DYNAMICS OF MACROPARTICLES IN A MAGNETIC FILTER FOR A VACUUM ARC PLASMA SOURCES

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The possibility of transportation of charged macroparticles (MPs) through a magnetic filter is studied. It is shown that when MPs moves through the curved magnetic filter its can be charged either positively or negatively. The trajectories of charged MPs are changed due to the negative space charge in the plasma duct. It is found that positively charged MPs may be retained in plasma duct, depending on the parameters of plasma and MPs. The conditions determining their transportation through the filter are obtained.

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INTRODUCTION

Vacuum arc discharge is an effective source of plasma with a wide range of scientific and technological applications [1, 2]. One of the most important technological applications of vacuum arc plasma is associated with its use for ion-plasma deposition of coatings that improve the properties of products. When the vacuum arc is burning the main plasma source are cathode spots, however, in the cathode spot an erosion of the cathode surface leads to the formation not only of the plasma flow but also macroparticles – droplets of cathode material. Ratio of the droplet fraction in the total erosion of the cathode is a significant part (is about 90%), as in terms of the characteristics of the plasma source is a negative factor. This is due to the fact that the deposited droplets on the surface of the products impair some important characteristics of the surface layer, such as porosity and surface roughness, the adhesion of the coating to the surface corrosion and other surface properties [3].

In practice, most of the specific ways of reducing the flow of droplets on the products are based on the separation of the ion trajectories and streams of the droplets. First of all, is used the fact that (due to the different nature of the formation of the ion flow and droplet flow) most of the droplets moves at a low angle to the surface of the cathode, while the main ion flow is moving normal to the surface. More effective are the various filters where the ion flow separates from the droplet flow by the magnetic field. However, the higher the required degree of the ion flow purification from drops, the more complex and expensive construction of the filter is, and the greater the become losses ionic component of the filtered flow [3].

However, experiments show that a small portion of the MPs passes through the filter. One of the mechanisms of the transportation of the MP through the filter is changing their trajectories due to elastic collisions of the MPs with the walls of the filter [3]. In this paper, we study the possibility of transportation of the MPs through the magnetic filter as a result of their retention by the electric field inside the plasma duct.

1. CHARGE OF THE PARTICLES IN THE VACUUM-ARC PLASMA SOURCES

It is known that the MP immersed in 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 [4].

The charge of the MPs varies widely depending on the energy of the particles of plasma as well as ratio of their densities and can take both negative and positive values [5]. The value of the charge and its sign determine the character of interaction of the MP with an electric field presented in the plasma duct and hence determine the trajectory of the MP in the filter. Charge of the MP is determined by the balance of ion and electron currents on its surface. Calculation of the currents from plasma on the MP in presence of the magnetic field is a intricate problem, however in some cases various approximations are used successfully. In particular, if the magnetic field is not large enough such that condition

$$r_g >> \lambda_d >> a \tag{1}$$

is true, where r_g is the Larmor radius of electron, λ_d is the Debye length, a is the radius of the MP, in collisionless plasma the OML theory for calculating the ion and electron currents on the spherical probe is used. In this paper we consider plasma created by a stationary arc discharge with the density $n_0 = 10^{10}...10^{12}$ cm^{-3} and electron temperature $T_e = 1...5$ eV. Ion component has a directed velocity with the energy distribution close to Maxwellian. The average energy of directed motion of the ions is equal to $\varepsilon_i^{fl} = 25...50$ eV [4]. The strength of the magnetic field B in the filter is equal to 100 G. With these parameters, typical for vacuum-arc systems, the condition (1) is true and OML theory is correct.

Currents of electrons and ions from plasma to the surface of the MP have the form:

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

$$I_i = \sqrt{\pi} e n_0 < Z > v_{Ti} \pi a^2 \left(1 - \frac{< Z > e\varphi_a}{T_i}\right), \tag{3}$$

where e is the elementary charge, n_0 is the plasma density, $T_{e(i)}$ are the temperatures of the plasma electrons and ions, $v_{Te(i)} = \sqrt{T_{e(i)} / m_{e(i)}}$ are their thermal velocities $< Z >= 1\cdot\alpha_1 + 2\cdot\alpha_2 + 3\cdot\alpha_3$ is the averaged ion charge of ions, $\alpha_1, \alpha_2, \alpha_3$ are the relative concentrations of ions with charges Z=1, 2, 3 respectively, φ_a is the potential on the surface of the MP.

To focus the plasma flow created by vacuum arc discharge a negative potential to the substrate u_{sub}

(Fig. 1) is applied, that leads to an acceleration of the ions up to energies $\varepsilon_i^{fl} = eZu_{sub}$.

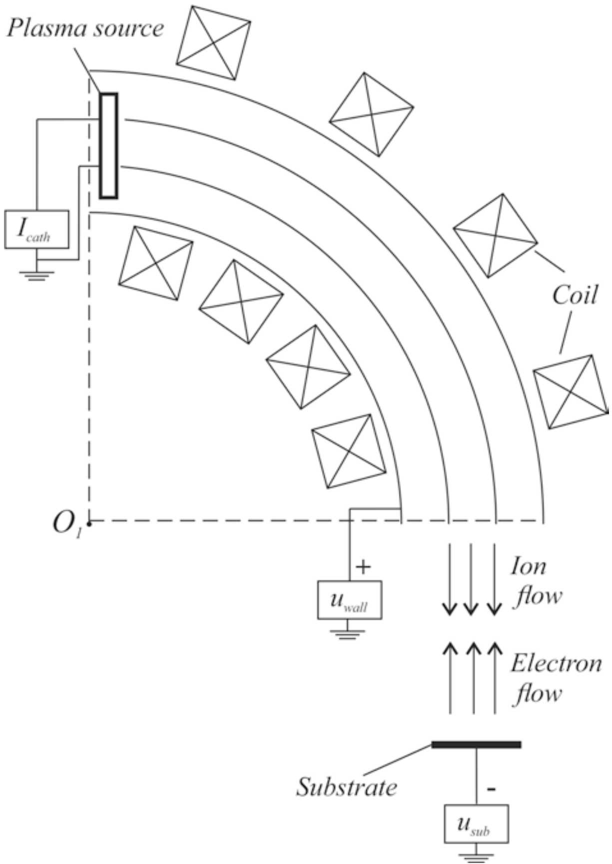

Fig. 1. Scheme of formation of the electron flow on a substrate in vacuum-arc systems with curved magnetic filters

The interaction of the ion component of the plasma flow with the substrate causes the formation of the flow of secondary electrons (see Fig. 1), whose density is determined by the secondary electron yield. Taking into account that in the plasma flow the ions with varying degree of ionization exist, it is advisable to introduce the average secondary electron yield:

$$\delta_s^{i-e} = \alpha_1 \cdot \delta_{s1}^{i-e} + \alpha_2 \cdot \delta_{s2}^{i-e} + \alpha_3 \cdot \delta_{s3}^{i-e}, \quad (4)$$

where δ_{sZ}^{i-e} is the secondary electron yield for the ions with charge Z.

The energy of the secondary electrons ε_e^{fl} is determined by the negative potential on the substrate u_{sub} and has negligible variation that corresponds to the energy spectrum of the secondary electrons.

The density of the secondary electron flow is related with an ion current density j_j on the substrate by the relation:

$$j_e^{fl} = \delta_s^{i-e} j_i . \quad (5)$$

Current of these secondary electrons on the surface of the MP is determined by the OML theory:

$$I_e^{fl} = j_e^{fl} \pi a^2 \left(1 + \frac{e\varphi_a}{T_i}\right). \quad (6)$$

An important process that affects on the magnitude of the charge of the MP is the emission of electrons from the surface. We will consider the following main mechanisms of electron emission: ion-electron emission, electron-electron emission. Value of the current of the ion-electron emission from the surface of the MP is given by:

$$I_s^{i-e} = \delta_s^{i-e} I_i . \quad (7)$$

Using (3) and (7) for ease, we assume that on the surface of the MP the effective current flows.

$$I_i^{eff} = I_i + I_s^{i-e}. \quad (8)$$

Expression for the current of the secondary electron-electron emission has a similar form:

$$I_s^{e-e} = I_e^{fl} \delta_s^{e-e}, \quad (9)$$

where δ_s^{i-e} is the secondary electron yield. By analogy with ion current, we introduce an efficient electron current:

$$I_e^{eff} = I_e^{pl} + I_e^{fl} - I_s^{e-e} . \quad (10)$$

The floating potential of the MP is determined by equating the currents (8) and (10) on its surface:

$$I_e^{eff}(\varphi_a) + I_i^{eff}(\varphi_a) = 0 . \quad (11)$$

The potential of the particle and its charge are related by the following equation:

$$Q_{mp} = a \cdot \varphi_a . \quad (12)$$

Equation (11) was solved numerically. The results of this solution are shown in Fig. 2.

From the figure follows, that interval of energies of the electron flow, where the MP has the positive charge and potential, exists. This interval corresponds to the energy of the electron flow, where the secondary yield δ_s^{e-e} greater than unity.

The maximum value of the charge of the MP in the energy interval $\varepsilon_1 > \varepsilon_e^{fl} > \varepsilon_2$ is determined by the energy of the secondary electrons.

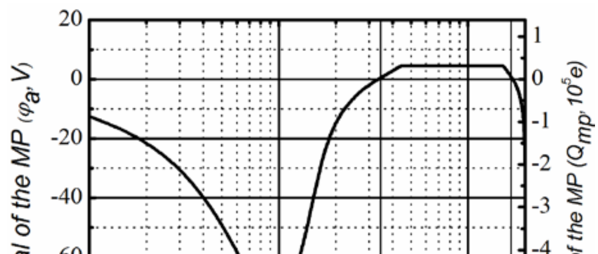

Fig. 2. Dependence of the potential and charge tungsten MP versus the energy of the electron flow
($n_0 = 10^{11} cm^{-3}$, $T_e = 3eV$, $\varepsilon_i^{fl} = 25eV$)

2. MOTION OF THE MACROPARTICLES IN A CURVED FILTER

Plasma in a magnetic filter is transported through a duct which is a part of the torus, therefore for description of the motion of the MP in duct it is advisable to introduce the toroidal coordinate system (r, ξ, θ) with an axis of symmetry O_1 (Fig. 3,a). Let us consider the forces that determine the trajectory of the MP in the filter, depending on its parameters (size, velocity). It is known that in the plasma duct of the magnetic filter a radial electric field exists due to space charge and applied positive potential to the wall of the plasma duct (see Fig. 1) [3]. The magnetic filter operating principle is that the MP moves rectilinearly, in contrast to ion flow, and therefore has to deposit on the wall. However, if the MP has a positive charge, that is possible, as shown above, due to the effect of secondary electron-electron emission, then Coulomb force acts on the MP towards to the axial line of the duct O_2 (Fig. 3,b). As a result MP can be retained inside the duct. Besides the Coulomb force when the MP moves along the axial line of the torus, the centrifugal force directed away from the axis O_1 of the torus acts on it.

In order to determine the conditions when retention of the MP inside the filter is possible, let us consider the laws of conservation of energy as well as of conservation of angular momentum. We consider the case when there is no azimuthal motion of the MP, i.e. when $v_\xi = 0$. The law of conservation of energy in this case has the form:

$$E_0 = \frac{M_{mp} v_0^2}{2} + U(r_1) = U(r) + \frac{M_{mp} v_\theta^2}{2} + \frac{M_{mp} v_r^2}{2}, \quad (13)$$

where M_{mp} is the mass of the MP, v_θ and v_r are θ and r components of velocity respectively and $v_{\theta 0}$ and v_{r0} their initial values, $v_0^2 = v_{\theta 0}^2 + v_{r0}^2$, $U(r_1) = Q_{mp}\varphi(r_1)$, r_1 is the distance from the point of formation of the MP to the axial line of the plasma duct O_2, $\varphi(r_1)$ is the potential at the point of MP formation, r is the current distance from the MP to the axial line of the plasma duct.

The law of conservation of angular momentum in our case has the form:

$$M_{mp} v_\theta R = M_{mp} v_{\theta 0} R_1, \quad (14)$$

where R_1 is the distance from the axis O_1 to the MP in point of it formation, R is the current distance from the axis to the MP. From the law of conservation of angular momentum (14) we find the longitudinal velocity of the MP:

$$v_\theta = v_{\theta 0} \frac{R_1}{R}. \quad (15)$$

Taking into account (15) the law of conservation of energy (10) takes the form:

$$E_0 = U(r) + \frac{M_{mp} v_{\theta 0}^2}{2} \left(\frac{R_1}{R} \right)^2 + \frac{M_{mp} v_r^2}{2}. \quad (16)$$

MPs are retained inside of the plasma duct when the condition $v_r = 0$ in the range $r < r_0$ is true, so the equation that determines the boundary of the MP motion inside of the plasma duct has the form:

$$E_0 = U(r_0) + \frac{M_{mp} v_{\theta 0}^2}{2} \left(\frac{R_1}{R_1 + r_0} \right)^2, \quad (17)$$

where $U(r_0) = Q_{mp}\varphi(r_0)$ is the potential on the wall of the plasma duct.

After simple transformations, the condition (17) takes the form:

$$E_0 \left(1 - \frac{v_{\theta 0}^2}{v_0^2} \left(\frac{R_1}{R_1 + r_0} \right)^2 \right) = Q_{MP}\varphi(r_0). \quad (18)$$

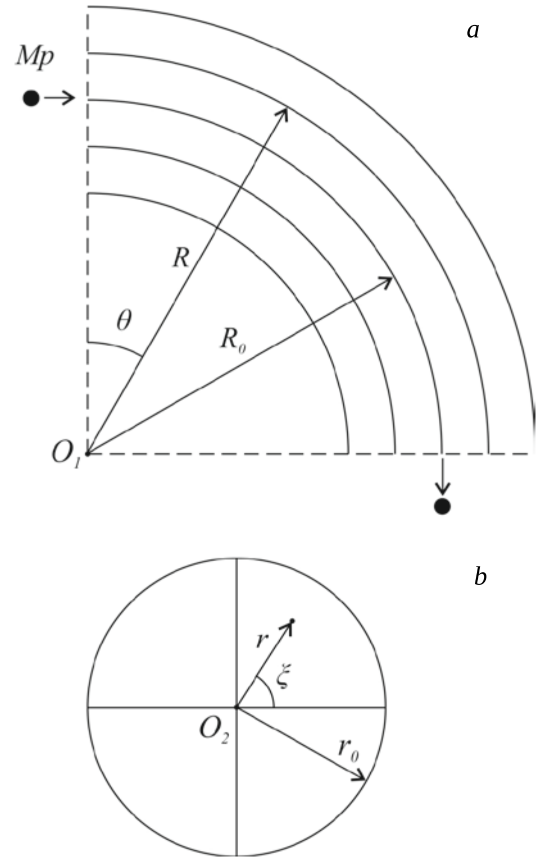

Fig. 3. The coordinate system is in the curvilinear filter. R_0 and r_0 are major radius and minor radius of the torus respectively

The main problem now is to determine from (18) the parameters of the particles that can be retained in the plasma duct. These parameters are the initial velocity of the MP and its size. Based on this the equation (18) was solved numerically for several substances. Fig. 3 shows the results of the numerical solution of equation (18) for tungsten particles in the two extreme cases when the velocity vector is directed normally to the plane of the cathode (in this case $v_{r0} = 0$), and the case when the velocity vector is directed at a small angle to the surface of the cathode (in this case $v_{\theta 0} = 0$).

The curves shown in Fig. 4 determine boundary of the parameters (velocity of the MP and its size) that separates the MPs into two groups: MPs that pass through the filter and MPs that are deposited on its walls. MPs parameters of that are below the curves pass through the filter and accordingly, MPs with velocities and sizes from the region above the curves are deposited on the walls of the filter.

Thus by comparing the results of calculations presented in the paper with data of experimental observations [3] we can see that in the plasma flow formed by stationary arc the MPs that can pass through the magnetic filter are present. The calculations carried out for particles of other materials differ from those calculations insignificantly.

It should also be noted, that even the MP, whose energy is sufficient to overcoming the potential barrier, at collision with the wall of duct can not only to subside but reflected from it also (elastically or inelastically).

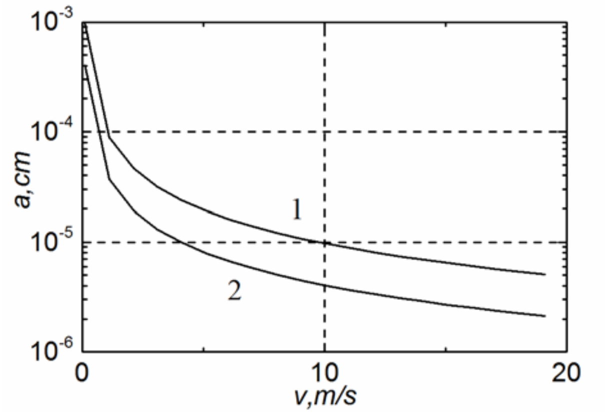

Fig. 4. Dependence of the critical size of the tungsten MP versus its initial velocity (1 – $v_{r0} = 0$; 2 – $v_{\theta 0} = 0$)

As a result of the collision the direction as well as the value of speed is changed, so the favorable conditions for the further transportation of MP may be created.

CONCLUSIONS

It was found that the MPs which formed during the operation of stationary vacuum arc plasma sources can be positively charged due to the effect of secondary electron-electron emission as a result of their interaction with the electron flow that is formed on the substrate.

The main processes that determine the trajectory of the positively charged MPs in the curved plasma duct are the interaction MP with the radial electric field which created by a negative space charge as well as centrifugal repulsion. Coulomb force turns the MPs so that its moves along a curved path in plasma duct and can be trapped in the potential well and then transported to the substrate. The conditions on the size and initial velocity of the MPs that can pass through the magnetic filter are determined.

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ДИНАМИКА МАКРОЧАСТИЦ В МАГНИТНЫХ ФИЛЬТРАХ ВАКУУМНО-ДУГОВЫХ ИСТОЧНИКОВ ПЛАЗМЫ

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Изучена возможность транспортировки заряженных макрочастиц (МЧ) через магнитный фильтр. Показано, что при движении МЧ в криволинейном магнитном фильтре они могут заряжаться как положительно, так и отрицательно. При условии существования радиального электрического поля в плазмоводе происходит изменение траекторий заряженных МЧ. Установлено, что положительно заряженные МЧ могут быть удержаны в плазмоводе в зависимости от их параметров и параметров плазмы. Получены условия, определяющие транспортировку МЧ через фильтр.

ДИНАМІКА МАКРОЧАСТИНОК У МАГНІТНИХ ФІЛЬТРАХ ВАКУУМНО-ДУГОВИХ ДЖЕРЕЛ ПЛАЗМИ

О.А. Бізюков, Д.В. Чібісов, О.Д. Чібісов, О.В. Ромащенко, В.В. Коваленко

Вивчено можливість транспортування заряджених макрочастинок (МЧ) через магнітний фільтр. Показано, що при русі МЧ у криволінійному магнітному фільтрі вони можуть заряджатися як позитивно, так і негативно. За умови існування радіального електричного поля в плазмоводі відбувається зміна траєкторій заряджених МЧ. Встановлено, що позитивно заряджені МЧ можуть бути утримані в плазмоводі залежно від їхніх параметрів та параметрів плазми. Отримано умови, що визначають транспортування МЧ через фільтр.