Pulsed High-Current Vacuum Arc Evaporator for Coating Technologies[1]

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Abstract – Plasma sources based on vacuum arc discharge have an important disadvantage that is a high share of droplets exists in the cathode erosion material. To "cut off" droplets, various kind of bended magnetic filters are used. We have suggested one more approach to reduce droplet content in arc discharge plasma, which is intense evaporation of droplets in a discharge cell caused by ignition of "droplet spots". Penning-type arc discharge cell was recognized to be one providing favourable conditions for ignition of droplet spots. At such a cell, a uniform plasma column is formed, which temperature and concentration are much higher than those of a usual vacuum arc of the same discharge current. Further increase in energy density in plasma of a reflective-discharge cell could be achieved by means of the both increase in discharge current and *B*-field optimisation. The present paper reports results of development and characterisation of a plasma source combining well-known high-current vacuum arc evaporator with a Penning-type discharge cell. It has been recognized that ion current density amplitude at the source output is as high as 800 A/cm^2, plasma density up to 10^{14} cm^{-3}, and electron plasma temperature 6–8 eV. Those conditions lead to intensive evaporation of droplets in fly. Copper film deposition rate was measured to be of 1.5 nm per pulse, which corresponds to instantaneous rate of 2000 nm/s.

1. Introduction

Plasma generators based on the vacuum-arc discharge (the arc evaporators) are used widely in technologies for ion-plasma deposition of coatings [1]. At many advantages that vacuum-arc discharges possess there is a serious deficiency to be a fact that more than half of yields of erosion of the cathode represents the droplet fraction which not only does not participate in plasma generation, but also pollutes it and worsens properties of coatings. The problem of disposal of a plasma flow from droplets in the arc evaporators is solved basically by a separating of plasma from droplets with use of various type curvilinear electrical and magnetic filters (plasma conductors) that inevitably results in the significant losses of intensity of a plasma flow on the filter output. In [2] other approach to a problem of disposal of plasma flow from droplets has been explored, which is intense evaporation of droplets in flight by means of initiation of "droplet spots" on them. As it has been shown, requirements for initiation of the droplet spots and evaporation of droplets can be realized at rather low-current (< 200 A) vacuum arc burning in a Penning-type discharge system. At such discharge the column of plasma is formed which has essentially greater temperature and electron density than at burning of a usual vacuum arc at the same current. The further increase of energy input in plasma column is possible by increasing of a current up to a level of high-current plasma sources [3, 4]. In the offered evaporator integration of known type of a high-current plasma source with the Penning-type discharge system is realized to form a power intense plasma column of reflective discharge.

2. Design of the evaporator

The sketch of the evaporator is shown in Fig. 1.

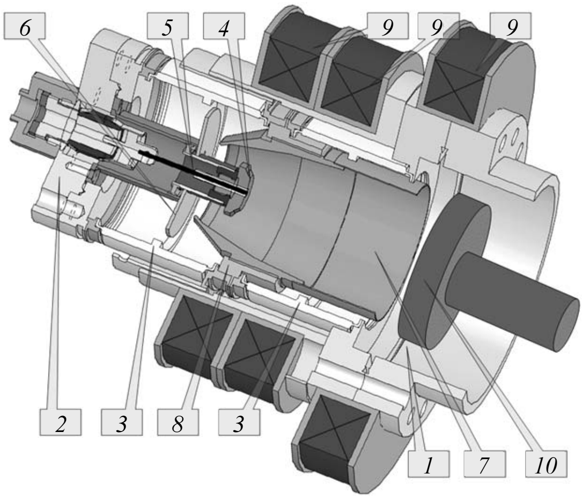

Fig. 1. The design of the evaporator

The evaporator is based on the standard flange CF-100 and blending to a docking flange *1* of vacuum chamber. The cathode unit is based on the standard flange DU-40 *2* joined to flange CF-100 through two standard ceramic insulators *3*. The cathode unit contains the cathode – an insertion *4* which material is used for deposition of the coating, igniting electrode *5*

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inside of a ceramic tube for ignition of the discharge between the cathode and an igniting electrode, and also the shield *6* for a guard of cathode insulator. The anode *7* is fulfilled also in view of necessity of screening of insulator from plasma and connected with an exterior electrical circuit through a ring *8* pairing insulators *3*. Use of two insulators allows doing potential either the anode, or the cathode, or both of an electrode that ensures freedom at sampling regimes of power supplies of the evaporator at its integration in various electrophysical setups. For generate a magnetic field in a discharge cell solenoids *9* are used. The second cathode of reflective discharge is the object table *10* on which substrates are fixed.

3. Power supplies of the evaporator

The diagram of electrical circuit of the evaporator is shown in Fig. 2.

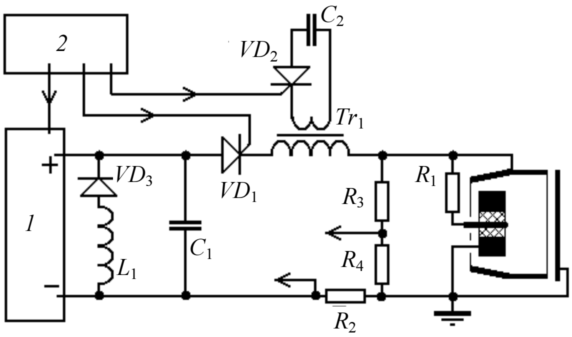


Fig. 2. The basic circuit diagram of the evaporator

The basic discharge circuit represented a low-resistance harmonic *LC*-circuit of an impedance of 0.4 Ohm and a half-period of oscillations 750 μs. It has been formed by capacitance of capacitor battery C_1 and inductance of secondary winding of transformer Tr_1. The battery was charged by of charging unit *1* to voltage V_{ch} = 0.5–2 kV. The thyristor VD_1 was used as the discharge switch. The voltage pulse was applied both to a discharge gap, and, through resistor R_1, to an igniting gap. Such manner of switching on of an igniting gap was used for optimization of duration of an igniting current. In an initial moment the voltage pulse of 25 μs duration from the igniting generator formed by elements C_2, Tr_1, and thyristor switch VD_2 was superimposed on a discharge pulse for improvement of reliability of discharge ignition in the basic discharge cell. Open-circuit voltage of the igniting generator was 5 kV, a peak current (short circuit) – 150 A. The low-resistance harmonic contour formed by L_1 C_1 VD_3 elements was served for recuperation of energy of the battery. For registration of a discharge current and voltage the low-inducting shunt R_2 and resistive divider R_3/R_4 was served, respectively.

External magnetic field of the evaporator was created by solenoids supplied with the separate generator. For control of delays of driving pulses the control unit *2* was used.

4. Technique of experiment

The current in solenoids was half-sinusoidal of 5 ms duration. Initiation of discharge was realized for ~300 μs before reaching amplitude of a current in solenoids. All solenoids have been connected in series and contained a various amount of coils so lines of a magnetic field formed a configuration divergencing from first to the second cathode. The maximum induction of magnetic field B_{max} (at maximum amplitude of a current in solenoids) was ~160 mT in a plane of the first cathode and ~40 mT in a plane of the second cathode.

In experiments the copper cathode of 2.5 cm in diameter was used. Ion-emission characteristics of the evaporator discharge plasma was studying by measuring an ion-saturation current on collectors located behind orifices of 3.3 mm in diameter on the radial positions 0, 8, 16, 24, and 32 mm in the second cathode. The negative bias –50 V was applied to collectors. The distance from the first to the second cathode was made as 14 cm. Deposition rate was measured by a weighting a foil substrates located in central and circumferential regions of the second cathode. Investigation of motion character of cathode spots was carrying out using of high-speed four-channel video-system HSFC-Pro. At that the object table was left, the role of the second cathode was fulfilled with a vacuum chamber wall; the flange opposite to the cathode was equipped with a window.

All experiments were carried out at a residual pressure of ~10^{-7} Torr by using a turbo-pump.

5. Characteristics of the evaporator

In Fig. 3 typical oscillograms of a current and discharge voltage obtained at maximum charge voltage of the battery both in absence and at presence of an external magnetic field are presented.

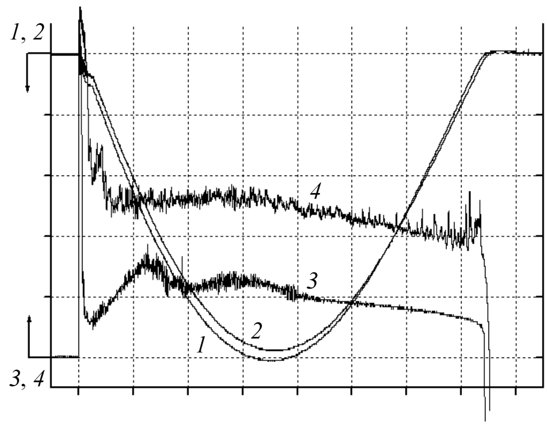


Fig. 3. Oscillograms of a current (*1*, *2* – 1 kA/div) and discharge voltages (*3*, *4* – 50 V/div) in the absence (*1*, *3*) and presence of external magnetic field $B = B_{max}$ (*2*, *4*). Time scale is 100 μs/div; charge voltage V_{ch} = 1.95 kV

The discharge voltage at transition from a usual arc to a reflective discharge mode essentially increased, at that amplitude and a pulse shape of a current varied only inappreciably. Let's note, that in absence of an external magnetic field in process of current increasing in the first 200–300 μs the burning voltage reaches of 60–80 V that essentially exceeds minimum values of discharge voltage (20–25 V). The yielded effect can be related to contraction of a current-carrying plasma flow affected by the intrinsic magnetic field. In order to analyze the influence of an external magnetic field on discharge just a minimum values of discharge voltage were measured. Typical dependence of minimum discharge voltage on an induction of an external magnetic field is presented in Fig. 4.

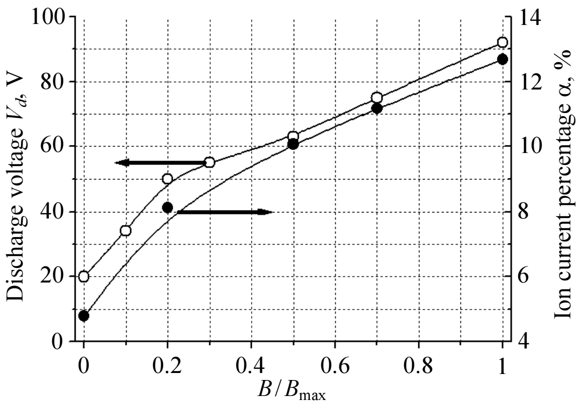
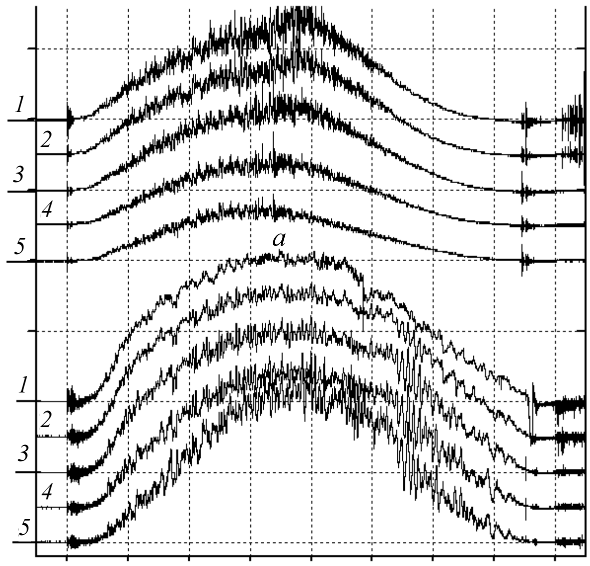


Fig. 4. Dependence of minimum discharge voltage and percentage of ion current on the second cathode relative to a discharge current on an external magnetic field induction. V_{ch} = 0.8 kV (current I_{ampl} = 2 kA)

The dependence well agrees with that obtained by us earlier for a case of rather more low-current (< 200 A) discharge of the same type [2].

In Fig. 5 the typical oscillograms of ion current on collectors located behind orifices in the second cathode are presented. From the presented data it can be shown that at applying of an external magnetic field on the discharge cell an ion current, at first, essentially increases; and secondly, it becomes more homogeneous. Taking into account of the similar data reflecting radial ion current density distribution the overall ion current on the second cathode was reconstructed. For the cases presented in Fig. 5 (discharge current amplitude I_{ampl} = 3.2 kA) the amplitude of overall ion current achieved 210 A at $B = 0$ and 470 A at $B = B_{max}$. For discharge currents I_{ampl} = 3.7 kA and 5 kA the overall ion current at $B = B_{max}$ achieved 570 A and 800 A, respectively. Dependence of a pulse-averaged ion current percentage of a discharge current on a magnetic field induction is presented in Fig. 4. It is shown that ion current percentage increases at transition from usual arc to a reflective discharge mode approximately in 2.5 times. This dependence qualitatively agrees with data presented in [2]. At $B = B_{max}$ the value of ion current achieved 12–13% at a discharge current 2 kA, exceeded 14% at a current 3 kA, 15% at a current 4 kA, and 16% at a current 5 kA (the maximum current produced by basic discharge circuit). Such high values of an ion current testify to high efficiency of ion flow formation on the second cathode. They essentially exceed both measured by us in [2], and even a known magnitude of an overall ion current percentage of vacuum arcs [5]. On the other hand, increase of an ion current percentage in the present experiments qualitatively agrees with the analogous effect, observed by authors of [6].



b

Fig. 5. Oscillograms of an ion saturation current on collectors *1–5* (*a*, *1* – central orifice; *5* – the most-distant from an axis) at V_{ch} = 1.2 kV (I_{ampl} = 3.2 kA) at $B = 0$ (*a*) and $B = B_{max}$ (*b*); 100 μs/div, 0.5 A/div

The deposition rate of a coating measured by the weight method was found close to value of 1.5 nm per pulse at current amplitude of 5 kA and instantaneous deposition rate (at pulse duration of 750 μs) reached 2000 nm/s. These magnitudes surpass the reached in [3, 4].

In Fig. 6 the typical photos illustrating light emission and character of spots motion on the cathode surface are presented. By count of spots number a current per one spot has been determined. It has appeared that it is ~110 A per spot and this value practically does not depend on magnitude of an external magnetic field and amplitude of a discharge current. As shown in investigations with the higher spatial resolution [7], the spot with a similar current represents some "macrospot" consisting of separate fragments, locating on micron distances from each other.

At absence of an external magnetic field cathode spots rapidly run away from the central region forming similitude of a circle, and after 400–500 μs reach a lateral surface of the cathode. The similar effect was observed repeatedly earlier (see for example [4]) and is explained by "anti-ampere" pushing away of cathode spots taking place at interacting their own magnetic fields. As shown, character of motion of cathode spots

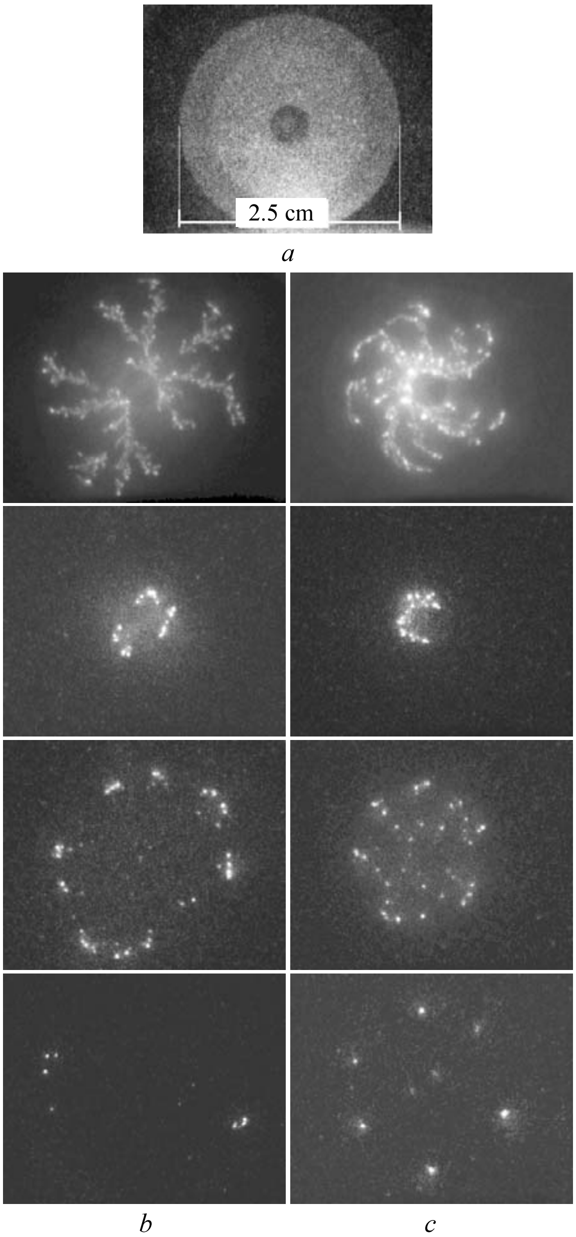


Fig. 6. Photos of the cathode: the reference (*a*) and the four-frame series obtained in individual pulses at V_{ch} = 1.8 kV (I_{ampl} = 4.7 kA) at $B = 0$ (*b*) and $B = B_{max}$ (*c*). The upper frame in series – the shutter open, subsequent frames are of an exposure 10 μs with a delay of 100, 400, and 700 μs from the instant of discharge starts

changes at transition from $B = 0$ to $B = B_{max}$ at that it depends on the cathode shape. On a flat (central) part of the cathode where lines of an external magnetic field are normal to the cathode surface, an external magnetic field reduces slightly the velocity of directional motion of cathode spots. At reaching by spots of the splay part of the cathode a character of motion changes essentially – spots preferentially move in one ("retrograde") direction. At that the trajectory of their motion represents the part of circle. Let's note, that in case of $B = B_{max}$ spots do not reach a lateral surface of the cathode.

6. Conclusion

In this paper, the high-current pulsed vacuum-arc evaporator for deposition of coatings is presented. By measuring density of an ion flow and weight measuring of deposition rate, high efficiency of the evaporator is shown. This evaporator is characterized by high radial homogeneity of a plasma flow and high instantaneous deposition rate. These results were obtained at maximum discharge current of evaporator in which reflective vacuum arc discharge mode is used. It was shown that optimization of a configuration of the cathode, of the anode and an external magnetic field in a discharge cell are of great importance.

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