ON THE MECHANISM AND SOME PECULIARITIES OF THE EROSION OF THE ACTIVE SURFACE IN CATHODE-COMPENSATOR OF ELECTRIC PROPULSION

I. M. Yartsev and V. P. Polistchook

Institute for High Temperatures Academy of Science, Moscow, Russia

V. A. Petrosov

The Scientific-Research Institute of Thermal Processes, Moscow, Russia

Abstract

Hot hollow-cathodes (HC) are known to be widely used as cathodes-compensators in electric thrusters (ET). So the lifetime of ET is usually defined by the HC erosion rate. There are two possible mechanisms of the HC erosion, namely thermal evaporation and cathode sputtering. In this work the nondimensional parameter $\beta$ has been suggested, allowing to determine the relative fraction of these mechanisms in the total erosion of the cathode. This parameter takes into account the relation between electron and ion current on the cathode surface and the physical properties of the cathode material: a cathode sputtering coefficient $Y$, evaporation rate and thermionic current density. The values of $\beta$ for the different cathodes have been considered. According to the value of $\beta$ two main modes of the HC erosion are marked out: the mode of prevailing evaporation and the mode of prevailing sputtering.

It has been shown that for the cathode with low work function the mode of the prevailing sputtering may be observed even if $Y$ is less than $10^{-6}$. The known data on the erosion of the HC have been considered, with application of parameter $\beta$. The analysis of some peculiarities of HC erosion has been fulfilled. It has been shown that the small impurity of the double charged ions in plasma results in essential increase of the cathode sputtering and apparent decrease of the threshold energy of the sputtering.

The results obtained may be used for analysis and optimization of the working characteristics of HC.

1. Introduction

One of the elements, defining electric thruster (ET) lifetime, is a cathode-compensator. Usually this element is a hot gas-ducting hollow cathode (HC), operating at the arc mode. In this paper some general matters of HC erosion are considered, which can also be applied to the ET cathodes-compensators.

As it is known, the electron flux from the arc HC active surface is caused by thermionic emission. Therefore, such a cathode must be heated to high temperatures, which results in evaporation. In its turn, the heating is basically caused by the bombardment of the cathode with plasma ions, which results in the sputtering of the cathode. The main mechanism of the HC erosion is evaporation; however, the sputtering can play a considerable part in a number of modes.

2. Initial relations and defining parameters

A relation between two erosion mechanisms may be obtained if to introduce a ratio of the sputtered atoms flux density $f_s = Y_0 \frac{Y_0}{\xi}$ to evaporated atoms flux density $f_v = \xi \frac{Y}{\xi}$

\[ f_s = \frac{Y_0}{\xi} \]

where $Y_0$ is the ion flux density to the cathode; $Y_0$ is an average coefficient of the cathode sputtering with plasma ions; $\Gamma_e$ is the thermal electrons flux density from the cathode; $\xi$ is the atom-electron ratio introduced in [1].

\[ f_v = \Gamma_e \]

\[ Y_p = f_v Y_0 \text{ cathode effective sputtering coefficient.} \]

Depending on the $\beta$ value, the two following typical erosion modes can be marked out. At $\beta < 1$, the prevailing evaporation mode (PEM) takes place, and at $\beta > 1$, the prevailing sputtering mode (PSM) takes place. At the transient mode ($\beta = 1$ or $\xi = Y_p^* = Y_0^*$) both mechanisms are of the same intensity. At the PSM mode, intensive sputtering is added to inevitable for the HC evaporation, resulting in strong erosion enhancement. It is essential that HC erosion at the PEM and PSM depends on various defining parameters. Specifying the mode allows to predict the influence of discharge parameters and external conditions alternation on the erosion and HC lifetime.

According to the relation (1), an erosion mode is defined by three parameters $-f_1, Y_0$ and $\xi$. The parameter $f_1 = \frac{S_1}{1 - S_1}$ is an integrated characteristic of the near-anode processes, which can be determined by $S_1$, i.e. a
portion of the ion current in the total arc current. According to (2), $i_f = 0.4-2.3$. For qualitative estimations, $i_f$ can be assumed to equal to 1.

The $Y_0$ value is determined by the elementary sputtering coefficient $Y$. This coefficient data are presented in [3,4] for various ion energy values $W_i$ and ion/target combinations. According to these data, at small energy values ($W_i \leq 10^{-40}$ eV) the coefficient $Y$ sharply decreases down to $< 10^{-3} - 10^{-6}$, so it is possible to suggest the existence of the sputtering threshold energy $W_i^\text{th}$.

Using the electron work function $\varphi_e$ and atom evaporation heat $\varphi$ of the cathode material, the atom-electron ratio may be presented as

$$\xi = A(T_c) \exp \left( \frac{\varphi - \varphi_e}{kT_c} \right), \quad (2)$$

where $A(T_c)$ is a function depending on the temperature $T_c$ of the given cathode. Let us clarify the $\xi$ physical meaning. First, according to (1), the transient mode takes place at $Y_p = \xi$. Thus, knowing $\xi$, one can determine the critical value of $Y_p$. On the other hand, the greater $\xi$ is, the greater HC erosion is caused by evaporation. Therefore, the value $K = 1/\xi$ characterizes the thermal erosion resistance (TER) of the cathode material. Since $Y_p K = 1$, the greater TER (and, hence, $K$) is, the more sensible to the sputtering the cathode is (the smaller $Y_p$ is).

Fig.1 presents the values of $\xi = Y_p^* \psi$ for a number of metals according to [1]. As it can be seen, these values strongly depend on the temperature $T_e$ and two following two groups of metals may be marked out depending on $\xi$. For the metals of the first group (from Fe to Hg), $\varphi > \varphi_e$ and $\xi = Y_p^* \psi > 1$. These values of $Y_p^*$ are not achievable in arc discharges. For the metals of the second group, $\varphi < \varphi_e$ and at $T < 3 \times 10^3 K$, $Y_p^* \psi < 1$. This group includes basically refractory and rare-earth metals (W, Ta, Mo, Gd and others). Due to their high TER values, these metals are used for manufacturing conventional HC. However, because of small $Y_p$ values, these HC are highly sensible to the sputtering and may operate in the PSM. The probability of this mode increases with decrease of $T_e$.

An important characteristic of the HC is the thermoemission flux density from its surface $j_{te} = e \Gamma_{te}$. In Fig. 2 $\xi = Y_p^* \psi$ is plotted against $j_{te}$. As seen, with decrease of $j_{te}$, the coefficient $Y_p^* \psi$ decreases. For W and Ta $Y_p^* \psi = 10^{-5} ... 10^{-6}$ at $j_{te} \lesssim 1...10 A/cm^2$. In principle, these values of $Y$ are achievable in arc discharges, too. The greater cathode efficiency is, the smaller $Y_p$ is. For example, for the cathode-compensator made of LaB$_6$, $Y_p^* \psi = (0.4...4) \times 10^7$ at $j_{te} = 1...10 A/cm^2$. Therefore, this cathode has to transfer to the PSM even at such small $Y_p$ values.

![Fig.2. $\xi = Y_p^* \psi$ values versus thermoionic current density $j_{te}$ for a number of cathode materials](image)

3. Experimental data analysis

Most experimental data on erosion were obtained for metallic HCs. These data may be presented as a non-dimension parameter

$$K = \frac{e}{m} \frac{G_a}{I}$$

where $e$ is electron charge, $m$ is the mass of an evaporated atom, $I$ is a current, $G_a$ is an erosion value (measured in kg/s).
To analyse qualitatively, it can be assumed that the thermo-emission current from the cathode $I_w = 1$. Then it is possible to compare the $\kappa$ and $\xi$ values directly. In the PEM a portion of the atoms vaporized can return to the cathode, hence $\kappa < \xi$. For HCs the condition $\kappa < \xi$ is usually observed. However, in a number of works [5-8] uprated erosion rates were measured. Fig. 3 presents the results of these works. Exceeding the measured values of $\kappa$ over $\xi$ values points out uprated erosion of the HC comparatively with its evapo-ration. To explain the HC erosion observed by sputtering in the PSM at $\kappa \gg \xi$, it is necessary that the condition $Y_0 + \frac{\kappa}{\xi}$ might take place. For the data in Fig. 3, the necessary values of $Y_0$ range from $10^{-5}$ to $10^{-3} \ldots 10^{-2}$. According to the classic date for cold targets [3,4], these sputtering coefficients are realized at the ion energy $W_i = 30...60$ eV.

![Fig.3. $\xi$ and $\kappa$ values for various cathode materials: 1 - $\xi$ calculated data. Data on $\eta$ value are taken from experimental studies: 1 - [5]; 2 - [6]; 3 - [7]; 4 - [8]](image)

4. Some peculiarities of hollow cathodes sputtering

Analysing the role of the sputtering in the erosion, one should take into account the features of the sputtering process proper. These features may include high temperature of the cathode, possibility of the presence of multi-charge ions in the flow of sputtering particles and the presence of the ion energy distribution. All these features must result in increase of the coefficient and role of the sputtering. The influence of the target temperature on the sputtering was considered in [9]; according to this work, with increase of the temperature, the sputtering coefficient may increase by 100 and more times. There is still no clear physi cal model allowing to predict the temperature influence on the sputtering.

![Fig.4. Variation of mean coefficient $Y_0$ of cathode sputtering versus Xe double-charged ions portion at different values: 1 - $e\Delta v_e = 1.04 W_i^{th}$; 2 - $e\Delta v_e = W_i^{th}$; 3 - $e\Delta v_e = 0.8 W_i^{th}$; 4 - $e\Delta v_e = 0.7 W_i^{th}$.]

Near-cathode arc plasma is characterized by high intensity of ionization processes. It can result in formation of multi-charged positive ions in plasma ($Z_i > 1$). The cinetik energy of these ions coming to the cathode can be estimated by the expression $W_i = Z_i e \Delta V_c$, where $\Delta V_c$ is a cathode potential drop, $Z_i$ is ion charge. This energy is $Z_i$ times greater than the energy of one-charge ions which are usually taken into account. In consequence of that, on the one hand, the seeming threshold sputtering energy $W_i^{th}$ decreases by a factor of $Z_i$. Besides, near the threshold, the sputtering coefficient very strongly depends on the energy $W_i$. For example, doubling $W_i$, which must take place for the ions with $Z_i = 2$, results in increase of $V$ by $10^3 ... 10^4$ times. So even a small portion of double-charged ions (about $10^{-3} ... 10^{-4}$) significantly enlarges the average sputtering coefficient $Y_0$. This increase is illustrated by the data in Fig. 4. Thus, the ions with $Z_i > 1$, not influencing considerably on the current and energy balance on the cathode surface, may cause significant sputtering.

Special experiments were conducted with the cathode-compensator of the material based on W-Ba and with pumping xenon to detect two-charge ions in plasma. The brightest Xe III lines including those of $\lambda = 3624.05$; 3654.63 and 3676.63 A wave length were recorded with the help of spectral methods. The line intensity proportion was $1 : 0.1 : 0.35$. The line Xe III intensity with $\lambda = 3624.05$ A was higher than the intensity of the Xe atomic lines with $\lambda = 3610.32$ and 3669.91 A. At varying the current from its nominal values $I_n$ to $1.5I_n$, the line Xe III intensity sharply increased practically by $10^2$. A
more detailed analysis of the influence of double charged ions on the cathode erosion requires additional studies. The near-cathode HC plasma ions are definitely distributed in energy. Relatively, the ions, bombarding the cathode, are not monoenergetic. The presence of the ions of the energy over $e\Delta v_c$ essentially increase the coefficient $Y_0$. If to assume, that plasma ions are of Maxwell distribution in energies with the temperature $T_i$, then it is possible to average the sputtering coefficient on this distribution taking into account the directed kinetic energy of ions $e\Delta v_c$. The results of such averaging point out the ability of the high-energy ions to increase the value $Y_0$ essentially (by up to 10...100 times) at $e\Delta v_c = W_0^b$ and $T_i = 10^4$ K.

5. Conclusion

A simple criterium $\beta = f/Y_0$ is obtained allowing to determine the relationship between the hollow cathode erosion rates caused by sputtering and evaporation. This criterium accounts the processes occurring at the near-cathode region and on the cathode surface, as well as the cathode material properties. At $\beta < 1$, the mode of the cathode erosion caused primarily by evaporation takes place, and at $\beta > 1$ the erosion is caused mainly by sputtering. With increase of the cathode efficiency, its sensitivity to the sputtering increases. For example, for the cathode-compensator made of LaB$_6$, the PEM must be observed already at small sputter coefficient values ($< 10^{-6}$).

Some peculiarities of the sputtering process proper have been considered. The matter of the role of the double charged ions requires special attention. The contribution of these ions into the sputtering is greater than their contribution into the current and energy balance on the cathode surface by $10^3...10^4$ times.

References