DECAY OF LIQUID METALLIC MACROPARTICLES IN PLASMA-BEAM SYSTEMS DUE TO RAYLEIGH INSTABILITY

***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 decay of liquid macroparticles (MP) in collisionless plasma of vacuum arc source as a result of charging by high-energy electron beam and subsequent development of the Rayleigh instability is studied. The criteria of droplets decay are obtained. It has been estimated the charge time of droplets by electron beam, the time of droplets decay, as well as the heating time to a temperature when the thermionic emission occurs. It was shown that the MP heating time significantly exceeds the development of the Rayleigh instability.

PACS: 52.40.Hf

INTRODUCTION

In the preparation of a high-quality coatings using the vacuum-arc plasma sources, there is a problem of elimination of the cathode material macroparticles (MP) with a typical size of 1…20 microns which appears during operation of vacuum arc. To solve this problem in [1] the possibility of MP heating and evaporation by an electron beam of high energy was considered. It was shown that MP with typical dimensions of about 10 microns is evaporated for a time shorter than their time of flight through a drift space from the plasma source to the substrate due to the irradiation of an electron beam having a number density $10^9\,\mathrm{cm}^{-3}$ and energy greater than 5 keV. In [2] the possibility of heating and evaporation of droplets as a result of varying plasma parameters was discussed. It was shown that to evaporate the MP for a time less than the time of flight of the particles in plasma at a electron temperature of about 10 eV, the electron number density of plasma must exceed $10^{13}\mathrm{cm}^{-3}$. An advantage of the considered methods of getting rid of droplets compared with the magnetic filtering method, when droplets are separated from the plasma flow, is that the substance of evaporated droplets is involved in the coating process without deterioration in its quality. Application of electron beam irradiation in addition to the heating and evaporation of droplets, as described in [1], may also lead to the decay of droplets and their subsequent disappearance as a result of the forces of electrostatic repulsion (Rayleigh instability). This effect can occurs when an electrical potential of droplets exceeds a certain critical value. The aim of this paper is to examine the possibility of reducing the number of MPs in plasma by creating conditions for development of the Rayleigh instability and the subsequent decay liquid MP (drops) due to their charging by the electron beam. We determine the charge time of drops by beam, the time of drops breakup due to electrostatic repulsion forces, as well as the time of heating to a temperature when the thermionic emission occurs and leads to decreasing of MP potential lower than critical value, so that the Rayleigh instability becomes impossible.

RAYLEIGH INSTABILITY PARAMETERS

It is known that for highly charged conductive droplets the Coulomb repulsion forces of charges may exceed the forces of surface tension, whereby such drops become unstable and can be divided into smaller drops (the Rayleigh instability) [3]. The critical value of the charge of a spherical droplet when it becomes unstable is determined by criterion [3]:

$$Q^2 \ge 16\pi\alpha a^3, \qquad (1)$$

where Q is the charge of droplet, α is the surface tension, a is the radius of droplet. Electrostatic potential of droplet that corresponds to its critical charge is equal:

$$\varphi_a^{cr} = \frac{Q_{cr}}{a} = 4\sqrt{\pi\alpha a},$$

and the value of critical electric field is:

$$\left|E_a^{cr}\right| = 4\sqrt{\frac{\pi\alpha}{a}}.$$

When the criterion (1) is satisfied, the electrostatic repulsion forces exceed the surface tension and the drop becomes unstable, divided into two. The instability development time is of the order of magnitude inversely proportional to the growth rate γ of instability:

$$\tau_0 = \gamma^{-1} = \left(\sqrt{\beta - 1}\sqrt{\frac{\alpha}{\rho}}a^{3/2}\right)^{-1},$$

where $\beta = E_a / E_a^{cr} > 1$ is the degree of overcharge of the droplet, ρ is the droplet substance density. In [4] it is shown that the charge loss in Rayleigh decay of droplets is about 23%, and the weight loss is approximately 5%. Thus, the daughter droplets have a charge greater than the critical (1) and hence such droplets will also decay into smaller ones. The dependence of the critical value of the potential of droplets on its size is shown in Fig. 1.

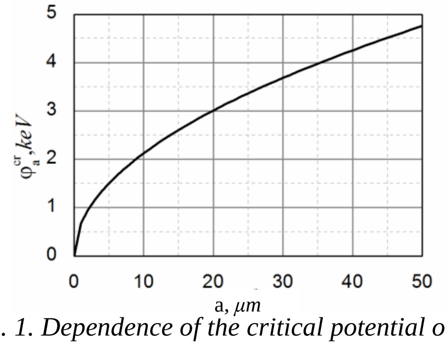

Fig. 1. Dependence of the critical potential on the droplet radius

As can be seen from the Fig. 1,a large enough potential φ_a for decay of droplet (liquid MP then just

ISSN 1562-6016. ВАНТ. 2017. №1(107)
PROBLEMS OF ATOMIC SCIENCE AND TECHNOLOGY. 2017, № 1. Series: Plasma Physics (23), p. 163-166.

MP) is required, which can be reached as a result of irradiation of the MP by high energy electron beam. At the same time, irradiation of the MP by electron beam leads to intense heating of MP up to temperatures $T > T_{Th}$ [5], when the MP is discharged due to the thermionic current and decay of the MP is impossible. Thus, the problem about the decay of a liquid charged MP reduced to the calculation of the MP decay time and the calculation of the time when MP decay is possible.

CONDITIONS OF MP DECAY

Dependence of the MP temperature and its potential on the irradiation time in plasma- beam system can be found by solving the set of equations:

$$\begin{cases} I_e^{pl}\ \varphi_a\ + I_e^b - I_e^s\ \varphi_a\ - I_e^{th}\ \varphi_a, T_a\ - I_i^{pl}\ \varphi_a\ = a\dfrac{d\varphi_a}{dt}, \\ P_e^{pl} + P_e^b + P_i^{pl} - P_e^s - P_r - P_{evpr} - P_{th} = m_{MP} c\dfrac{dT}{dt}. \end{cases} \quad (2)$$

where c is the heat capacity of the MP substance. The rate of change of the MP potential $d\varphi_a/dt$ (the first equation in (2)) is determined by balance of electrical currents on the MP surface.

$I_{i(e)}$ is the ion and electron currents, I_e^b is the electron beam current, $I_e^s\ \varphi_a$ is the secondary electron current, $I_e^{th}\ \varphi_a, T_a$ is the thermionic current. Formulas which describe the processes listed above have forms:

$$I_{i(e)}^{pl}\ \varphi_a\ = e < n_0 v_{i(e)} \sigma_{i(e)}^{OML} >= e\cdot\Gamma_{i(e)},$$

where

$$\Gamma_i = \sqrt{8\pi} a^2 n_0 v_{Ti}\left(1 - \frac{e\varphi_a}{kT_i}\right),\ \Gamma_e = \sqrt{8\pi} a^2 n_0 v_{Te} \exp\left(-\frac{e\varphi_a}{kT_e}\right),$$

$v_{Ti(e)}$ is the ion (electron) thermal velocity;

$$I_e^b = e\cdot\Gamma_e^b = \pi a^2 n_b e\sqrt{\frac{k\varepsilon_b}{m_e}}\cdot\left(1 + \frac{2e\varphi_a}{m_e v_e^2}\right);\ I_e^s = \delta I_e^b,$$

where $\delta = \delta_{\max}\dfrac{kE_b - e\varphi_a}{kE_m}\exp\left(2(1 - \sqrt{\dfrac{kE_b - e\varphi_a}{kE_m}})\right)$ is the secondary emission yield: E_b is the kinetic energy of primary electron, E_m is the electron energy which corresponds to the maximum of secondary emission yield $\delta_{\max}$.

$$I_e^{th} = 4\pi a^2 A T_a^2 \exp\left(\frac{e\Phi - \Delta W}{k_B T_a}\right),\text{ where, } A = \frac{4\pi m_e k_B^2 e}{h^3},$$

h is the Planck constant, k_B is the Stefan–Boltzmann constant, $e\Phi$ is the work function, T_a is the temperature of the MP. $\Delta W = \sqrt{e^3\varphi_a / a}$ is the decreasing of the electron work function (Schottky effect).

The second equation of (2) describes the rate of change of the MP temperature that is determined by the energy flows caused by the processes listed below: $P_{i(e)}^{pl}$ is the energy flow of plasma particles to the MP; P_e^b is the energy flow of electron beam; P_r is the energy radiated from the MP surface, P_{evpr} is the cooling due to evaporation of MP substance, P_{th} is the energy flow from the MP surface is transferred by the electrons of thermionic current P_e^s is the energy flow due to the secondary electron emission. The values of the respective energy flows are determined by the following relations:

$$P_e^{pl} = \Gamma_e\cdot(2kT_e + e\Phi),\ P_i^{pl} = \Gamma_i\cdot(2kT_i + e\varphi + ZI + e\Phi),$$

$$P_r = \sigma T^4,\ P_{evpr}^{-} = \Gamma_a\cdot(2k_B T_a + p),\ P_{th} = \Gamma_e^{th}\cdot(2k_b T_a),$$

$$P_e^s = \Gamma_s\cdot(< \varepsilon_s > + e\Phi)$$

where $\Gamma_a = n^{'}\sqrt{\dfrac{k_B T_a}{2\pi m_a}}\exp\left(-\dfrac{p}{k_B T_a}\right)$ is the atom flow of evaporated MP substance, $n^{'}$ is the concentration of atoms in metal, p is the energy of evaporation an atom, $\Gamma_e^{th} = I_e^{th}/e$, $\Gamma_s = I_s^{e-e}/e$, $<\varepsilon_s>$ is the averaged energy of the secondary electrons.

Set of equations (4) have been solved numerically, initial MP temperature was assumed equal to melting temperature of copper. Results of calculations are shown in the Fig. 2.

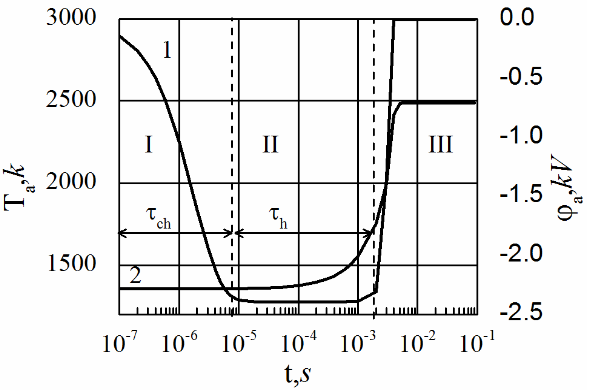

Fig. 2. Dependence of the MP potential (1) and MP temperature (2) on the time of irradiation by electron beam ($n_0 = 10^9\,cm^{-3}$, $n_b = 10^9\,cm^{-3}$, $E_b = 5\,keV$, $a = 10\,\mu m$ *)*

The plot shows that the MP potential has a complicated dependence on time. We can distinguish three areas of potential values which are separated by dotted lines: region (I) corresponds to MP charging, in this time interval (τ_{ch}) MP potential increases and its temperature is almost constant; region (II) corresponds to the stationary value of MP potential, that is, $d\varphi_a/dt = 0$ and MP temperature increases; region (III) corresponds to the MP heating up to the temperature $T_a > T_{th}$ when MP potential decreases sharply as a result of discharging due to thermionic emission. The temperature T_{th} is in the range $1700...2000\,\mathrm{K}$ and depends on the MP size (Schottky effect), and the electron beam energy. The region (II) corresponds to optimal conditions for developing the Rayleigh instability (maximum value of MP potential), thus, the possibility of the MP decay is limited by heating time τ_h:

$$\tau_{decay} \approx \tau_{ch} + \tau_0 < \tau_h.$$

Let us estimate the time scale of the problem. The charging time of the MP is approximately equal:

$$\tau_{ch} \approx \frac{kE_b}{4\pi a e^2 n v_e} \ln\left(1+\frac{e\varphi_a}{kE_b}\right).$$

The time when the MP is charged τ_h that corresponds to the region (II) is the heating time on the value $\Delta T = T_{th} - T_0$ we can estimate as:

$$\tau_h \approx \frac{m_a c(T_{Th} - T_0)}{P^{\Sigma}},$$

where $P^{\Sigma} = P_e^{pl} + P_e^{b} + P_i^{pl} - P_e^{s} - P_r - P_{evrp} - P_{th}$ is the total energy flow. Calculation of MP heating time τ_h and typical decay time τ_{decay} are shown in Fig. 3.

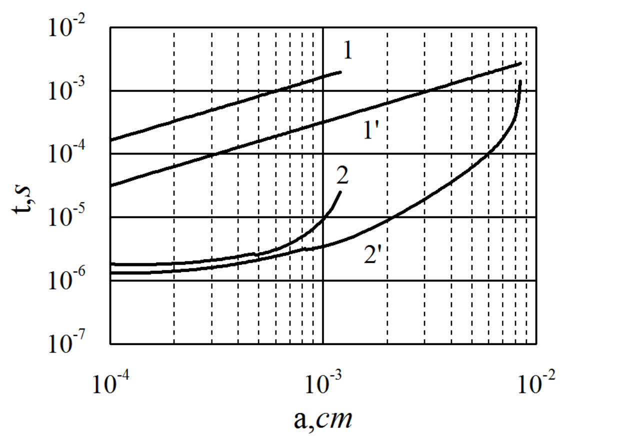

Fig. 3. Typical heating time of the MP τ_h *on the value* $\Delta T = 100K$ *(1 –* $E_b = 5\,keV$ *; 1'–* $E_b = 10\,keV$ *); typical decay time of the MP (2 –* $E_b = 5\,keV$ *; 2'–* $E_b = 10\,keV$ *)*

The plot shows that the typical MP decay time much less than the heating time. The decay number of the MP for τ_h we can estimate as:

$$N = \frac{\tau_h}{\tau_{decay}}.$$

In Fig. 4 are shown calculations of the decay number of the MP.

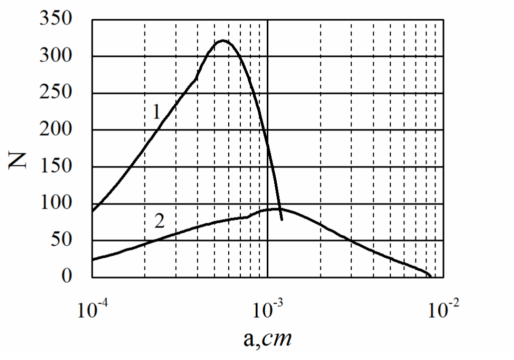

Fig. 4. The decay number of the MP for the time τ_h *,* $\Delta T_a = 100K$ *(1 –* $E_b = 5\,keV$ *; 2 –* $E_b = 10\,keV$ *)*

Calculations shows that irradiation of the MP by the electron beam can lead to its decay into multiple smaller droplets, which continue to decay. The maximum of the decay number curve are caused the next reasons. The number of decays of the MP is determined by two parameters: MP heating time τ_h and MP decay time τ_{decay}. Decay time $\tau_{decay} \approx \tau_{ch} + \tau_0$ at small values of MP size grows as charging time to critical value φ_a^{cr} $\tau_{ch} \sim a^{-1/2}$ and at bigger values of MP size grows as instability development time $\tau_0 \sim a^{3/2}$, simultaneously heating time is proportional to the MP size $\tau_h \sim a$.

Fig. 4 shows that the MP decay number at irradiation by the electron beam with energy $5\,keV$ (curve 1) is considerably greater than the electron beam with energy $10\,keV$ (curve 2) for the same MP. This effect is explained by the fact that the MP charging time (4) and instability development time (2) depend on the electron beam energy weakly (see Fig. 3, curves 2 and 2'), but increasing the beam energy increases the heating rate of the MP (see Fig. 3, curves 1, 1'). Should be noted that irradiation of the MP by the electron beam with a higher energy causes decay of more large MPs. The dependence of the MP size, which can be broken up due to the electron beam irradiation are shown in Fig. 5.

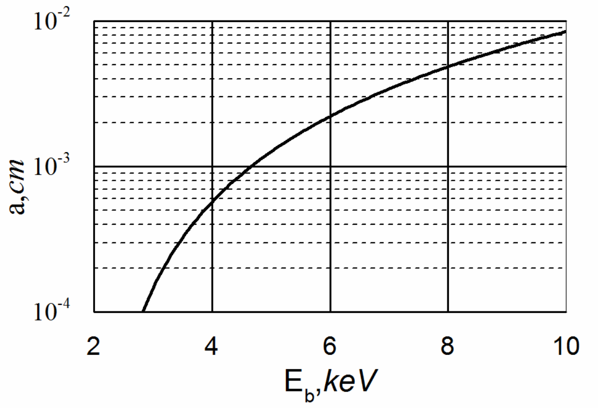

Fig. 5. The critical radius of the MP which can be destroyed due to electron beam irradiation

Fig. 5 shows that the MPs which size are typical for vacuum-arc plasma sources $a = 1...20\,\mu m$ can be divided into smaller MPs as a result of electron beam irradiation with energy $6\,keV$.

CONCLUSIONS

The dependencies of the self-consistent values of the MP potential and its temperature on the irradiation time by an electron beam have been obtained. It is shown that the time interval exists where needed conditions for the Rayleigh instability development of the liquid MP. The duration of this interval is determined by the heating time from the initial MP temperature T_0 to the MP temperature $1700...2000\,K$ where discharge due to thermionic emission starts. MP decay time has been obtained. It is shown that for the 'small' MPs, size of which is about $a \sim 1\,\mu m$ the decay time is approximately equal to the MP charging time, for more large MPs ($a >> 10\,\mu m$) decay time is approximately equal to the time of the development Rayleigh instability. For medium-sized ($a \approx 10\ \mu m$) MPs conditions for developing Rayleigh instability are optimal. The dependence of the number of MP decays on its size has been obtained. For the medium-sized MPs there is the maximum of decay number that corresponds to the optimal conditions to possibility of MP decay. When the beam energy increases the bigger MPs can be divided, but the number of divisions smaller MPs are reduced as a result of its more intensive heating.

REFERENCES

1. 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, № 4, v. 7, p. 189-192 (in Russian).
2. A.A. Bizyukov, A.D. Chibisov, et al. Charging processes and phase states of macroparticles in low-pressure arc discharge // *Problems of Atomic Science and Technology. Series "Plasma Electronics and New Methods of Acceleration"*. 2013, №4, v. 8, p. 176-178.
3. A.I. Grigor'yev, S.O. Shiryayeva. *Analiticheskiye raschety ostsillyatsiy zaryazhennoy kapli*. Yaroslavl', 2011 (in Russian).
4. J.W. Schweizer, D.N. Hanson. Stability limit of charged drops // *J. Coll. Interface Sci*. 1971, v. 35, № 3, p. 417-423.
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.

Article received 12.11.2016

РАСПАД ЖИДКИХ МЕТАЛЛИЧЕСКИХ МАКРОЧАСТИЦ В ПЛАЗМЕННО-ПУЧКОВЫХ СИСТЕМАХ В РЕЗУЛЬТАТЕ РАЗВИТИЯ НЕУСТОЙЧИВОСТИ РЭЛЕЯ

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

Изучена возможность распада жидких макрочастиц (МЧ) в бесстолкновительной плазме вакуумного дугового источника плазмы в результате их зарядки электронным пучком высоких энергий и последующим развитием неустойчивости Рэлея. Получены критерии распада МЧ, время зарядки МЧ электронным пучком, время распада МЧ, а также время нагревания до температуры, когда происходит разрядка МЧ термоэмиссионным током. Показано, что время разогрева МЧ значительно превышает время развития неустойчивости Рэлея.

РОЗПАД РІДКИХ МЕТАЛЕВИХ МАКРОЧАСТОК У ПЛАЗМОВО-ПУЧКОВИХ СИСТЕМАХ У РЕЗУЛЬТАТІ РОЗВИТКУ НЕСТІЙКОСТІ РЕЛЕЯ

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

Вивчено можливість розпаду рідких макрочасток (МЧ) у плазмі без зіткнень, яка створюється вакуумно-дуговим джерелом плазми, в результаті їх зарядки електронним пучком високих енергій і подальшим розвитком нестійкості Релея. Отримано критерії розпаду МЧ, час зарядки МЧ електронним пучком, час розпаду МЧ, а також час нагрівання до температури, коли відбувається розрядка МЧ термоемісійним струмом. Показано, що час розігріву МЧ значно перевищує час розвитку нестійкості Релея.