VAPORIZATION OF METALLIC MACROPARTICLES IN THE HIGH TEMPERATURE TECHNOLOGY PLASMA

***A.A. Bizyukov*[1]*, A.D. Chibisov*[1]*, E.V. Romashchenko*[1]*, Yu.E. Kolyada*[2]**

[1]*V.N. Karazin Kharkiv National University, Kharkov, Ukraine;*
[2]*Mariupol State University, Mariupol, Ukraine*

The possibility of evaporation of macroparticles (MP) in collisionless plasma as a result of MP heating due to collisions with the plasma particles is studied. The problem of determining the self-consistent values of stationary MP temperature and its potential as a function of the plasma number density and the electron temperature is solved. The time of complete evaporation of the MP is calculated. Parameters of the MP which can be evaporated during the passage through the region of heated plasma are determined. Degree of ionization of the evaporated atoms of the MP substance is evaluated.

PACS: 52.40.Hf

INTRODUCTION

One of the most important technological applications of vacuum arc plasma is the using for ion-plasma depositions which improve the properties of products. During the vacuum arc operating, the cathode spots generate not only plasma flow but also macroparticles (MP) – droplets of cathode material. Part of the droplet fraction in the total erosion of the cathode is about 90% that in terms of the characteristics of the plasma source is a negative factor. This is caused by the fact that the deposited droplets on the surface of the product impair characteristics of the deposition [1-3].

In practice, majority of ways of reducing the droplet flow on the processed surface are based on the separation of the ion trajectories and the droplet flow. Most effective filters are ones where the ion flow is separated from the droplets flow by the magnetic field. However, the higher is required degree of the ion flow purification from drops, the more complex and expensive construction of the filter is, and the greater losses of ionic component of the filtered flow become [3].

To solve the problem of reducing the droplet flow in [4] the possibility of MP heating and evaporation by an electron beam of high energy was considered. A preference of this method of getting rid of droplets compared with the magnetic filtering method, is that the material of evaporated droplets take part in the coating process without deterioration in its quality. In addition in [5] the capability of heating and evaporation of droplets as a result of varying plasma number density was discussed.

In this paper, we study the possibility of evaporation of the MPs due to collisions with the plasma ions and electrons which are heated by RF.

CHARGING PROCESSES OF THE MP IN PLASMA

It is known that the MP immersed in the plasma is charged as a result of absorption of electrons and ions of plasma, as well as various types of electron emission from the MP surface. The magnitude of the charge determines which way MP interacts with the plasma and is one of the key parameters affecting on the energy balance of the MP. Charge of the MP is determined by the condition that the sum of the electrical currents on the surface of the MP is equal to zero. Calculation of the currents from plasma on the MP in presence of the magnetic field is a difficult problem, however in some cases various approximations are used successfully. In particular, if the magnetic field is not strong enough such the condition

$$r_g >> \lambda_d >> a\,, \qquad (1)$$

is correct, where r_g is the Larmor radius of electron, λ_d is the Debye length, a is the MP radius, in a collisionless plasma, for describing of the ion and electron currents on the MP Orbital-Motion-Limited (OML) theory is used [6]. In this paper we consider metallic plasma created by the low pressure arc discharge, which plasma number density n_0 is $10^{10}\ldots10^{11}$ cm^{-3}, electron T_e and ion T_i temperatures are 10…100 eV and 1 eV respectively. In order to confine plasma during heating, the magnetic field directed along the plasma flow is created. Strength of the magnetic field B is such that the condition (1) is correct and we can use the OML theory.

According to the OML theory, electron and ion currents from the plasma to the MP surface have the form:

$$I_{i(e)} =< en_0 v_{i(e)} \sigma_{i(e)}^{OML} >= e \cdot \Gamma_{i(e)}, \qquad (2)$$

where $\sigma_{i(e)}^{OML} = \pi a^2 \left(1 \pm \frac{2e\varphi_a}{m_{i(e)} v_{i(e)}^2} \right)$ is the absorption cross section of ions (electrons) in the OML theory,

$$\Gamma_i = \sqrt{8\pi} a^2 n_0 v_{Ti} \left(1 - e\phi_a / T_i\right)$$

and

$$\Gamma_e = \sqrt{8\pi} a^2 n_0 v_{Te} \exp\left(-e\varphi_a / T_e\right),$$

are the flows of the ions and electrons on the MP surface, φ_a is the potential of the MP surface, $v_{Ti(e)} = \sqrt{T_{i(e)} / m_{i(e)}}$ is the ion (electron) thermal velocities. Electric current of a secondary electron from the MP surface can be found by averaging over all energies of the electrons:

$$I_s^{e-e} =< n_0 e v_e \sigma_e^{OML} \delta^{e-e} >, \qquad (3)$$

Where $\delta^{e\text{-}e}$ is the secondary emission yield:

$\delta^{e-e} = \delta_{\max} \frac{E - e\varphi_a}{E_m} \exp\left(2(1 - \sqrt{\frac{E + e\varphi_a}{E_m}}) \right)$, where E is the kinetic energy of primary electron, E_m is the electron

ISSN 1562-6016. ВАНТ. 2016. №6(106)

PROBLEMS OF ATOMIC SCIENCE AND TECHNOLOGY. 2016, № 6. Series: Plasma Physics (22), p. 268-271.

energy which corresponds to the maximum of secondary emission yield δ_{max}. One more charge process caused by the heating of the MP due to collisions with plasma particles is the thermionic emission, which is described by Richardson low:

$$I_e^{th} = 4\pi a^2 A T_a^2 \exp\left(\frac{e\Phi}{k_B T_a}\right), \tag{4}$$

where, $A=4\pi m_e k_B^2 e/h^3$, h is the Planck constant, k_B is the Boltzmann constant, $e\Phi$ is the electron work function, T_a is the temperature of the MP.

Taking into account the charging processes described above (1)-(4), the MP potential is determined by the equation of electric currents balance:

$$I_e^{pl}(\varphi_a) - I_e^s(\varphi_a) - I_e^{th}(\varphi_a, T_a) - I_i^{pl}(\varphi_a) = 0. \tag{5}$$

It is seen that the solution of the equation of electric currents balance depends on the MP temperature, thus, it has to consider the processes which lead to the heating of the MP.

ELECTRICAL POTENTIAL AND STATIONARY TEMPERATURE OF THE MP

Consider the processes that are involved in energy exchange. The indexes "+" and "-" denote the energy flows which heat and cool the MP respectively. In plasma with a Maxwellian velocity distribution of particles in the OML theory, energy flows are described by:

$$P_i^+ = \Gamma_i \cdot (2kT_i + e\varphi_a + I + e\Phi), \tag{6}$$

$$P_e^+ = \Gamma_e \cdot (2kT_e + e\Phi), \tag{7}$$

where I is the ionization energy of an atom. The power radiated from the MP surface is described by the Stefan–Boltzmann law:

$$P_r^- = 4\pi a^2 \sigma T_a^4, \tag{8}$$

where σ is the Stefan-Boltzmann constant. Energy flow due to evaporation of MP substance is described by:

$$P_{evpr}^- = \Gamma_a \cdot (2k_B T_a + p), \tag{9}$$

where

$$\Gamma_a = 4\pi a^2 n' \sqrt{\frac{k_B T_a}{2\pi m_a}} \exp\left(-\frac{p}{k_B T_a}\right)$$

is the flow of the evaporated atoms of the MP substance, n is the concentration of the atoms in the metal, p is the heat of evaporation of an atom. Energy flow due to thermionic emission is:

$$P_{th}^- = \Gamma_e^{th} \cdot (2k_b T_a + e\Phi), \tag{10}$$

where $\Gamma_e^{th} = I_e^{th}/e$. Energy flow due to the secondary electron emission is equal to:

$$P_s^- = \Gamma_s \cdot (<\varepsilon_s> + e\Phi), \tag{11}$$

where $\Gamma_s = I_s^{e-e}/e$ is the secondary electron flow, $<\varepsilon_S>$ is the averaged energy of the secondary electrons. Stationary temperature of the MP T_a^{st} and respective potential can be found as a result of solution of the set of equations balance of electrical current (5) and energy balance (6)-(11) on the MP surface:

$$\begin{cases} I_e^{pl} - I_e^s - I_e^{th} - I_i^{pl} - I_e^s = 0 \\ P_e^+ + P_i^+ - P_s^- - P_r^- - P_{evrp}^- - P_{th}^- = 0. \end{cases} \tag{12}$$

The set of equations (12) have been solved numerically. There were obtained dependences of stationary temperature of the MP and its potential as function of electron temperature (Fig. 1).

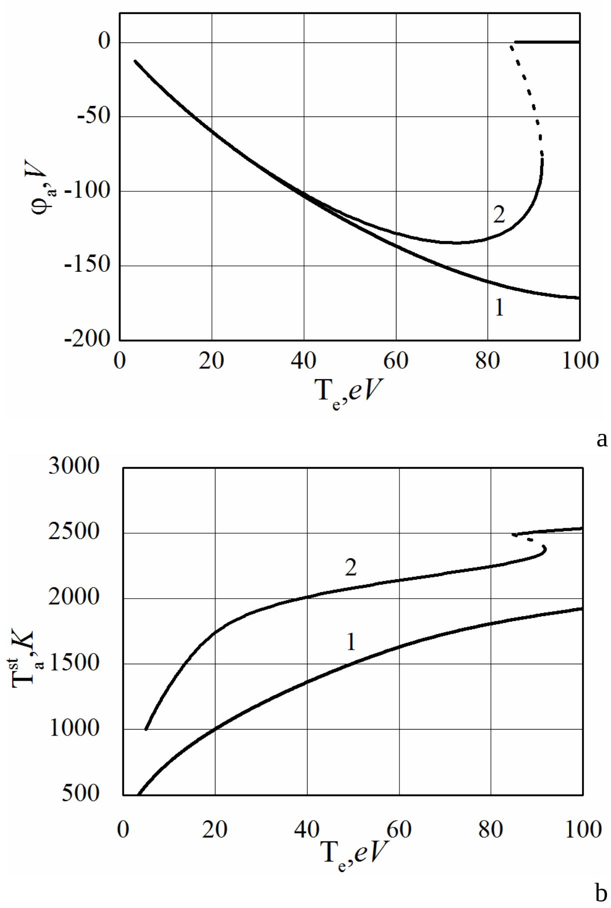

Fig. 1. Potential of the MP (a) and stationary temperature of the MP (b) as a function of electron temperature (1 – $n_0=10^{10}$ cm^{-3}; 2 – $n_0=10^{11}$ cm^{-3})

Numerical calculations were performed for copper, but similar results can be obtained for the other metals. The plot (see Fig.1) shows that there is a region of electrons temperature and MP temperature where for the same electron temperature three values of stationary MP temperature exist. This region denoted the dashed line and is unstable against temperature fluctuations. The temperature deviation from the stationary value leads to heating or cooling to the stable states which are denoted by the solid line. Thus, in practice, only stationary solutions take place and heating (cooling) mode is determined by the initial MP temperature.

EVAPORATION OF THE MP

During the evaporation (vaporization), changing of the mass of the MP substance is described by the equation:

$$dm = \frac{P_{evpr}(T_a^{eq}, \varphi_a) \cdot dt}{H}, \tag{13}$$

where $P_{evpr}(T_a^{eq}, \varphi_a) = P_e^+ + P_i^+ - P_s^- - P_r^- - P_{th}^-$ is the power density which is spent to evaporation of the MP substance, H is the heat of evaporation. Time of evaporation of the MP with a radius a is calculated by integrating of the equality (13):

$$t_{evpr}=\frac{4\pi a^3\rho H}{3P_{evpr}(T_a^{eq},\varphi_a)}.$$

Dependence of the evaporation time of the MP on the electron temperature is shown in Fig. 2.

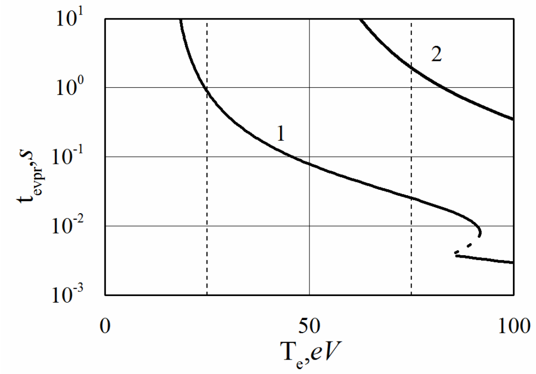

Fig. 2. Total evaporation time of the cooper MP, plasma density n_0 is 10^{11} cm^{-3} (1 – a=1 μm; 2 – a=10 μm)

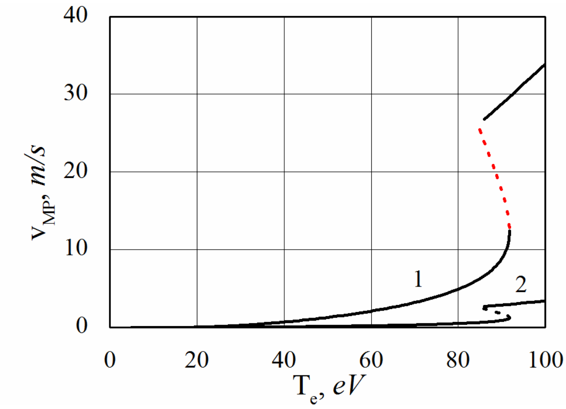

Fig. 3. Speed of the MP wich can be evaporated on the distance L=10 cm, plasma density n_0 is 10^{11} cm^{-3} (1 – a=1 μm; 2 – a=10 μm)

The curves represented in Fig. 3 show the critical values of MP speed which can be evaporated within the passage through the plasma as a function of electron temperature. Macroparticles, speed values of which are below the curve, that is, pass through the plasma at a lower speed and therefore are in the plasma for a longer time, can be evaporated completely. Macroparticles, speeds of which are above the curves are evaporated partly. Taking into account the fact that during operation of the stationary vacuum arc the MPs with the typical sizes 1…20 microns and speeds 1…30 m/s are formed [3], it follows from obtained results that in the plasma flow there are MPs, which can be evaporated partly or completely.

IONIZATION OF EVAPORATED MP SUBSTANCE

Now we will estimate the possibility of ionization of the evaporated MP substance. For this we determine the ionization probability of an atom which was evaporated from the MP surface depending on the plasma parameters.

The number of ionization events in the plasma per unit of time is determined by the averaged ionization rate

$$K_i=<n_0v_e\sigma_i>,$$

where

$$\sigma_i=\frac{\pi e^4}{T_e}\left(\frac{1}{I}-\frac{1}{T_e}\right)$$

is the electron impact ionization cross section, I is the ionization potential. Mean time needed for ionization of one atom is equal to $\tau_i=\frac{1}{K_i}$, $\tau_0=\frac{L}{v_a}$ is the time of MP passage through the heated plasma on the distance L, $v_a=\sqrt{\frac{k_BT_a}{m_a}}$ is the atom velocity. Probability of atom ionization we can estimate as:

$$w=\begin{cases}\tau_0/\tau_i, & \tau_0<\tau_i,\\ 1, & \tau_0>\tau_i.\end{cases}$$

Results of calculation of atom ionization probability are represented in Fig. 4.

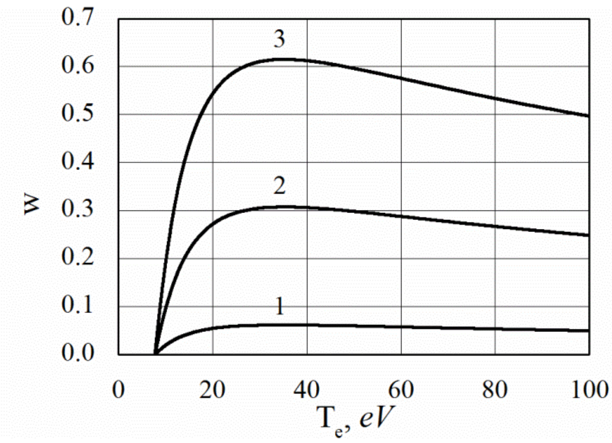

Fig. 4. The ionization probability of an evaporated atom of MP substance during the passage through plasma on distance L=10 cm (1 – n_0= 10^{10} cm^{-3}; 2 – n_0= $5\cdot10^{10}$ cm^{-3}; 3 – n_0=10^{11} cm^{-3})

The plot shows that the atom ionization probability in quite dense plasma with number density n_0 ~ 10^{11} cm^{-3} and electron temperature T_e=15…100 eV are in the range 0.5…0.6, this means that 50…60 % of the evaporated MP substance can be ionized. Degree of ionization of evaporated atoms is proportional to a plasma number density, and hence is reduced when plasma number density is reduced.

CONCLUSIONS

Self-consistent values of the floating MP potential and its temperature in the plasma (plasma number density n_0= 10^{10}…10^{11} cm^{-3}, electron temperature is in the range 10…100 eV, ion temperature is 1 eV) have been obtained. It has been shown that there is a range of values of the electron temperature where exists three values of stationary MP temperature, and middle value is unstable with respect to fluctuations of the MP temperature. Stationary MP temperature and its potential in this region are determined by the initial MP temperature. Characteristics of the MPs (size and speed) which can be evaporated during passage through heated plasma have been found. It has been shown that the degree of ionization of the evaporated substance of the MP can reach up to 60 % for the considered plasma parameters.

REFERENCES

1. R.L. Boxman, D.M. Sanders, P.J. Martin. *Handbook of Vacuum Arc Science and Technology: Fundamentals and Applications*. NJ: “Noyes Publ”, 1995, p. 742.

2. A. Anders. *Cathodic Arcs: From Fractal Spots to Energetic Condensation*. Springer: “Science Business Media”. LLC, 2008, p. 540.

3. I.I. Aksenov, A.A. Andreyev, et al. *Vakuumnaya duga: istochniki plazmy, osazhdeniye pokrytiy, poverkhnostnoye modifitsirovaniye.* Kiev: “Naukova dumka»”. 2012, p. 238-273 (in Russian).

4. A.A. Bizyukov, K.N. Sereda, et al. Nagrev i ispareniye metallicheskikh makrochastits v puchkovo-plazmennykh sistemakh // *Problems of Atomic Science and Technology. Series “Plasma Electronics and New Methods of Acceleration”.* 2010, v. 7, № 4, p. 189-192 (in Russian).

5. A.A. Bizyukov, A.D. Chibisov, E.V. Romashchenko. Effect of the parameters of a gas-discharge plasma on the equilibrium temperature and floating potential of macroparticle// *Problems of Atomic Science and Technology. Series “Plasma Physics”.* 2012, № 6, v. 18, p. 175-177.

6. V.E. Fortov, A.G. Khrapak, et al. Dusty plasma // *UFN*. 2004, v. 174, № 5, p. 495-544.

Article received 22.10.2016

ИСПАРЕНИЕ МЕТАЛЛИЧЕСКИХ МАКРОЧАСТИЦ В ВЫСОКОТЕМПЕРАТУРНОЙ ТЕХНОЛОГИЧЕСКОЙ ПЛАЗМЕ

А.А. Бизюков, А.Д. Чибисов, Е.В. Ромащенко, Ю.Е. Коляда

Изучается возможность испарения макрочастиц (МЧ) в бесстолкновительной плазме в результате нагрева МЧ из-за столкновений с частицами плазмы. Решается задача по определению самосогласованных значений стационарной температуры и потенциала МЧ в зависимости от плотности плазмы и температуры электронов. Вычисляется время полного испарения МЧ. Определяются параметры МЧ, которые можно испарить при прохождении через область нагретой плазмы. Оценивается степень ионизации испарившихся атомов вещества МЧ.

ВИПАРОВУВАННЯ МЕТАЛЕВИХ МАКРОЧАСТОК У ВИСОКОТЕМПЕРАТУРНІЙ ТЕХНОЛОГІЧНІЙ ПЛАЗМІ

О.А. Бізюков, О.Д. Чібісов, О.В. Ромащенко, Ю.Є. Коляда

Вивчається можливість випаровування макрочасток (МЧ) у плазмі без зіткнень у результаті нагрівання через зіткнення МЧ з частинками плазми. Вирішується задача по визначенню самоузгоджених значень стаціонарної температури і потенціалу МЧ в залежності від густини плазми і температури електронів. Обчислюється час повного випаровування МЧ. Визначаються параметри МЧ, які можна випарувати при проходженні через область нагрітої плазми. Оцінюється ступінь іонізації випарених атомів речовини МЧ.