MACROPARTICLES IN BEAM-PLASMA SYSTEMS

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The macroparticle (MP) contamination is the most important technological problem of vacuum arc deposition of coatings. The results of theoretical study of MP charging and dynamics in the near-substrate sheath are presented. The charge and dynamics of MP are governed by local parameters of ion and secondary electron emission fluxes in the sheath. It is shown that the maximum possible velocity of repelled MP increases with increasing substrate bias voltage. The effect of substrate biasing is seen to be larger for MPs emitted at small angles to the cathode plane of arc evaporator.

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INTRODUCTION

One of the central concepts in plasma physics is that of the charging of macroparticle (MP) by surrounding plasma. The charging process in the gaseous plasmas has been well studied [1]. The MPs are charged by the collection of the plasma particles flowing onto their surfaces. Because of the high thermal velocity of the electrons compared to the ions, MPs are negatively charged. For beam-plasma systems, in addition to collecting thermal plasma particles, MPs are subjected to fluxes of beam particles. The presence of beams in systems produces significant effect on dynamics of charging process. The energetic beams are not only intentionally introduced into plasma but energetic ion beams are also formed from a plasma by a set of extractor electrodes in vacuum arc deposition (VAD) systems to obtain layers of cathode material on substrate. The vacuum arc sources generate highly ionized metal plasma with multiply charged ions (MCIs) [2]. The mean ion charge state is 2…3 and typically higher for materials with high melting point. The ions have supersonic velocities, corresponding to ion energy in the range 20…200 eV, depending on the source material [3]. By applying negative high-voltage bias to the substrate, ions are extracted from the plasma, accelerated across the sheath and deposited into the surface [4]. A disadvantage of VAD is the emission of macroparticles (MPs) during arcing. MPs are generally molten metal droplets (sometimes solid) generated by the action of the cathode spots [5]. The MPs occur in the range of size from fraction to tens of microns. There is a strong dependence of MP production on the cathode material. The cathode erosion in the droplet phase decreases with increasing cathode material melting temperature [6], but monotonic relationship between MP production and melting point of the different cathode materials could not be established. MPs and plasma fluxes are partially separated. The plasma flux is peaked in the direction of the normal to the cathode surface [7] whereas most of MPs produced by a steady vacuum arc leave the cathode at small angles to the cathode plane [8]. However, MP flux emitted in the direction of the normal to the cathode surface can still be large. The peak emission angle with respect to the cathode plane increases with decreasing MP size [6]. The incorporation of MPs into the coating degrades the quality of the films, e.g. produces surface roughening, protuberances, bumps and pinholes [9]. MPs may constitute a considerable fraction of the coatings mass. This substantially limits the possibilities of vacuum arc plasma in coating technologies. Thus, MP contamination is regarded as the most important technological problem. Several methods connected with different aspects of the MP process have been developed to eliminate MPs, such as magnetic filters [10], magnetically steered arc [11], substrate biasing [12], and nontraditional (hot refractory anode vacuum arc, shunting vacuum arc) [13]. Among these methods, the substrate biasing has been considered as a positive means in our previous study [14]. We have proposed a model of MP transport in vacuum arc sheath, and appreciable progress was made towards explaining the reduction of MPs which has been approached by substrate biasing. It is obtained that the use of substrate bias of -300 V may be capable of repelling MPs with a size less than 1 μm from the substrate at normal incidence of MPs. In the present work, we report further results on the accumulation of MPs on a negatively biased substrate immersed in vacuum arc plasma using measured size and angular distributions of MPs [15]-[16].

1. DISTRIBUTIONS OF MPS

The size and angular distributions of MPs have been investigated by a number of authors [17-20] for a range of cathode material. Tuma et al. [18] obtained that copper MPs have a monotonically decreasing size distribution, which has a maximum for MPs of diameter in the range 0..1 μm. Similar results for a variety of cathode material have been reported by Anders et al [20]. MPs have a peaked distribution which tailed off with increasing MP volume. Therefore, MPs with smaller volumes dominate the number density.

MPs have a size distribution *f(d)* that can be described by a power law [9]

$$f(d) = Ad^{-\alpha}, \qquad (1)$$

where *d* is the MP diameter, and the parameters A and α are material dependent. This shape of size distribution *f(d)* follows from the fractal nature of cathode spot phenomena.

MP size distribution *f(d)* can be represented by a straight line in log-log presentation as shown in Fig. 1.

Fig. 1 demonstrates the MP size distribution f of Ti MP diameter d (in μm) normalized to the area (in mm^2) and time deposition (in s). MP sizes for Ti range up to 40 μm in the absence of background gas and 30 μm in the presence of nitrogen [15].

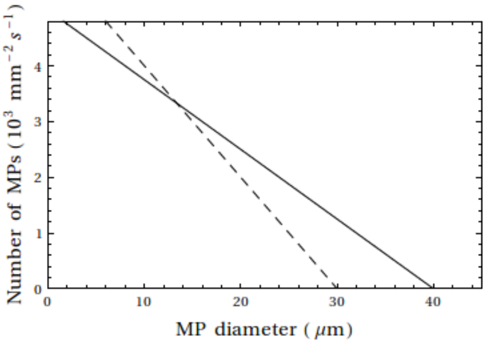

Fig. 1. MP size distribution for Ti, normalized as MP number per area and time deposition for pressures 10^{-3} Pa (solid line) and 1Pa (dashed line). Experimental results were taken from Ref. [15]

As one can see from the Fig. 2, the MP flux is peaked with a most probable angle below 30^0 with respect to the cathode plane in vacuum as well as in the presence of nitrogen. McClure [21] proposed theory which explains the emission of the MPs at the small angles to the cathode surface. The plasma expands from the cathode spots into the vacuum. In addition to the outward flow of ions, there is a back flow of ions accelerated towards the liquid cathode surface of the arc spot. The back-streaming ions press inward on the molten metal. The plasma pressure is stronger in center than at the sides of the crater. Therefore, MPs are pushed towards the edge of the crater leading to the observed angular distribution.

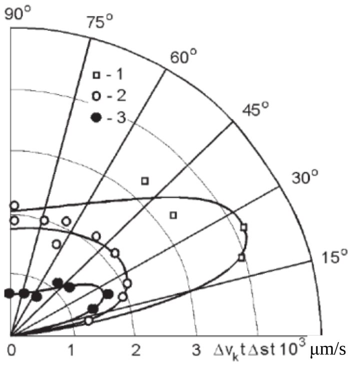

Fig. 2. MP angular distribution for Ti, normalized as MP volume per are and time deposition for different values of pressure: 1 – 10^{-3} Pa; 2 – 0.1 Pa; 3 – 1 Pa [16]

MODEL DESCRIPTION

Let us consider a negatively biased substrate, immersed into vacuum arc produced plasma. Application of high negative bias V_b to the substrate leads to positive sheath formation near the substrate. This is because the electrons are repelled from the substrate whereas ions are accelerated towards the substrate [22].

In our coordinate system a plama-sheath interface is taken to be the origin, *x=0,* and the position of the substrate is determined by the sheath thickness. The ions, hitting the substrate, may cause an electron emission. Because of the relatively low kinetic energy of the ions (below 1 keV), only the potential electron emission (PEE) is of importance in the vacuum arcs [9].

The flux of secondary electrons is accelerated away from the substrate in the sheath electric field that accelerated flux of MCIs towards the substrate. To obtain potential distribution $\Phi(x)$ within the sheath one has to consider both particle fluxes to and from the substrate in Poisson's equation

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

where ε_0 is the permittivity constant, *e* is the elementary charge, *k* is the ion charge state number, n_{ik} is the individual ion densities of the *k*-th species, n_{ek} is the individual densities of secondary electrons produced by the ions of the *k*-th species.

The boundary conditions for integration are $\Phi(0)=0$; $d\Phi/dx=0$. The space charge of MPs is neglected (i. e., we assume that the MP number density to be small). The potential variation in the sheath can be found numerically by integration Eq. (2).

We consider the MP with radius *a* as a spherical probe immersed in counter streams of ions and electrons where the directed particle velocity is much greater than the MP velocity [24]. The MP charge Q is one of the most important characteristics for the MP dynamics. The MP charge Q is determined by the MP potential with respect to the local sheath potential V_d

$$Q(x) = CV_d(x), \tag{3}$$

where C is the capacitance of the MP. If the MP radius is much smaller than the Debye length λ_D the capacitance is

$$C = 4\pi\varepsilon_0(1 + a/\lambda_D) \approx 4\pi\varepsilon_0 a, \tag{4}$$

where $\lambda_D = (\varepsilon_0 T_e / n_0 e^2)^{1/2}$.

The MP charging time is shorter than the time of flight through the plasma sheath. 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 currents to the grain ($V_d < 0$)

$$I_i(V_d) + I_e(V_d) + I_{i-e}(V_d) + I_{e-e}(V_d) = 0, \tag{5}$$

where I_i is the ion current, I_e is the current of fast secondary electrons emitted from the substrate, I_{i-e} is the secondary electron current from the MP surface caused by the impact of MCIs, I_{e-e} is the current of secondary electrons emitted from the MP surface due to fast electron bombardment.

We calculate the currents I_i and I_e to the MP surface by using the orbital motion limited (OML) approach.

$$I_i = \sum_{k=1}^{N} I_{ik} = \pi a^2 \sum_{k=1}^{N} j_{ik} \left(1 - \frac{2keV_d}{m_i u_{ik}^2} \right), \qquad (6)$$

$$I_e = \sum_{k=2}^{N} I_{ek} = \pi a^2 \sum_{k=1}^{N} j_{ek} \left(1 + \frac{2eV_d}{m_e u_e^2} \right), \qquad (7)$$

$$I_{i-e} = \sum_{k=2}^{N} I_{i-e,k} = \sum_{k=1}^{N} \frac{\gamma_k}{k} I_{ik}, \qquad (8)$$

$$I_{e-e} = \delta I_e, \quad \delta = 7.4 \cdot \delta_m \cdot \frac{\varepsilon_e}{\varepsilon_{em}} Exp\left(-2\sqrt{\frac{\varepsilon_e}{\varepsilon_{em}}} \right), \quad (9)$$

where δ is the secondary electron yield [24]; j_{ik} is the current density of the ions of the k-th species, j_{ek} is the current density of secondary electrons produced by the ions of the k-th species; γ_k is a partial PEE yield , I_{ik} =0, if $2keV_d / m_i u_{ik}^2$>1; and I_e =0, if $2eV_d/m_e u_e^2$ <1, m_i (m_e) is the ion (electron) mass, u_{ik} is the velocity of each ion species in the sheath, u_e is the velocity of secondary electrons.

Electrostatic repulsion of MPs should occur if the potential energy exceeds the kinetic energy

$$U_{pot}(x) \geq MV_n^2/2, \qquad (10)$$

where $U_{pot} = Q(x)\Phi(x)$, is the potential energy of MP at the local sheath position V_n is the velocity component normal to the substrate (V_n=$V_p \sin\theta$, where V_p is the MP velocity, θ is the angle with the respect to the cathode plane).

Repulsion criterion (10) is recast as

$$V_p a < \left(6\varepsilon_0 V_d(x)\Phi(x) / \rho \sin^2\theta \right)^{1/2}. \qquad (11)$$

While we do not know of any detailed measurements of both velocity V_n and radius a, the analysis of inequality can provide an answer to the question whether MP with given radius may be reflected from a substrate. We can find dependence of the MP critical velocity as a function of MP position for different angles. It says that MP with a given radius must penetrate through the sheath region with a velocity greater than the critical velocity.

3. RESULTS AND DISCUSSION

The numerical calculations were carried out for titanium ions, bombarding a negatively biased titanium substrate. The specific plasma parameters and energy of ions have been taken as typical values from experiments: the electron temperature T_e =1 eV, the plasma bulk density n=10^{16} m^{-3}, mean initial kinetic energy of ions ε_i =54 eV, mean ion charge Z=1.98, I_e/I_i=1.3. We consider, as an example, MP with radius 0.25 μm.

Numerical solutions of set of Eqs. (2)-(9), (11) allow to determine MP critical velocity as a function of MP position z for different angles.

MP critical velocities for substrate bias -100 V, -200 V, -300 V are shown in Fig. 3. The maximum possible velocity of repelled MP is defined by a maximum of curves. The critical velocity increases with substrate bias voltage (see Figs. 3,a,c). It may be seen from Fig. 3,a, for substrate bias V_b=-100 V, all MPs with velocity 20 m/s reach the substrate. MPs moving at angle θ=30^0 to the cathode plane reach the substrate at substrate bias V_b= -100 V with velocity 20 m/s (see Fig. 3,a), whereas they become closer to the substrate with such velocity at V_b= -200 V (see Fig. 3,b).

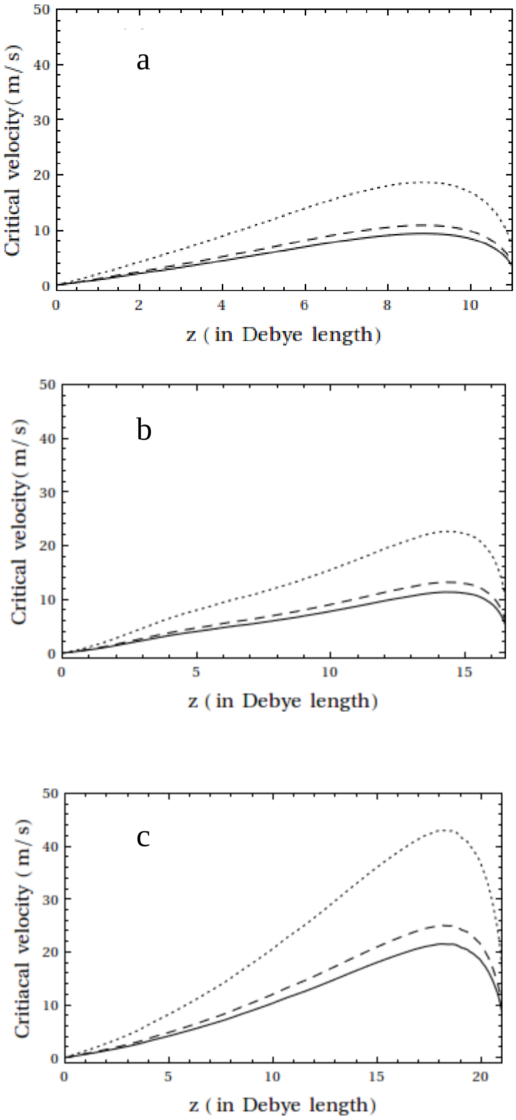

Fig. 3. The dependence of the critical velocity of the MP radius with radius 0.25 μm on its position z for different angles and substrate biases: (a) V_b=-100 V; (b) V_b=-200 V; (c) V_b=-300 V. The curves correspond to θ=90^0 (solid line), θ=60^0 (dashed line); θ=30^0 (dotted line)

MPs with radius 0.25 μm and velocity 20 m/s emitted in the direction of the normal to the cathode surface can be eliminated using substrate bias V_b=-300V(see Fig. 3,c).

CONCLUSIONS

The numerical results of MP content in films deposited by a titanium vacuum arc for different substrate bias voltage and MP flight angle with respect to the cathode surface have been presented.

Substrate bias voltage and cathode-to-substrate geometry are the key factors that influence the density of MPs. The effect of substrate biasing is larger for MPs emitted at small angles to the cathode plane than for

MPs emitted in the direction of the normal to the cathode surface. As most of MPs produced by a steady vacuum arc leave the cathode at small angles to the cathode plane, the substrate biasing is the effective method to reduce MP contaminations of the coatings.

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МАКРОЧАСТИЦЫ В ПУЧКОВО-ПЛАЗМЕННЫХ СИСТЕМАХ

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Наиболее важной технологической проблемой вакуумно-дугового осаждения покрытий является загрязнение макрочастицами (МЧ). Представлены результаты теоретического исследования зарядки и динамики МЧ в слое у подложки. Заряд и динамика МЧ определяются локальными параметрами ионных и электронных вторично-эмиссионных потоков в слое. Показано, что максимально возможная скорость отраженной МЧ возрастает с увеличением потенциала подложки. Эффект смещения потенциала подложки больше для МЧ, которые эмитируют под малыми углами к плоскости катода вакуумного испарителя.

МАКРОЧАСТИНКИ В ПУЧКОВО-ПЛАЗМОВИХ СИСТЕМАХ

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Найбільш важливою технологічною проблемою вакуумно-дугового осадження покриттів є забруднення макрочастинками (МЧ). Представлено результати теоретичного дослідження зарядки та динаміки МЧ у шарі біля підкладки. Заряд і динаміка МЧ визначаються локальними параметрами іонних та електронних вторинно-емісійних потоків у шарі. Показано, що максимально можлива швидкість відбитої МЧ зростає зі збільшенням потенціалу підкладки. Ефект зсуву потенціалу підкладки більший для МЧ, які емітують під малими кутами к площині катоду вакуумного випарника.