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MECHANISMS AFFECTING THE SPEED AND DIRECTION OF VACUUM ARC CATHODE SPOTS MOVEMENT IN A MAGNETIC FIELD

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Based on the known experimental and theoretical data, a new model of the plasma jet, which emit by cathode spot (CS) along the magnetic field proposed. According to this model, the plasma jet contains an oppositely directed current of accelerated ions of the cathode material with an excess positive charge and a current of accelerated electrons with an excess negative charge, between which an electric field of polarization of the plasma jet formed. Based on this model, the basic parameters of the plasma jet from the external parameters of the magnetic field, the arc current, and the average charge state of the ions calculated. The main mechanisms affecting the speed and direction of movement of the arc CS on the cathode end surface clarified for the first time.

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INTRODUCTION

Vacuum-arc cathode plasma of electric arc discharge is one of the most amazing and currently most used objects for the synthesis of various strengthening coatings. An arc discharge is characterized by the formation on the surface of the cathode of very small non-stationary cathode spots (CS), the surfaces of which emit plasma jets that concentrate very high current and power densities at a relatively low cathode fall of the potential (~ 20 V), which fluctuates [1]. The main mechanism of arc discharge excitation is the creation of collective emission processes on the cathode surface, regardless of the absolute values of current and voltage [2, 3]. These processes can be thermo emissive or determined by a strong electric field. Nonlinear enhancement of thermo ion and field emission can also lead to the well-known thermal field emission (TFE) [1].

The places where this happens can evaporate with an explosion, which leads to the appearance of a new form of electron emission, which is not stationary in nature, since the place of emission changes explosively. This non-stationary form of emission is so-called explosive electron emission (EEE). EEE requires a minimum of action, which need to invest in the "quantum" of the explosive process, the so-called ecton.

The ignition of the emission center is not just the ignition of an arc discharge it is a constant mechanism of the existence of an arc discharge, based on the existence of local places of electron emission from the surface of the cathode with a low work output. In these places, as a rule, local energy input, this leads to EEE. This stage of the emission is the basis of the "ecton" model developed by Mesyats and co-authors [4, 5]. According to the ectons model [4, 6, 7], thermal acceleration occurs on micro protrusions until they explode with a delay associated with the action of the material. The explosion also creates plasma of the cathode material, as the result of the rapid heating of a small volume of this material to a temperature that turns it into a supercritical fluid, which gradually turns into fully ionized plasma without any transition through the classical liquid and vapor phases. At the same time, there is a definite, short-lived state of the cathode material with a high density, which can best of all be described as an imperfect plasma [8].

This plasma, expanding explosively, leaves behind a crater covered with a thin layer of molten cathode material. Subjected to the high explosive pressure of the plasma, the remains of the molten material of the cathode ejected from the explosion crater and quickly cool, forming macro-particles and micro-protrusions that can serve as new ignition points. At least one of them will be the most suitable for thermal acceleration, which leads to the next explosion and creates conditions for the ignition of the next ekton. This transition is extremely fast, shorter than 1 ns, and can occur only at the beginning of the explosive stage of a new emission region.

Material in this region reaches a maximum temperature and, due to the extreme pressure gradient in the environment expands and cools. As the dense non-ideal plasma of the cathode material expands, it becomes weakly non-ideal and with further expansion, after about 10 ns, the plasma density decreases so much that the frequency of collisions drops to the level at which the condition of equilibrium violated. The plasma enters a non-equilibrium state, which plays an important role when considering the properties of the plasma in the inter-electrode space.

In the process of the transition of the plasma to the non-equilibrium state, the plasma ions accelerate to supersonic speeds [9, 10-14]. At the same time, need to note, that after the end of the explosive stage of the development of the emission center in the CS, begins the next quasi-stationary stage, in which continues the emission of electrons from the molten metal layer of the newly created crater. The cathode material evaporates from the surface of this crater and ionizes very close to the cathode surface due to the intense electron beam formed in the thin cathode layer. Electrons in this beam have an energy corresponding to the cathode fall (about 20 V), and its current density is determined by field-enhanced thermo electron emission.

Most of the ions returning to the cathode formed as the result of electron-atom interaction in the relaxation zone of the electron beam in the immediate vicinity of the cathode surface [15]. Accelerated by the electric field in the cathode layer of the potential fall, these ions bombard the molten surface of the newly created crater, which sputtered with the formation of macroparticles. At the same time, need to note, that under the influence of thermal conductivity, the area, that emits electrons, expands and its temperature gradually decrease. These leads to a decrease in the density of the electron beam, which, in the final stage, is not sufficient for ionization of vapors of the cathode material in the cathode layer.

Despite the lower cathode surface temperature and lower electrical voltage, this stage can be important for the overall cathode erosion because the hot surface can still deliver metal vapors, especially when the cathode material has a high vapor pressure [16].

Numerical modeling using a time-dependent two-dimensional hydrodynamic model showed that the distribution of the ion current on the cathode at the end of the explosive stage of the emission site is circular, and not a peak in the center of the emission site [17, 18]. The same distribution of the ion current on the cathode can assumed and for the fractal model of the CS, in which the CS contains many emission centers that are concentrated on the periphery of the CS.

In the absence of a transverse magnetic field, any places on the edge of newly created craters around the CS can equally likely turn into new active places of emission. At the same time, in the presence of a magnetic field with a transverse component at the location of the CS, the ring symmetry of the formation of emission centers around the CS is broken. It, as is known [19, 20], causes the movement of the CS in the direction of the most likely ignition of new emission areas of spots 2-th type.

At first glance, this seems fair, but it causes a contradiction in that the CS will move in the most likely places of ignition of emission centers around the CS according to the acute angle rule. According to literature data, this rule declares that the CS during its retrograde movement across the tangential component of the magnetic field on the cathode surface shifts toward the maximum of the tangential component of the magnetic field on the working surface of the cathode. That is in the direction of the acute angle between the working surface of the cathode and the force lines of the magnetic field, which cross this surface. As a result, the cathode surface erodes in such a way that the force lines of the magnetic field eventually become perpendicular to this surface. It would seem that in this case the CS should move across the working surface randomly without any definite direction. However, as experiments show, this is not the case. The directionality of the predominant speed of the CS movement is preserved. This indicates that the existing concepts of controlling the movement of the CS along the working surface of the cathode only by the magnetic field do not allow fully identify the mechanisms affecting the speed and direction of this movement.

The purpose of this work is to identify the main existing mechanisms that affect the speed and direction of CS movement on the cathode surface in the case when the force lines of the magnetic field cross this surface at right angles, as well as to identify conditions that effectively increased the deposition rate of coatings.

1. THEORETICAL ESTIMATIONT OF THE PARAMETERS OF THE VACUUM-ARC PLASMA JET

In order to ignite a vacuum-arc discharge, it is necessary that initial plasma of a certain density and temperature have to be creating near the surface of the cathode, which has the places with a low work output. As mentioned above in these places, as a rule, local energy input, which leads to EEE (ecton). The EEE creates plasma of the cathode material, as the result of the rapid heating of a small volume of this material to a temperature that turns it into a supercritical fluid, which gradually turns into a fully ionized plasma high density. This plasma explosively expansions and accelerates ions along the magnetic field to supersonic speeds V_i, leaving behind craters.

At the same time, the flow of electrons emitting from the surface of the craters simultaneously accelerates in the same direction to the energy of the cathode drop potential above the EEE site (this is approximately 20 eV). As a result, accelerated flows of ions and electrons directed in one direction along the magnetic field form the plasma jet with oppositely directed electric currents of ions I_i with an excess positive charge Q_i and of electrons I_e with an excess negative charge Q_e.

In addition, it known, that in each of these currents, between charges of the same name, which move in the same direction with the same speed V and are directed perpendicular to the line connecting them, there are forces of magnetic interaction (the forces of attraction) [21], which focus these currents around their axes.

According to the Bio-Savar-Laplace law [21], transverse magnetic fields $\mathbf{H}_T$ form around, the above-mentioned, oppositely directed currents I_i and I_e, which push these currents away from each other by Ampere's force [21]. At the same time, excess opposite electric charges, that accumulated in these electric currents in a result of their separation in a plasma jet, that moving along a non-uniform curvilinear magnetic field, create electric fields with an intensity **E** between them. The force lines of these electric fields are equipotential lines, so they cross the lines of force of the magnetic field $\mathbf{H}_T$, covering these currents, at a right angle.

The total effect of these electric fields between the oppositely directed currents I_i and I_e balance the repulsive Ampere force between them, which is created at a certain distance *a* between these currents.

If two focused and oppositely directed electric currents I_i and I_e are formed in the plasma jet, which can be considered as separate conductors of finite length L >> a, where *a* is the distance between the conductors, then the Ampere force F of repulsion between these currents will be approximately equal to [21]:

$$F = \mu_0 2 I_i I_a L / 4\pi a, \tag{1}$$

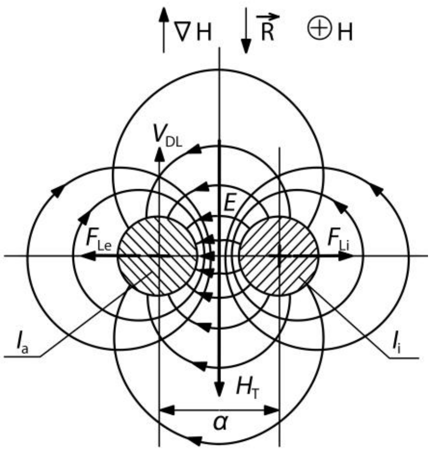
where $\mu_0 = 4\pi 10^{-7}$ Hn/m is the magnetic constant.

Thus, it can be assumed that when the plasma jet of vacuum-arc plasma emitted by the CS along the magnetic field **H** that cross an anode it contains two separated from each other, oppositely directed electric currents I_i and $I_a >> I_i$ with opposite excess electric charges Q_i and $Q_e = - Q_i$.

When the plasma jet hits a metal surface that is not an anode, then according to Kirchhoff's first law, the current of electrons I_e will be equal to the oppositely current of ions $I_i << I_a$ and their excess electric charges $Q_e = - Q_i$. These charges will create an electromotive force (EMF) for the oppositely directed currents I_i and I_e, which ensures their continuity.

On of this assumption, a new model of the plasma jet created. It allows us to adequately estimate its parameters from the intensity of the external magnetic field H_0, the arc current I_a, and the configuration of the magnetic field in the middle of the anode covering this plasma jet.

To explain this model in Figure shows a schematic representation of the cross-sectional structure of a plasma jet emitting CS at a distance from the end of the cathode along the magnetic field, where the electron are became magnetized.



Schematic representation of the cross-section of the plasma jet near the end of the evaporating cathode

In the Figure, $\mathbf{F}_{Le}$ is the Lorentz force acting on electrons; $\mathbf{F}_{Li}$ is the Lorentz force acting on ions. I_e and I_i – respectively, the current of electrons and ions in their cross section; $\mathbf{H}_T$ is the intensity of the transverse magnetic field formed between oppositely directed electric currents I_e and I_i; a – is the distance between the centers of electric currents I_e and I_i; **E** – the intensities of the transverse electric fields formed between the outer surfaces, which cover the electric currents I_e and I_i, respectively, with excess negative and excess positive charges; **H** is the strength of the longitudinal magnetic field in the middle of the plasma jet.

To carry out estimated calculations of the electron density of the plasma inside the plasma jet and in its structural elements, the following assumptions used, that simplify these calculations. It are the following. a) The entire arc currents $I_a \leq 100$ A that passes through one CS. b) The current of accelerated ions along the plasma jet is 10% of the arc current, which corresponds to the experimental results obtained for titanium plasma. c) The density of plasma diffusion flows across the magnetic field is much smaller than once compared to the density of its flows along the magnetic field.

It known that plasma is a diamagnetic medium. This is due to the cyclotron rotation of charged plasma particles around the force lines of the magnetic field, which create magnetic moments of the orbit, μ, the magnitude of which is determined in vector form as [22]:

$$\boldsymbol{\mu} = - (Mv_{\perp}^2 /2H^2)\, \mathbf{H}. \quad (2)$$

Thus, the magnetic induction inside the plasma will be equal to [22]:

$$\mathbf{B} = \mathbf{H_0}\, (1 + 4\pi\chi). \quad (3)$$

Here χ is the magnetic susceptibility of the plasma. Since the magnetic moments of all particles directed against the external field $\mathbf{H}_0$, the magnetic susceptibility χ is negative. It can express in terms of the transverse pressure of the plasma, $P_{\perp}$, held by the magnetic field H_0 [22]:

$$\chi = P_{\perp}/\mathbf{H}_0. \quad (4)$$

If the transverse pressure of the plasma inside the plasma jet is $P_{\perp}$ equal to the pressure of the external magnetic field, which is equal to $H_0^2/8\pi$, then the induction of the magnetic field **B** inside the plasma jet will be equal to $\mathbf{B} = \mathbf{H}_0/2$.

From the condition of equilibrium of the transverse pressure of the plasma $P_{\perp}$ inside the plasma jet and the external pressure of the magnetic field with the intensity $\mathbf{H}_0$, it is possible to estimate easily the maximum density of the plasma and the density of the ion flow along the plasma jet from the following system of equations.

$$P_{\perp} = n_e kT_e + n_i kT_i + \mathbf{H}_0^2/16\pi = \mathbf{H}_0^2/8\pi. \quad (5)$$

To take in account that $T_e = T_i$ and $n_e = n_i Z$

$$n_i = \mathbf{H}_0^2/16\pi kT_e\, (Z+1), \quad (6)$$

$$j_i = I a\Lambda/s_i = Zen_iV_i, \quad (7)$$

or from (7)

$$n_i = I_a\Lambda/s_iZeV_i, \quad (8)$$

where j_i, e, n_e, n_i, Z, and T_e are, respectively, the average ion current density in the plasma jet, the electron charge, the density of electrons, the ion density, the average charge state of ions and the electron temperature of the plasma; k – Boltzmann's constant; I_a, and s_i – are the arc current and the cross-sectional area of the jet through which the electric current of accelerated ions passes, and V_i – the average speed of accelerated plasma ions along the magnetic field, respectively; Λ – is the value of the plasma ion current along the plasma jet relative to the arc current.

Equating (6) and (8), we find the value of the cross-sectional area of the plasma jet s_i from the magnetic field strength and the arc current in the plane of its intersection across the magnetic field **H** for that part of it where the current carry by accelerated ions:

$$s_i = 16\pi Ia\Lambda kTe(1+1/Z)/(\mathbf{H}_0^2 eV_i). \quad (9)$$

By substituting the values of s_i from (9) into (7), we obtain the value of the average ion current density j_i in the plane of the given cross section of the plasma jet:

$$j_i = \mathbf{H}_0^2 eV_i/16\pi kT_e\, (1+1/Z). \quad (10)$$

It seen from relations (6), and (10) that the density of the plasma and ion current in the cross-sectional plane of the plasma jet do not depend on the arc current passing through the CS, but are depends mainly on the square of the intensity of the external magnetic field $\mathbf{H}_0$ in this cross-sectional plane. As can be seen from relation (9), the cross-sectional area of the plasma jet s_i varies as I_a and Λ and is weakly dependent on Z. Therefore, the coating deposition rate in the cross-section of the plasma jet also changes depending on these parameters, other things being equal. Similarly, we obtain expressions for n_e, s_e, and j_e for the second part of the plasma jet, in which the electric current carried exclusively by electrons accelerated in the cathode layer of this jet. These expressions have the following form:

$$n_e = \mathbf{H}_0^2/16\pi kT_e\,(1+1/Z), \quad (11)$$

$$s_e = 16\pi I_a kT_e\,(1+1/Z)/(\mathbf{H}_0^2 eV_e), \quad (12)$$

$$j_e = \mathbf{H}_0^2 eV_e/16\pi kT_e\,(1+1/Z), \quad (13)$$

where V_e is the speed of electrons accelerating in the cathode layer of this jet.

When comparing expressions (9) and (12), it seen that the cross-sectional area of the ion current is approximately in Λ times smaller than the cross-sectional area of the electron current, at least near the cathode surface end.

Substituting in (6) the value of the plasma electron temperature T_e in the plasma jet, which usually does not exceed 3 eV, can easy to estimate the minimum average density of plasma in the plasma jet from the intensity of the external magnetic field from the expression:

$$n_i = 0.83 \cdot 10^{10}\mathbf{H}_0^2/(Z+1). \quad (14)$$

Substituting in (10) additionally the value of the average ions speed movement Vi in the plasma jet along the magnetic field, which, according to experimental data, is on average equal to $1.5 \cdot 10^4$ m/s [23], can easy to estimate the minimum average density of the ion current in the plasma jet from the expression:

$$j_i = 0.995 \cdot 10^{-3}\mathbf{H}_0^2/(1+1/Z). \quad (15)$$

As an example, the table shows the calculated average values of the plasma density, ion current density and the cross-sectional area of the plasma jet at I_a = 100 A and Λ = 0.1 for two fixed values of the magnetic field: H_0 = 500 E and H_0 = 100 E near the cathode surface end.

Main parameters of the ion current of the plasma jet from the magnetic field strength H_0

H_0, Oe	n_i, cm^{-3}	j_i, A/cm^2	s_i, cm^2
500	$2.08 \cdot 10^{15}$/ (Z +1)	497.6/(1+1/Z)	$3.22 \cdot 10^{-2}$/ (1+1/Z)
100	$0.83 \cdot 10^{14}$/ (Z +1)	20/(1+1/Z)	0.8/(1+1/Z)

The results obtained are necessary for elucidating the main mechanisms affecting the speed and direction of the CS movement on the cathode end.

2. ADDITIONAL PARAMETERS OF THE PLASMA JET OF THE VACUUM-ARC DISCHARGE

The solution of the problem aimed at increasing the speed of the CS arc movement on the surface of the evaporating cathode is of urgent importance, since it ensures a decrease in the droplet phase in the erosion products of the cathode material, which occurs during its evaporation from the emission centers of the CS. It assume that this can be achieved by simultaneously increasing the probability of ignition of new emission centers near the CS and the rate of suppression of still active emission centers in the area of this CS. To implement this idea, it is necessary to consider in more detail the parameters of the plasma jet and its structural elements, which can affect the speed and direction of CS movement on the surface of the evaporating cathode, depending on the parameters of the magnetic field and the arc current.

Electrons moving along the magnetic field in the plasma jet can reach the anode in two different ways, which depend on the configuration of the magnetic field.

The first path of electrons from the cathode to the anode in a magnetic field is a direct path. It is realized when the force lines of the magnetic field, along which the plasma jet emanating from the CS spreads, simultaneously cross the surfaces of the cathode and anode. As a result, the current of the vacuum arc discharge between the cathode and the anode I_a is provided, mainly, by the electronic current of thermal electrons, which are accelerated along the magnetic field by the external electric field. This field creates by the power source of the vacuum arc discharge between the cathode and the anode.

At the same time, the bipolarity of plasma jet provides separately by currents of accelerated ions I_i with an excess positive charge Q_i and electrons I_e with an excess negative charge Q_e. But in order to maintain excess charges, in the currents at a certain level, the magnetic field must be divergent, which is characterized by a transverse gradient directed from the axis of the cathode, as well as by the radius of curvature of the force lines of the magnetic field along which the plasma jet spreads. In this case the bipolar structure of the plasma jet is supported as a result of the constant distribution of electric charges in the plasma jet, which occurs in a non-homogeneous, in particular, in a divergent, curvilinear, magnetic field, which causes a gradient and centrifugal drift of magnetized electrons across the magnetic field relative to slow-moving, non-magnetized, ions [22].

It should also note that the plasma through which these currents pass retains its quasi-neutrality, which violate only at the boundaries of these currents. Therefore, an excess negative charge Q_e accumulates at the boundary of the electron current I_e, and an excess positive charge $Q_i = -Q_e$ accumulates at the boundary of the ion current I_i. These charges form transverse electric fields $\mathbf{E}$ between the boundaries of these currents, which provide an electric force of attraction between these currents.

If the plasma jet falls on the anode, then electric currents I_i and $I_e = I_a$ also fall on the anode, which significantly reduces the coatings deposition rate from accelerated ions of the cathode material on another surface that is not the anode. As a result, the coatings deposition rate from accelerated ions will depend only on the rate of their diffusion from the plasma jet across the magnetic field **H** toward the axis of the cathode. At the same the validity of the quasi-stationary and final stages of the development of the CS emission centers are simultaneously increasing.

The increase of these terms occurs as the result of the direct outflow of accelerated electrons from the electric current I_a to the anode that increase the cathode potential drop between the cathode and the plasma of the plasma jet. It will lead to an increase in I_e from $I_e = I_i$ to the full current of the arc discharge $I_a >> I_i$, which, respectively, will increase the heating temperature of the cathode surface, which emits electrons. In this case will significantly increase the evaporation rate of the cathode material with the formation of macroparticles.

In the case, when the plasma jet spreads along the force lines of the magnetic field, that do not cross the anode, then to ensure the arc current on the anode, the intensity of the electric field of polarization of the plasma jet **E** is of great importance. This electric field will ensure the drift current of electrons from the plasma jet to the anode across the magnetic field **H**. The density of this drift current $\mathbf{J}_{De}$ is calculated from the well-known expression [22]:

$$\mathbf{J}_{De} = en_e\,[\mathbf{EH}]/H^2, \qquad (16)$$

where n_e is the average plasma density in the plasma jet between its electric currents I_i and I_e.

In addition, thanks to this drift of the electrons the polarization electric field **E** of plasma jet will strengthen by the external electric field, which will penetrate into the middle of the plasma jet along the electric field of the **E** from the anode side. As a result, the $\mathbf{J}_{De}$ electron current density to the anode across the magnetic field **H** will increase accordingly. The total current of electrons to the anode I_a along the entire length of the plasma jet L, taking into account (19), can be approximately calculated from the following expression:

$$I_a = aL\mathbf{J}_{De}, \qquad (17)$$

where a is the distance between oppositely directed electric currents I_i and I_e, in the middle of the across section of the plasma jet (see Figure).

At the same time, the electric current of accelerated ions I_i can fully use for the deposition of coatings, and the electronic current of accelerated electrons I_e, upon reaching the surface of the coating deposition will provide a negative potential on it. As a result, the density of electron currents from the emission centers of the CS will decrease. It will ultimately lead to a decrease in the temperature of their surfaces, as quickly as possible, and a complete cessation of the creation of vapor phase of the cathode material with the formation of macroparticles.

If the speed of accelerated electrons in the electron current I_e is equal to $\mathbf{V}_e$, then the geometric sum of the Lorentz forces acting on all the electrons accelerated in this current, $\mathbf{F}_{Le}$, (see Figure) will be equal to:

$$\mathbf{F}_{Le} = en_e s_e\,[\mathbf{V}_e\,\mathbf{H}_T]. \qquad (18)$$

Under the action of this force, all electrons accelerated along the magnetic field **H,** will move across the magnetic field **H** with the drift speed $\mathbf{V}_{DL}$ (see Figure), which calculated from the known expression [22]:

$$\mathbf{V}_{DL} = [\mathbf{F}_{Le}\,\mathbf{H}]/eH^2 = -s_e\,[\mathbf{J}_e\mathbf{H}]/H^2. \qquad (19)$$

If the current of accelerated electrons I_e and the ion current of accelerated ions I_i, which are separated from each other by a distance a, pass through the plasma jet along the magnetic field **H**, then the rotation frequency $\mathbf{\Omega}_e$ of the electron current I_e around the ion current I_i with non-magnetized ions will be equal to:

$$\mathbf{\Omega}_e = \mathbf{V}_{DЛ}/a = -s_e[\mathbf{J}_e\mathbf{H}]/aH^2. \qquad (20)$$

According to the directions $\mathbf{F}_{Le}$ and **H**, indicated in Figure, the direction of rotation of the electron current I_e around the ion current I_i with non-magnetized ions will be clockwise. At the same time, the vector of the maximum electric field of polarization of the plasma jet **E** formed between the oppositely directed electric currents I_i and I_e, respectively, with excess positive charge Q_i and excess negative charge Q_e, will also rotate with the same frequency $\mathbf{\Omega}_e$ around the ion current I_i. As a result, the direction of CS movement along the cathode surface towards the positively charged part of the plasma jet will also change with the same frequency $\mathbf{\Omega}_e$.

Thus, the CS, moving against the electric field of the polarization of the plasma jet **E**, will constantly change its direction of movement synchronously with the change in the direction of this electric field, which, on average, will ensure the uniform movement of the CS along the surface end of the evaporating cathode, along a cycloid trajectory. Such movement of the CS will ensure uniform erosion of the cathode over its entire evaporating surface.

CONCLUSIONS

For the first time was assumed, that the plasma jet of a vacuum-arc plasma contains oppositely directed currents of the accelerated ions of the cathode material with an excess positive charge and of accelerated electrons with an excess negative charge, between which an electric field of polarization of the plasma jet is formed.

Based on this assumption, a new model of the plasma jet proposed for the first time. This model allows adequately estimate its parameters from the configuration and intensity of the external magnetic field, the arc current and the intensity of the electric field of the plasma jet polarization.

The calculations were made of electron density of the plasma jet, the density of ion and electron currents along the magnetic field, as well as the maximum transverse diameters of these currents from the external parameters of the magnetic field, the arc current, and the average charge state of the ions in the plasma jet.

It theoretically shown for the first time that the current of accelerated electrons under the action of the total Lorentz force rotates around the axis of the ion current with a frequency inversely proportional to the distance between these oppositely directed currents, which ensures the balance of the forces of magnetic and electric interaction between them. The electric field formed between these currents changes its direction relative to the ion current axis with the same frequency.

It shown that the CS, moving against the electric field of the polarization of the plasma jet, must constantly change its direction of movement synchronously with the change in the direction of the electric field of the polarization of the plasma jet. This, on average, will ensure a uniform movement of CS along the surface end of the evaporating cathode along a cycloid trajectory. Such movement of the CS will ensure uniform erosion of the cathode over its entire evaporating surface.

It theoretically shown for the first time that the highest coatings deposition rate from accelerated ion flows obtained only in a curvilinear magnetic field diverging from the axis of the cathode, at least not crossing the surface of the anode, which covered the bipolar plasma jet. In addition, it shown that in this case the evaporation rate of the cathode material with the macroparticles formation reduced to a minimum.

At the first time, the main mechanisms affecting the speed and direction of the CS movement on the surface end of the evaporating cathode clarified.

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МЕХАНІЗМИ, ЩО ВПЛИВАЮТЬ НА ШВИДКІСТЬ І НАПРЯМОК РУХУ КАТОДНИХ ПЛЯМ ВАКУУМНОЇ ДУГИ В МАГНІТНОМУ ПОЛІ

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На основі відомих експериментальних і теоретичних даних запропонована нова модель плазмового струменя, який емітує катодні плями (КП) вздовж магнітного поля. Згідно цієї моделі він містить протилежно направлені струм прискорених іонів матеріалу катода з надлишковим позитивним зарядом і струм прискорених електронів з надлишковим негативним зарядом, між якими утворюється електричне поле поляризації плазмового струменя. На основі цієї моделі вперше виконані розрахунки основних параметрів плазмового струменя від зовнішніх параметрів магнітного поля, струму дуги та середнього зарядового стану іонів у плазмовому струмені. Вперше з'ясовані основні механізми, що впливають на швидкість і напрямок руху КП дуги по поверхні торця катода, що випаровується.