Measurement and modelling of the inside channel deposition of the sputtered ceramics on HET PPSX000-ML. A tool to predict the erosion along the thruster lifetime.

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In this contribution, we present a new method to predict the ceramic erosion of the thruster channel inner walls. Silicon substrats are introduced into the channel of the PPSX000-ML Hall Effect Thruster (laboratory model) before four hours of firing for five sets of tooling ceramics in the PIVOINE french facility. The deposition layers of the sputtered ceramics by impinging ions are measured by means of profilometry after firing. Geometrical 1D model has been developed in order to determine the quantity of material sputtered. Thus evolution of the ceramic wear along the thruster virtual lifetime has been determined until 6000 to 7000 hours. OES erosion measurements were performed during tests using the silicon substrats. Good correlation was obtained between the substrat and spectroscopic methods.

I. Introduction

Ceramic erosion appears as an important wearing process in Hall effect thruster. Ions are created inside the channel and accelerated outwards yielding the thrust. Part of this ion flux directed towards the walls of the channel produces the erosion of the ceramic. Material components are sputtered, mainly towards outside and much less inside which are deposited on the inner walls. Modellisation of the erosion is difficult because the radial distribution of the electric field inside the channel and the sheath potentials are not well known. In addition, the geometrical shape of the ceramic changes during the erosion process. Therefore a new method to measure the material sputtered then deposited on the channel inner walls has been investigated to quantify the ceramic erosion.

Study of the ceramic erosion has been carried out by means of silicon substrats introduced into the channel inner walls of tooling ceramics of the PPSX000-ML Hall Effect Thruster (laboratory model). Five sets of inner and outer ceramics (5, 10, 15, 20 and 30°) have been used, equipped with eight substrats on each ceramic disposed azimuthally each 45° and beside the erosion zone. Results of the measure of the deposition are presented in the chapter III.

A geometrical 1D model is developed in the chapter IV which allows to relate the deposition with the quantity of sputtered material. The use of five sets of tooled ceramics gives the possibility to predict the ceramic wear along the life of the thruster.

Optical Emission Spectroscopy has been used to measure the relative ceramic sputtering density. OES erosion results are related to calculated erosion by geometrical 1D model.

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II. Experimental set-up

This section discusses the use of tooled ceramics, experimental procedure to measure the deposition, and Optical Emission Spectroscopy to measure ceramic erosion.

A. Use of tooled ceramics

![Figure 1. Schematic sketch of the 5 tooled ceramic sets with their respective tooling angles and their mark numbers.]

B. Deposition measurements

On each inner and outer ceramic eight $23 \times 2 \times 0.3$ mm silicon substrats were sticked by means of boron nitride liquid coating. Substrat end was disposed at 10 mm from the exit plane in order to avoid the sputtering of these substrats by impinging ions. The silicon substrats were located at 45° each other in order to study the azimuthal symmetry of the plasma.

Before sticking, about 15 lines were drawn on the substrats by means of a permanent marker. After sticking, distance of each marker line from the exit plane was measured.

Before firing, the ceramic (inner and outer) were outgasing during 2 hours into an oven at 120 °C.

After 4 hours of firing at the reference point (500 V, 6 mg/s [Xe]), the 16 substrats were removed (Fig. 3).

The marker lines were removed into an ultrasonic tank filled with acetone and the steps were measured by means of a profilometer (Veeco-Dektak-6M).

Typical profilometer screen capture of one substrat during step measurement is shown on the Fig. 4. Two step measurements (left and right) were performed for each trench obtained after marker line removing. In total, $5 \times 16 \times 15 \times 2 = 2400$ step measurements.

On Fig. 5 and 6 two typical trenches are shown in order to compare a strong deposition (about 1 $\mu$m on the 5° inner ceramic at 270° and 15.5 mm from the exit plane) and a weak deposition (about 0.07 $\mu$m on the 30° outer ceramic at 225° and 30 mm from the exit plane). The first one corresponds to the deposition near the exit plane and the second one to the deposition near the anode. The ratio signal/noise is very good for deposition thickness larger than 200 nm. Deposition thickness measurements become difficult above 50 or 100 nm.
Figure 3. Substrat after 4 hours of firing.

Figure 4. Profilometer screen during step measurements.

Figure 5. Deposition thickness on substrat #1 at 270° and 15.5 mm from exit plane.

Figure 6. Deposition thickness on substrat #10 at 225° and 30 mm from exit plane.

C. Optical Emission Spectroscopy to measure ceramic erosion

A schematic diagram of the experiment is shown in Fig. 7. A 45°-sight axis view of the channel entrance has been used in order to observe both: part of the exit plane where the erosion is large and part of the plasma inside the channel.

The light emitted by excited states of neutral and ionized xenon, neutral boron or silicon was collected by an external short focal quartz lens (10 cm).

One end of a 500 µm diameter quartz fiber was set in the focal plan of the quartz lens. So, a spatial resolution of 1 cm was obtained thanks to a large optical magnification (20) in order to integrate possible displacement either of the plasma or erosion.

The other end of the fiber was connected to the entrance slit of a 500 mm imaging spectrometer (ACTON 500i) equipped with a CCD camera. A good spectral resolution of .15 nm was obtained with an entrance slit of 25 µm wide.

Six spectral ranges (245-255; 387-397; 456-464; 480-488; 525-533 and 821-829 nm) were investigated to observe radiative emission of many excited states of neutral xenon, boron or silicon, and ionized xenon.

Three spectral ranges were chosen to determine the relative density of the sputtered ceramic. Fig. 8 shows the boron and silicon lines in the UV spectral range (among Xe+ lines), a strong Xe+ line in the visible spectral range.
which is principally populated by electrons from ionic xenon metastable state, and two neutral xenon lines in the near-IR spectral range (823 and 828 nm). Boron line, more intense than silicon one was used for the ceramic lines. The 828 nm xenon line was chosen because it is populated only by electronic collisions from the xenon ground state when the 823 nm can be excited also from neutral xenon metastable.

Using coronal model and actinometric hypothesis as reported previously\(^1\) and verified on many thrusters\(^2\)\(^-\)\(^4\) the ceramic erosion is obtained by the line intensity ratio:

\[
Erosion \propto \frac{I_B(250\,nm)}{I_{Xe}(828\,nm)} \times \frac{I_{Xe(484\,nm)}}{I_{Xe(828\,nm)}}
\]  

(1)

III. Results and discussion

The first section contains results of axial and azimuthal distributions of the deposition on the inner and outer ceramics obtained by means of profilometry. Differential sputter yields studied by various authors are used in order to interpret our results. The following section contains ceramic erosion results measured by Optical Emission Spectroscopy. Finally deposition and OES results are compared.

A. Axial and azimuthal deposition distribution

Layer thickness axial distribution is reported on Fig. 9 for each tooled inner and outer ceramics. These thickness correspond to four hours of firing at the reference point (500 V, 6 mg/s). Measured values of the deposition begin after the sputtered zone from \(z = 0\) (exit plane) to 10-12 mm.

Layer thickness is decreasing form the exit plane towards the anode which is indicated on the figure, this decrease is more pronounced for the inner ceramics. Near the sputtering zone \((z = 10\) to 17 mm\) the layer thickness is weaker than for greater \(z\), this trend can be explained by the sputtering of the deposition layer. The fact that the deposition layer of the outer ceramics are more affected by the sputtering indicates that the plasma is not centered into the channel but is nearer the outer ceramics than the inner's.

Measurements of the deposition layers near the anode can be extrapolated in order to obtain the values of the deposition on the anode surface.

Layer thickness is also decreasing with the tooling angle for the inner and outer ceramics. The eight substrats for each ceramic allow to measure the azimuthal distribution which is detailed on the Fig. 10 for \(z = 15, 20, 25\) and 30 mm.

A great azimuthal variation (up to 50%) of the deposition layer indicates a great asymmetry of the plasma intensity near the opposite ceramic.

Azimuthal distribution is about the same for tooling angle equal to 5, 10 and 15° but is different for the two other tooling angles.

Some points are erratic due to the sputtering of the layer for this position.
IV. Redeposition as a tool to predict the erosion along the thruster lifetime

Results of the redeposition on the substrats can be used to obtain the value of the erosion of the ceramics. In a first approximation an 1D (axial, z) description of the redeposition is here used. This approximation need an azimuthal symmetry which is not the case as seen in the previous section but is much easier for beginning and can
provide a good information about the azimuthally mean erosion and be a help for the understand of how to predict the erosion during the thruster lifetime. Next step will be a 2D (axial, z, azimuthal, \( \theta \)) description which will give the azimuthal erosion.

### A. Geometrical model of redeposition

The lack of data about impinging ion flow distribution, energy distribution of these ions, effect of the ceramic temperature on the sputtering and change of the geometrical shape of the channel near the exit plane make theoretical analysis difficult. In this geometrical 1D model two important hypothesis are used.

First hypothesis, the erosion is supposed to be linear along the axis z, as measured by Arkhipov\(^5\) on the SPT100 and Lovstov\(^6\) on the KM-45 and EM-900, and take the expression:

\[
h(z) = \lambda \left( \frac{z_0 - z}{z_0} \right)
\]

where \( z_0 \) is the length of the erosion along the z axis and \( \lambda \) the height of the erosion at the exit plane. Values of \( z_0 \) for inner ceramic (respectively outer) are obtained by the redeposition on the substrat on the same inner ceramic (respectively outer). For example, on the ceramic number 9 (Fig. 10) the decrease of the redeposition around 16 to 18 mm is explained by the sputtering of this redeposition. For this example, \( z_0 \) is taken equal to 17 mm. The parameter \( \lambda \) is an adjusting parameter.

The sputtered volume at the point \( I(z) \) is:

\[
2\pi R_{int} - (z_0 - z)\tan(u) \int \frac{\lambda}{z_0} dz \quad \text{(inner ceramic)}
\]

\[
2\pi R_{ext} + (z_0 - z)\tan(u) \int \frac{\lambda}{z_0} dz \quad \text{(outer ceramic)}
\]

This quantity of sputtered material is diffused principally towards the channel exit but a non negligible part is also scattered backwards inside the channel.

Second hypothesis, the differential yield profile has the shape of a lobe. Various works have investigated the differential distribution of sputtered particles from various targets, various incident ions, various incident ion energies, at varying angles of incidence. Measurements by Nakles\(^7\) for incident Xe\(^+\) of various energy (60 to 100 eV) on Mo target, by Wehner\(^8\) with 250 eV Hg\(^+\) on Mo, Yalin\(^9\) with 250, 350, 500 and 750 eV Xe\(^+\) on Mo target and 0, 30 and 45\(^\circ\) incident angles and recently by Tondu\(^10\) with 50 to 500 eV Xe\(^+\) on Al target and 0 to 80\(^\circ\) angles. Tondu has also developed a model (CSiPI: Code de Simulation de la Pulverisation Ionique) which, compare to TRIM model is more convenient to study the angular scattering of the sputtering. For all these experiments and CSiPI model, with various energies of various incident ions and various targets, the distribution of the sputtering products is about the same for our incident angles varying from 45 to 90\(^\circ\) (see Fig. 12) and here the mean value of these distributions Lobe(\( \beta \)) is taken as a good estimation, where \( \beta \) is the angle of diffusion counted positive from the normal of the tooled part of the ceramic towards the inside channel (see Fig.11 and 12). The quantity of sputtered products under the \( \beta \) angle is normalized by:

![Figure 11. Variable and parameter definition.](image1)

![Figure 12. Calculated and measured differential sputtering yield.](image2)
Then, the quantity diffused under the $\beta$ angle is:

$$2\pi[R_{int} - (z_0 - z)\tan(u)]\lambda\left(\frac{z_0 - z}{\zeta_0}\right) \frac{Lobe(\beta)\,d\beta}{\int_{-\pi/2}^{\pi/2} Lobe(\beta)\,d\beta}$$  (inner ceramic)

$$2\pi[R_{ext} + (z_0 - z)\tan(u)]\lambda\left(\frac{z_0 - z}{\zeta_0}\right) \frac{Lobe(\beta)\,d\beta}{\int_{-\pi/2}^{\pi/2} Lobe(\beta)\,d\beta}$$  (outer ceramic)

and the volume of the layer deposited is:

$$2\pi R_{int} e_{int}(x, z)\,dz\,dx = 2\pi[R_{ext} + (z_0 - z)\tan(u)]\lambda\left(\frac{z_0 - z}{\zeta_0}\right) \frac{Lobe(\beta)\,d\beta}{\int_{-\pi/2}^{\pi/2} Lobe(\beta)\,d\beta}$$  (inner ceramic)

$$2\pi R_{ext} e_{ext}(x, z)\,dz\,dx = 2\pi[R_{int} - (z_0 - z)\tan(u)]\lambda\left(\frac{z_0 - z}{\zeta_0}\right) \frac{Lobe(\beta)\,d\beta}{\int_{-\pi/2}^{\pi/2} Lobe(\beta)\,d\beta}$$  (outer ceramic)

where $e(x, z)$ is the contribution at the thickness of the layer at the point $D(x)$ of the sputtered products from the point $I(z)$, $u$ the tooling angle and $dx$ is:

$$dx = \frac{[H + (z_0 - z)\tan(u)]\,d\beta}{\cos^2(\beta - u)}$$

where $H = (R_{ext} - R_{int})$ is the height of the channel.

The total layer thickness at the point $D(x)$ is:

$$e(x) = \int_{z=0}^{z=z_0} e(x, z)\,dz$$

$$e_{int}(x) = \lambda \int_{z=0}^{z=z_0} \frac{[R_{ext} + (z_0 - z)\tan(u)]\left(\frac{z_0 - z}{\zeta_0}\right)\text{Lobe}[\beta(x, z)]\cos^2[\beta(x, z) - u]}{R_{int}[H + (z_0 - z)\tan(u)]\int_{-\pi/2}^{\pi/2} Lobe(\beta)\,d\beta}\,dz$$  (inner ceramic)

$$e_{ext}(x) = \lambda \int_{z=0}^{z=z_0} \frac{[R_{int} - (z_0 - z)\tan(u)]\left(\frac{z_0 - z}{\zeta_0}\right)\text{Lobe}[\beta(x, z)]\cos^2[\beta(x, z) - u]}{R_{ext}[H + (z_0 - z)\tan(u)]\int_{-\pi/2}^{\pi/2} Lobe(\beta)\,d\beta}\,dz$$  (outer ceramic)

where the diffusion angle $\beta$ is:

$$\beta(x, z) = u + \arctan\left(\frac{x - z}{H + (z_0 - z)\tan(u)}\right)$$

The calculated values $e_{int}(x)$ and $e_{ext}(x)$ are the layer thickness measured by profilometry after four hours of working and deposition on the substrates, apart from the value of the $\lambda$ parameter. This parameter is determined by comparison between $e_{int}(x)$ or $e_{ext}(x)$ and the mean value of the measured layer thickness.

Results are reported on the Fig. 13 and the value of the $\lambda$ parameter is indicated for each tooling angle of inner and outer ceramics. A good agreement is obtained for outer ceramic when a large discrepancy (20-30%) appears for the inner ceramics. These discrepancies for inner ceramics are probably due to the fact that the outer ceramic catches the totality of the inner ceramic sputtering whereas the outer ceramic sputtering is catching by the inner and the outer ceramics. A 2D geometric model is needed to take into account the sputtering in the plane perpendicular to the incident plane. This 2D geometric model has also to take into account the azimuthal dispersion of the deposition.
The $\lambda$ parameter values for the different tooling angles of inner and outer ceramics are reported on the Fig. 14 with a fit for inner and outer ceramics in order to obtain the $\lambda$ parameter value for ceramic tooling angles from 0 to 30°.

By taking the derivative of the $\lambda$ parameter as a function of the ceramic wearing angle we obtain the ceramic wearing angle as a function of the firing duration represented on the Fig.15. We can see on this figure that the outer ceramic is wearing faster than the inner ceramic, for example the 30° wearing angle is obtained for 6750 hours of firing for outer ceramic when it takes 6000 hours of firing for outer ceramic when it takes 6750 hours for the same wearing angle of the inner ceramic.

So, with the two hypothesis; linear erosion of the channel entrance and the choice of a lobe as scattering shape, add to five sets of tooled ceramics, we can predict the wear of the thruster ceramics. To go further into this geometric model it is necessary to test it robustness by using a quadratic erosion or by changing the slope of the
lobe before testing a 2D geometric model.

B. Optical Emission Spectroscopy Erosion measurements

Results of the Optical Emission Spectroscopy erosion measurements are reported on the Fig.16. On the same figure, are also shown the results of the calculated erosion velocity. The calculated erosion velocity are taken at the exit plane of the channel and for the inner ceramic which is principally observed by means of the optical mounting. Influence of the outer ceramic has to take into account to go further to a finest description of the optically observed erosion. As the OES measures are relative, OES erosion values are multiplied by a constant in order to compare these OES results to the calculated erosion velocity. A low discrepancy (< 8%) for all tooling angles except for 30° where the 35% large discrepancy is probably due to the large azimuthal dispersion of the scattering. This good agreement obtained between the two measurement methods trends to confirm the validity of each method.

![Figure 16. Calculated erosion compare to OES measured erosion.](image)

V. Conclusion

A new method to predict the thruster ceramic erosion during a lifetime test has been investigated by means of measures of the deposition inside the channel using few hypothesis. Some direct measurements are needed to confirm the wearing velocities. For a wearing velocity of about 1 µm/h it takes about 100 hours of firing to obtain a measurable erosion. Five or six tooling ceramics are sufficient to obtain the evolution of the ceramic wear for a lifetime of 10000 hours. These experiments offer a gain of a factor 10 on the firing duration. Following the erosion by OES measurements during these 100 firing hours allows to know the stability of the thruster and a finest insight of the ceramic wear.

Further work will include test on the robustness of the lobe azimuthal scattering hypothesis by modifying the slope of this lobe, include study of the deposition changes when the shape of wear changes from linear distribution to quadratic, and also include 2D model in order to take into account the scattering in the perpendicular plane of the incident ions.

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References


