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Ion Thruster Grid Lifetime Assessment Based on Its Structural Failure

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***Abstract*—**This article developed an ion thruster optic system sputter erosion depth numerical 3D model by IFE-PIC (Immersed Finite Element-Particle-in-Cell) and Mont Carlo method, and calculated the downstream surface sputter erosion rate of accelerator grid; compared with LIPS-200 life test data. The results of the numerical model are in reasonable agreement with the measured data. Finally, we predicted the lifetime of the 20cm diameter ion thruster via the erosion data obtained with the model. The ultimate result demonstrated that under normal operating condition, the erosion rate of the grooves wears on the downstream surface of the accelerator grid is 34.6μm⁄1000h, which means the conservative lifetime until structural failure occurring on the accelerator grid is 11500 hours.

***Keywords*—**Ion thruster, accelerator gird, sputter erosion, lifetime assessment.

I. INTRODUCTION

FROM the long-term statistics study of ion thruster found that the ion optics system failure modes is critical failure modes of ion thruster, it is likely to occur at the end of working life. Therefore, the ion optics system is one of key components that affect the working life of the ion thruster. Study the failure modes and failure mechanisms of the ion optics system, then establish its life prediction model is essential for long life and high reliability design and is necessary step to build the ion thruster life prediction model.

According the researches work up to now [1], two main wear failure modes of ion optics system are the accelerator grid structure broken failure and the electronic reflux failure. These two failure modes are both due to accelerator grid erosion from ion sputtering. In this paper, will aim at the structure failure mechanism, use numerical simulation method to calculate the sputter erosion rate, analysis and estimate its working life according to the given failure criteria.

Accelerator grid structure failure is the bridge between the holes has fractured by erosion, whole structure was destroyed and cannot extract ion beam any normal. Structural damage caused by the accelerator grid ion sputter erosion involves two main mechanisms [2]:

1) Beam ions that energy equivalent to total acceleration voltage sputter on the upstream surface of accelerator grid hole wall;
2) Charge-exchange (CEX) ions that energy equivalent to accelerator grid voltage sputter on the downstream surface of accelerator grid makes it pit and groove erosion.

The first type erosion mechanism can be avoided by a reasonable geometry design. The 20cm ion thruster studied in this paper has been optimized basically avoided the erosion of such a mechanism can be seen from the grid after 3700 hours operation, the upstream surface of the accelerator grid hole wall have no significant erosion.

The second type erosion mechanism is the main factor that would lead to structure failure of accelerator grid; this paper will focus on it.

II. ACCELERATOR GRID EROSION RATE

A. Numerical Simulation of Accelerator Grid Erosion Rate

Accelerator grid downstream surface erosion depth is calculated by probability statistics method. CEX ion generation is modeled using a Monte Carlo simulation and the trajectories of these ions are computed based on the previously calculated potential distribution. track and record the energy, inject angle and grid location of each CEX ions which bombard on accelerator grid, according to the inject energy and angle of each ion, using sputter yield empirical formula for xenon on molybdenum obtained based on experimental results [3], [4], calculated the accelerator grid erosion rate. Fig. 1 shows the accelerator grid downstream surface erosion profile obtained by numerical simulation. Blue area is present the hole of accelerator grid. Fig. 2 and Fig. 3 show the accelerator grid downstream surface pits and grooves erosion depth section per thousand hours that is line AB and AC in Fig. 1, from Fig. 2 and Fig. 3, we can know that the maximum pit and groove erosion rate is 18 μm/kh and 8 μm/kh separately.

The maximum pit and groove erosion rate got above is calculated by average beam current density and have not considered the double-charge ion. In fact, the accelerator grid lifetime is determined by the maximum ion beam density near axis area. Most beam ions is the single-charge ions, but still there are few of double-charge ions in the ion beam will be extracted from discharge chamber as well, this factor would bring some errors to numerical simulation. So simulated results should be amended.

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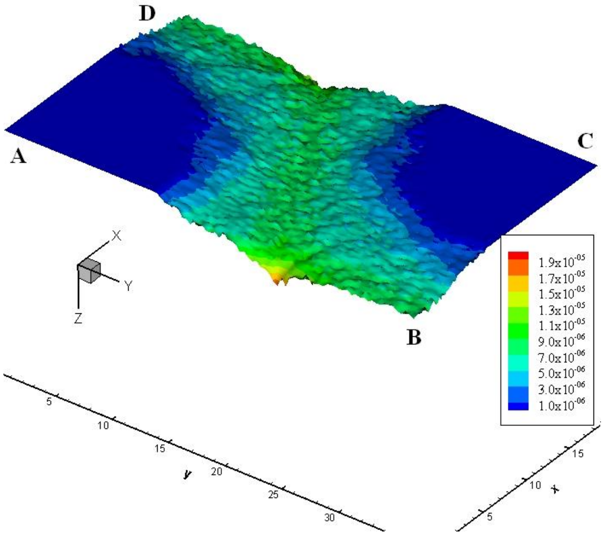


Fig. 1 Sputter erosion depth distribution of accelerator grid downstream surface (1000h)

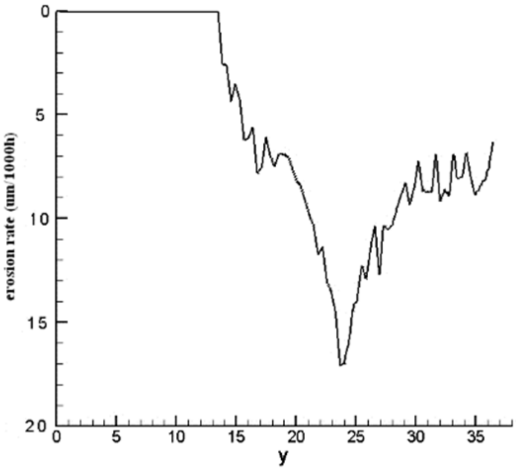


Fig. 2 Section of pit erosion rate

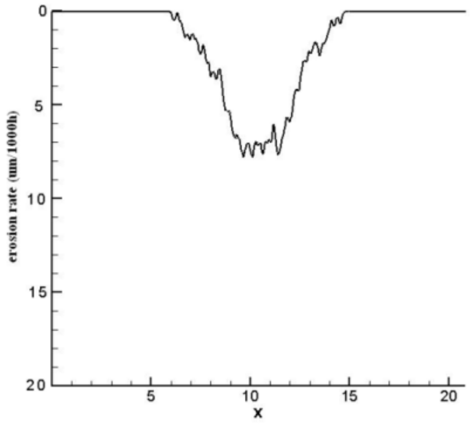


Fig. 3 Section of groove erosion rate

1. Uneven Beam Distribution Correction Factor

The ion thruster beam current density distribution is not uniform, but maximum in center area, and become smaller when closer to the edge. In the numerical simulation model, the beam current density input is an average all over the grid open areas, and the center area of grid was selected as measurement region, where maximum ion beam current density distribution. Assume that k_1 is the uneven beam distribution correction factor.

$$k_1 = \frac{1}{F}$$

Here, F is the ion beam current distribution flatness factor [5], defined as the ratio of the average beam current density and maximum beam current density.

$$F = \frac{j_{bavg}}{j_{bmax}}$$

2. Double-Charge Ion Correction Factor

In numerical simulation model, assumed that all ions extract from discharge chamber form to ion beam is single charge ion, double-charge ion was not been considered. In fact, there is a little portion of double-charge ions in the ion beam [5]. Suppose η_1 is discharge chamber propellant ionization rate without regard to double-charge ion, and η_2 is discharge chamber propellant ionization rate with regard to double-charge ion, then $\eta_1 > \eta_2$, that is the actual ionization rate when considering the double-charge ions is less than the ionization rate when ignore double-charge ions in case. That is, actually there will be more neutral atoms flow out from discharge chamber, then CEX ions density generated downstream grid will be higher, as a result, accelerator grid sputter erosion will be serious actually. Assume that k_2 is the double-charge ion correction factor.

$$k_2 = \frac{1-\eta_2}{1-\eta_1}$$

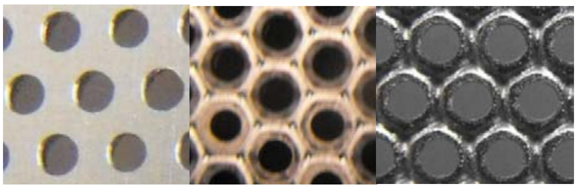
Corrected sputter erosion rate equal to calculated sputter erosion rate multiply with $k_1 k_2$.

B. Accelerator Grid Erosion Depth Measurement

The accelerator grid erosion depth was measured on QM-2 LIPS-200 Ion Thruster, when its life test [6] was conducted in TS-7 facility with a Φ3.8×10m vacuum chamber and less than 5×10^{-4}Pa at the full power ion thruster operating.

The accelerator grid erosion depth was measured by a specially configured optical method and device. The pit and groove depth were measured via this device and the 3D surface data were processed by computer software. Fig. 4 is the photo of 20cm ion thruster accelerator grid downstream surface erosion, the measured region is shown in Fig. 5, was divided into 6 equilateral triangle, pit is in the center area of each triangle, and groove is on the middle of each triangle sides.

Measured erosion depth has been compared with calculated erosion depth and shown in Fig. 6.



(a) (b) (c)

Fig. 4 Photo of accelerator grid downstream surface erosion; (a) new grid, (b) after 200h operating, (c) after 3700h operating

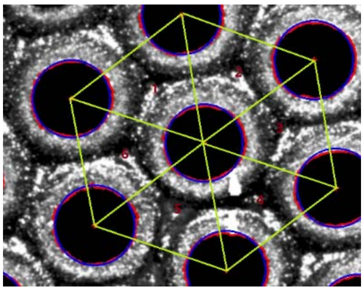


Fig. 5 Accel grid erosion measured region

C. Comparison with LIPS-200 Life Test Data

Calculated accelerator grid erosion depth was compared with LIPS-200 life test data. Fig. 6 shown the comparison between measured and calculated pit erosion depth, Fig. 7 has shown the comparison between measured and calculated groove erosion depth. The calculated result agrees well with the measured values at beginning but the deviation is increase with operation time goes by.

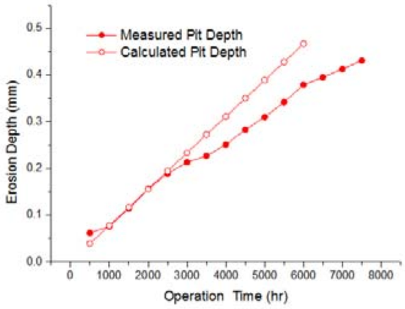


Fig. 6 Accel grid pit erosion comparison

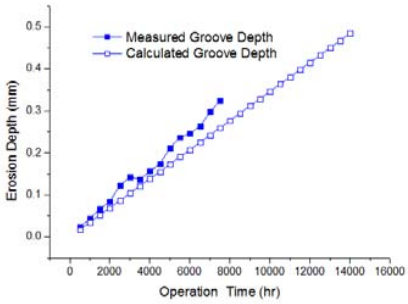


Fig. 7 Accel grid groove erosion comparison

The main error sources are listed below.

- **Model simplification:** The numerical simulation model not considered grid surface structural changes caused by ion sputter erosion that will lead to electric field distribution changes and then affect the erosion rate, but only count the number of ions which bombard on grid surface, then estimate the depth of erosion. This error will increase with operation time goes by that can be seen from Fig. 6 and Fig. 7.
- **Boundary effect:** The simulation model has only calculated a single whole area, the interaction between the holes is not considered to bring some calculation errors.
- **Measurement error:** The accelerator grid erosion depth measurement has unavoidable random error.

III. ACCELERATOR GRID STRUCTURAL FAILURE CRITERION AND LIFE PREDICTION

Accelerator grid structure failures depended on the downstream surface pits and grooves erosion depth. There have different versions of criterion on accelerate grid structural failure. Yanhui Jia [7] has estimated the accelerator grid lifetime by probability method, in his opinion, when the averaged depth of erosion pits and grooves reach to the thickness of accelerator grid, it means that the structure of accelerator grid has failed. But, [8] thought that erosion grooves depth reach to 80% of accelerator grid thickness means the structure of accelerator grid has failed when he estimate the lifetime of NSTAR-30 ion thrusters grid.

Although, even if erosion pits depth reach to thickness of grid, it will not destroy the integrity of the grid structure, the accelerator grid can continue to operate. Considering the error of numerical simulation, relatively conservative failure criterion been used here, regarded that accelerator grid structure fail when its maximum erosion grooves depth equal to 80% of the accelerator grid thickness.

Corrected accelerator grid groove erosion rate is 34.6μm/kh, according to the above failure criterion, a conservative estimate; LIPS-200 20cm ion thruster accelerator grid life is about 11,500 hours under nominal operating conditions.

IV. INFLUENCE OF ACCELERATOR GRID VOLTAGE TO ITS LIFETIME

The electric potential of accelerator grid would have more impact on the accelerator grid CEX ions erosion rate. It is the main factor that affects the accelerator grid lifetime based on the structural failure. Erosion rates on different accelerator grid voltage condition have been calculated, and the accelerator grid lifetime has been estimated on each condition, it is shown on Figs. 8 and 9. Calculated result shows that the lower accelerator grid potential will lead to the smaller sputter erosion of downstream surface, then the lifetime of accelerator grid based on the structural failure will be longer.

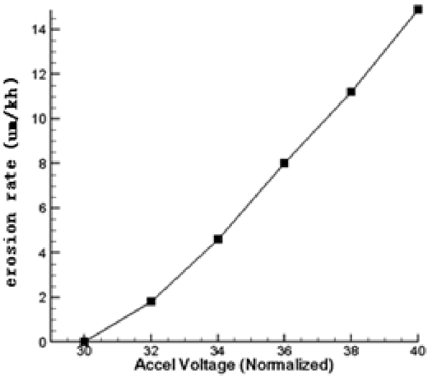


Fig. 8 Influence of the accelerator grid voltage on the erosion rate

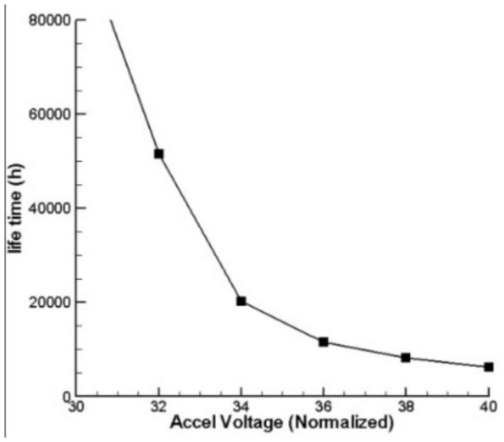


Fig. 9 Influence of the accelerator grid voltage on the grid lifetime

V. CONCLUSION

An ion optic system sputter erosion depth numerical 3D model was established by IFE-PIC (Immersed Finite Element -Particle in Cell) and Mont Carlo method, calculated the downstream surface maximum pits erosion rate is 77.8μm/kh, maximum grooves erosion rate is 34.6μm/kh, numerical simulate results are in reasonable agreement with the measured data.

Influence of accelerator grid voltage on its erosion rate and lifetime have been simulated, the results shown that the smaller accelerator gate voltage will make the smaller sputter erosion of downstream surface, then longer lifetime of accelerator grid based on structural failure. On the other hand, the negative accelerator grid voltages need to prevent electron back -streaming, a lower accelerator grid voltage will reduce its hole area voltage, and its ability to prevent the back-streaming of downstream electrons will reduce too, it will lead to another accelerator grid failure mechanism based on electron back –streaming. Therefore, it should consider a compromise when select the accelerator grid operating voltage, so its life achieve to optimal.

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