CHARGING OF MACROPARTICLES IN A HIGH-VOLTAGE VACUUM ARC SHEATH

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Charging of macroparticles (MPs) in front of the negatively biased surface emitted the secondary electrons due to bombardment by multiply charged ions (MCIs) has been investigated. It was found that MPs can be either reflected or attracted to the substrate depending on the substrate bias.

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INTRODUCTION

A vacuum arc discharge emits a plasma as well as macroparticles (MPs) in the form of molten droplets of cathode material [1]. The significant MP fraction substantially limits the possibilities of vacuum arc plasma in coating technologies. The MPs occur in the range of size from several microns to a few hundred microns, the velocity of MPs reaches maximum value of 700-800m/s. Cathodic vacuum arc plasma are known to contain multiply charged ions. These ions have kinetic energies of a few tens of eV. The mean ion charge state Z is generally higher than 1 for most materials. In many vacuum arc experiments, ions are collected at a negatively biased metal surface. The purpose of the present study is to investigate the behavior of charged MPs in front of the negatively biased surface emitted the secondary electrons due to bombardment by multiply charged ions (MCIs).

1. SHEATH MODEL

Let us consider a high-voltage substrate is immersed in a vacuum arc produced plasma. For a high-voltage sheath, the current to the substrate is almost all ion current [2]. The MPs are assumed to have no effect on the sheath structure. In our coordinate system a plasma-sheath interface (interface between quasi-neutral and nonneutral regions) is taken to be the origin, $x = 0$, and the positive direction is away from the it. The substrate, which is supposed to be at the constant potential V_b, is located at $x = x_d$ ($|eV_b| >> T_e$ |eV$_b$|>>T_e, where T_e is the electron temperature in energy units, e is the elementary charge). The ion temperature is assumed negligible in comparison with T_e. The generalized Bohm's criterion is over satisfied for vacuum arc plasmas [3].

The ions, hitting the substrate surface with kinetic energies below 300 eV, may cause a potential electron emission [4]. Such ion energies are typical for deposition a thin metallic film coating.

The total ion beam current density is the sum of each ion species k

$$j_i = \sum_{k=1}^{N} j_{ik} = e\sum_{k=1}^{N} Z_k n_{ik} u_{ik}, \tag{1}$$

where Z_k is the charge state, n_{ik} is the ion density of the k-th species, u_{ik} is the velocity of each species. The density fraction of the k-th species $f_k = n_{ik}/n_0$, where n_0 is the bulk plasma density.

A secondary electron beam produced at the substrate by the secondary emission is ejected from that place $x = x_d$ towards the plasma in the $-x$ direction [4].

$$j_e = \sum_{k=2}^{N} j_{ek} = \sum_{k=1}^{N} \frac{\gamma_k}{Z_k} j_{ik}, \tag{2}$$

where j_{ik} is the current density of secondary electrons produced by the ions of the k-th species, γ_k γk is the secondary ion-electron emission yield [4].

The potential variation φ in the sheath is found by solving Poisson's equation

$$\frac{d^2\varphi}{dx^2} = -\frac{e\left[\sum_{k=1}^{N} Z_k n_{ik} - \sum_{i=2}^{N} n_{ek}\right]}{\varepsilon_0}, \tag{3}$$

where n_{ek} is the secondary electron density; ε_o is the permittivity constant. The boundary conditions are $\varphi(0) = 0; \varphi'(0) = 0$.

The flux of ions is assumed to be continuous across the sheath in the collisionless model. From the equations of continuity and energy conservation for the ions we derive the ion density

$$n_{ik} = \frac{j_{ik}}{Z_k e}\sqrt{\frac{m_i}{2(\varepsilon_{k0} - Z_k e\varphi)}}, \tag{4}$$

where m_i is the ion mass, ε_{ko} is the initial ion energy of the k-th species.

On the analogy we obtain the secondary electron density n_{ek} produced by the secondary emission

$$n_{ek} = \frac{j_{ek}}{e}\sqrt{\frac{m_e}{2e(V_b + \varphi)}}, \tag{5}$$

where m_e is the electron mass.

Substituting in Eq. (3) the densities (4) and (5), we obtain the sheath equation for numerical integration.

2. MP CHARGING

We consider the MP with radius a as a spherical probe immersed in the plasma sheath [5]. The MP radius is much smaller than the electron Debye radius

λ_D. We assume instantaneous transfer of charge onto and off the MP at any MP position in the sheath. The steady-state potential to which a MP is charged is determined from the balance of particle fluxes to the grain

$$(1-\delta)\sum_{k=2}^{N} j_{ek} = \sum_{k=1}^{N}\left(1+\frac{\gamma_k}{Z_k}\right) j_{ik}, \qquad (6)$$

where δ is the secondary electron-electron emission coefficient [6].

The ions and electrons can be described as beam-like due to their high directed velocities. The expressions for the ion and electron fluxes are

$$j_{\alpha k} \approx q_{\alpha k} n_{\alpha k} u_{\alpha k} \sigma_{\alpha k}, \qquad (7)$$

where $\alpha = e, i$ represents the electrons and ions, respectively; the collection cross section for charging collisions between the macroparticle with the particle α based on the orbital motion limited (OML) approach is

$$\sigma_\alpha = \pi a^2 \left(1+\frac{2q_\alpha(\varphi(x)-\varphi_s(x))}{m_\alpha u_\alpha(x)^2}\right), \qquad (8)$$

where $\varphi_s(x)$ is the potential at the MP surface.

If

$$\frac{2q_\alpha(\varphi(x)-\varphi_s(x))}{m_\alpha u_\alpha(x)^2} \le -1, \sigma_\alpha = 0. \qquad (9)$$

Solving for $\varphi(x)$ Eq. (3) and for $\varphi_s(x)$ Eq. (6), we obtain MP charge

$$Q(x) = 4\pi\varepsilon_0(1+a/\lambda_D)(\varphi_s(x)-\varphi(x)) \approx$$
$$\approx 4\pi\varepsilon_0(\varphi_s(x)-\varphi(x)). \qquad (10)$$

The MP travels through the plasma sheath and is subject to electric force [7]

$$\vec{F} = Q\vec{E}\left(1+\frac{(a/\lambda_D)^2}{3(1+a/\lambda_D)}\right) \approx Q(x)\vec{E}(x), \qquad (11)$$

where $\vec{E}(x)$ is the electric field in the sheath.

The potential energy of given size at the local sheath position is

$$U(z) = -\int_0^x Q(x')\vec{E}(x')dx' . \qquad (12)$$

The profile of potential energy and initial kinetic energy of MP define the trapping of MP.

For numerical solutions it is convenient to introduce the new variables

$$z = x/\lambda_D = x\left(n_0 e^2/\varepsilon_0 T_e\right)^{1/2}, \Phi(z) = e\varphi/T_e,$$
$$\Phi_s(z) = e\varphi_s/T_e, \Phi_d(z) = \Phi_s(z) - \Phi(z). \qquad (13)$$

Copper is the most commonly used cathode material in vacuum arc experiments and consequently the calculations were carried out for copper ions, bombarding a copper substrate [1, 4]. Here, we present the results of numerical calculations of the dynamics of charging of a Cu-macroparticle of radius $a=1\,\mu m$ in the sheath with account of secondary electron emission due to ion and electron bombardment for the values of the parameters presented in Table. The electron temperature is usually not more than 1…2 eV. Thus, we gave $T_e = 1$ eV.

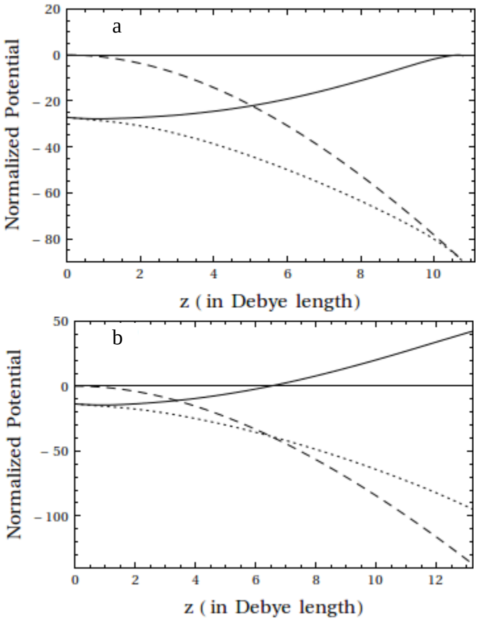

Fig. 1. The local sheath potential $\Phi(z)$ *Φ(z)(solid line), the potential at the MP surface* $\Phi_s(z)$ *(dotted line), the MP potential with respect to the local plasma potential* $\Phi_d(z)$ *(dashed line) as a function of distance* z *for a substrate bias:* V_b *= -90 V(a);*
V_b *= -140 V(b)*

Energies and secondary electron emission coefficients for the different fractions of Cu-ions: Ref [1, 4]

Ion charge Z	Ion state fraction, f_k	Ion energy, ε_{k0} (eV)	Secondary electron emission coefficient, γ_k
1	0.30	37	–
2	0.55	56	0.21
3	0.15	66	0.69

The results of the numerical solution of Eqs. (3) and (6) are shown in Fig.1. This plot demonstrates the dimensionless local sheath potential, the potential at the MP surface, the dust potential with respect to the local plasma potential as a function of normalized distance $z = x/\lambda_D$. In first case, substrate bias V_b = -90 V (Fig.1,a), the potential at the MP surface $\Phi_s(z)$ is negative, and the MP potential with respect to the local plasma potential $\Phi_d(z)$ is negative too.

For a substrate bias V_b = -140 V (Fig. 1,b), the dust potential at the MP surface $\Phi_s(z)$ is negative. However, the MP potential with respect to the local plasma potential $\Phi_d(z)$ is positive near the substrate because the sheath potential becomes more negative than the MP potential. In Fig. 2,a, the MP charge profile for a substrate bias V_b = -90 V is shown. The MP charge is negative. The MP charge determines the electric force. Therefore, the electric force will be negative too (see Fig. 2,b). The dependence of the potential energy of MP on the position $z = x/\lambda_D$ is shown in Fig. 2,c.

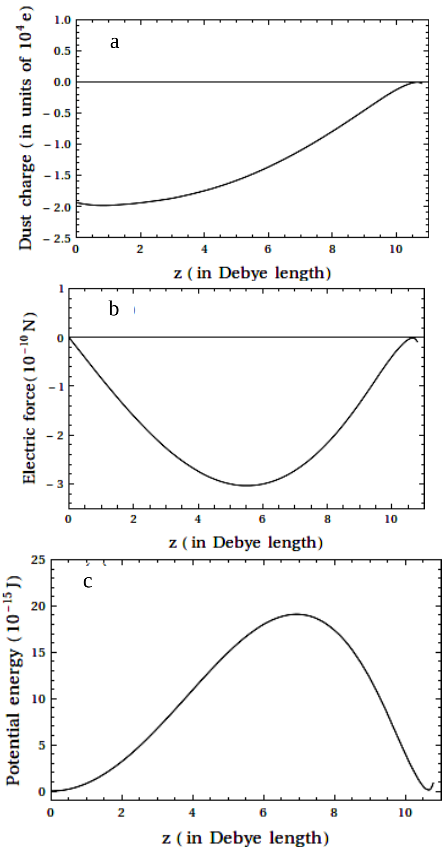

Fig. 2. The dependence of the MP charge on the position $z = x/\lambda_D$ for a substrate bias V_b = -90 V (a); The dependence of the electric force, acting on this MP charge (b); The dependence of the corresponding potential energy (c)

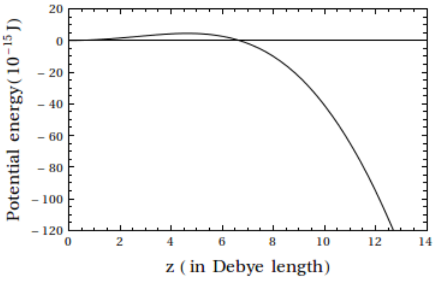

Fig. 3. The dependence of the potential energy of the MP on the position $z = x/\lambda_D$ $z = x/\lambda_D$ for a substrate bias V_b = -140 V

If the MP kinetic energy is large enough to overcome the potential barrier, a negatively charged MP may be attracted to the substrate. For copper, velocity range of MPs is 250…450 m/s. Mps with velocity above 400 m/s overcome the potential barrier and attracted to the substrate. For velocity range of MPs is 250…400 m/s, MPs are reflected.

For bias V_b = -140 V, the profile of potential energy of MP are shown in Fig. 3. This profile means that the MPs can be attracted to the substrate in all velocity range.

CONCLUSIONS

Charging of copper MPs and its influence on the MP motion in front of the negatively biased copper surface emitted the secondary electrons due to bombardment by MCIs have been investigated. It was found that the possibility of MP attraction increases with negative bias voltage. We show that the results presented here may be applicable to the control of the MPs by modifying the bias of the substrate.

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ЗАРЯДКА МАКРОЧАСТИЦ В СЛОЕ ВАКУУМНОЙ ДУГИ ВЫСОКОГО НАПРЯЖЕНИЯ

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Исследуется зарядка макрочастиц (МЧ) напротив отрицательно заряженной поверхности, испускающей вторичные электроны из-за бомбардировки многозарядными ионами (МЗИ). Было найдено, что МЧ могут либо притягиваться к подложке, либо отталкиваться в зависимости от потенциала подложки.

ЗАРЯДЖЕННЯ МАКРОЧАСТИНОК У ШАРІ ВАКУУМНОЇ ДУГИ ВИСОКОЇ НАПРУГИ

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Досліджено зарядження макрочастинок (МЧ) напроти від'ємно зарядженої поверхні, яка випромінює вторинні електрони завдяки бомбардуванню багатократно зарядженими іонами (БЗІ). Було знайдено, що МЧ можуть або притягатися до підкладки, або відштовхуватися в залежності від потенціалу підкладки.