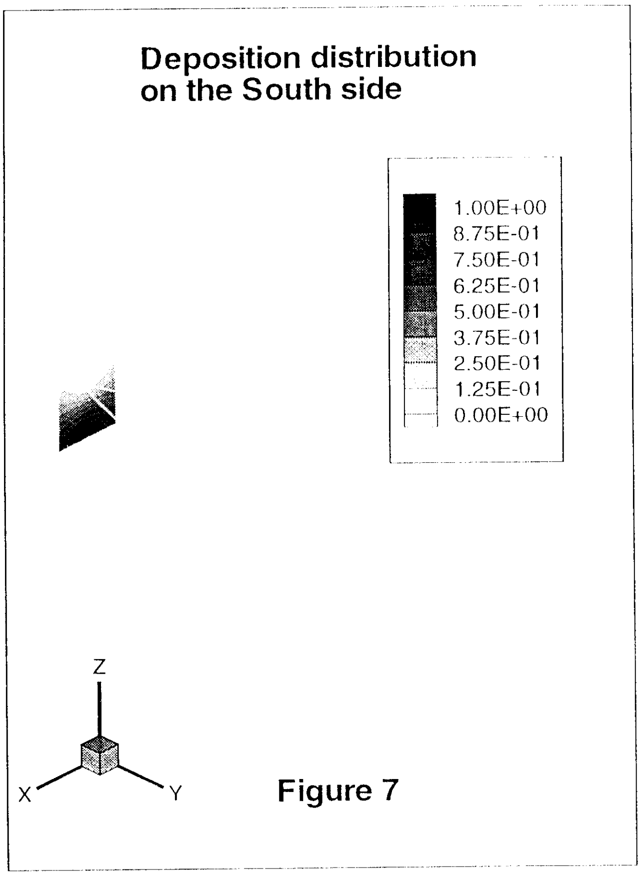
References

[1] D. Borie, V. Perrin, S. Khartov, A. Nadiradze, "The I.S.P. software : calculation of the SPT jet influence" *Second European Spacecraft Propulsion Conference,* ESTEC, Noordwijk, the Netherlands, 27-29 May 1997.



Erosion distribution on the solar array

Figure 6



Deposition distribution on the South side

Figure 7