Functional Materials 15, No.3 (2008)

# Vacuum arc plasma source with rectilinear filter for deposition of functional coatings

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*Received March 18, 2008*

Design and operation principle of a novel vacuum-arc source of filtered erosive plasma are described. The macroparticles are removed from the plasma by transformation of radial plasma streams emitted by the cathode spot of the arc on the side surface of cylindrical cathode, into axial stream by means of "single bottle neck" magnetic field. The efficiency factor of the source is about 3.5 %. The output plasma stream generated by the source in optimum conditions is characterized by highly homogeneous distribution of the ion component density over the stream cross-section about 12 cm in diameter. The growth rate of a carbon coating in a spot of the same diameter attains 35 μm/h at the condensate microhardness up to 150 GPa.

Описаны устройство и принцип действия вакуумно-дугового источника фильтрованной эрозионной плазмы. Очистка плазмы от макрочастиц осуществляется преобразованием радиальных потоков плазмы, эмитируемых катодным пятном дуги на боковой поверхности цилиндрического катода, в аксиальный поток с помощью "однопробочного" магнитного поля. Коэффициент эффективности источника составляет около 3,5 %. Выходной поток плазмы, генерируемый источником, в оптимальных условиях характеризуется высокой равномерностью распределения плотности ионной компоненты по сечению потока диаметром около 12 см. Скорость роста углеродного покрытия в пятне того же диаметра достигает 35 мкм/ч при микротвёрдости конденсата до 150 ГПа.

During the development of ionic-plasma technologies, the vacuum-arc methods of coating deposition and material surface modification gain increasingly wide recognition. This is due substantially to successes in development of means to form pure vacuum-arc erosive plasma [1]. The presence of the cathode material macro-scale particles (MPs) in plasma hindered for a long time the use of unique potentialities of the vacuum-arc methods in the field of high technologies. Today, the most effective means to solve the MPs problem is provided by magnetic filters. Experts of many research centers all over the world are involved in development and improvement of such filters [2]. Both in laboratories and in industry, the filters with curvilinear plasma duct are used most often. However, a relative complexity, unhandiness, and low productivity of the curvilinear filters hinder their large-scale commercialization. So-called rectilinear filters as more simple and, hence, cheaper, could be an alternative for the curvilinear filters though they are a little bit conceding in quality of cleaning of plasma. Boercker, Falabella and Sanders who have developed a plasma source with "dome-shaped" system of coils [3] have attained an appreciable increase in filtering efficiency of the rectilinear filter. However, their device is complex enough in design, and the density distribution of the ion component in the plasma stream at the source output is strongly inhomogeneous. A more simple analogue of the dome-shaped plasma source was proposed before [4]. Data on its characteristics were not published until now. The main performance characteristics of the new source are studied in this work.

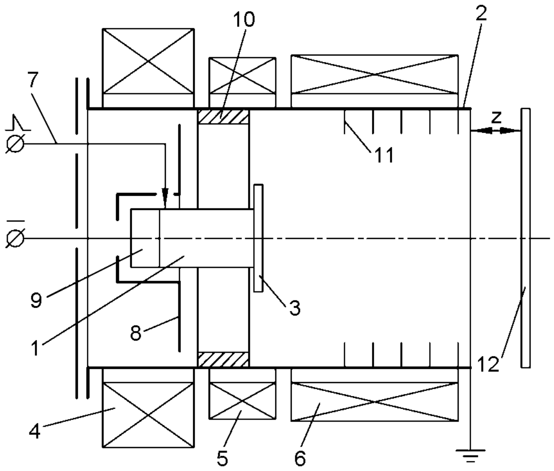

Fig. 1. Experimental plasma source. *1*, cathode; *2*, anode; *3*, shield; *4*, cathode coil; *5* and *6*, anode coils; *7*, trigger; *8*, cathode shield; *9* and *10*, magnetic concentrators; *11*, baffles; *12*, collector/substrate.

The schematic outline of the plasma source being studied is shown in Fig. 1. The source contains a consumable cylindrical cathode *1* of the plasma-forming material and a hollow cylindrical anode *2* made of non-magnetic stainless steel. The cathode diameter $d_c$ is 60 mm, with the working part length $l_c$ of 65 mm. The anode diameter $d_a$ and the length of its working (current-collecting) part $l_a$ are 180 and 230 mm, respectively. The cathode butt face turned to the source output is closed by a molybdenum shield *3* shaped as a disk of $d_s$ = 100 mm in diameter. Its edges form an $h$ = 20 mm ring ledge over the cathode side surface. The specified sizes of the cathode, the anode and the shield provide implementation of the condition

$$h = (d_a - d_c)/2 \ge (d_a - d_c)l_c/2l_a,$$

at which there is no direct line of sight between the output anode aperture and the cathode working surface. This, in turn, excludes the direct hit of the MPs emitted by cathode spot (CS) into the source output aperture. The back butt face of the cathode and walls of the anode are water-cooled (not shown). Magnetic coils (*4*, *5*, and *6*) with adjustable numbers of ampere-turns are placed on the anode, providing magnetic fields on their axes up to 200, 40 and 100 Oe, respectively. The cathode spot of the arc discharge is triggered on the cathode side surface by the triggering device *7* described elsewhere [5]. Near the cathode back butt the ferromagnetic concentrator *9* is placed that strengthens the magnetic field which is pushing out the CS towards the cathode working surface. Around the cathode working surface, the ferromagnetic ring *10* is fixed to the anode walls. The elements *9* and *10* are made of ferromagnetic steel.

The currents in coils of the plasma source generate a magnetic field therein that is stronger at the cathode back butt face (magnetic lines are convergent), and weaker in the anode cavity (Fig. 2). From here on, such magnetic field will be referred to as a "single bottle neck" magnetic field. As a whole, the magnetic field distribution geometry is similar to that in the dome-shaped source [3].

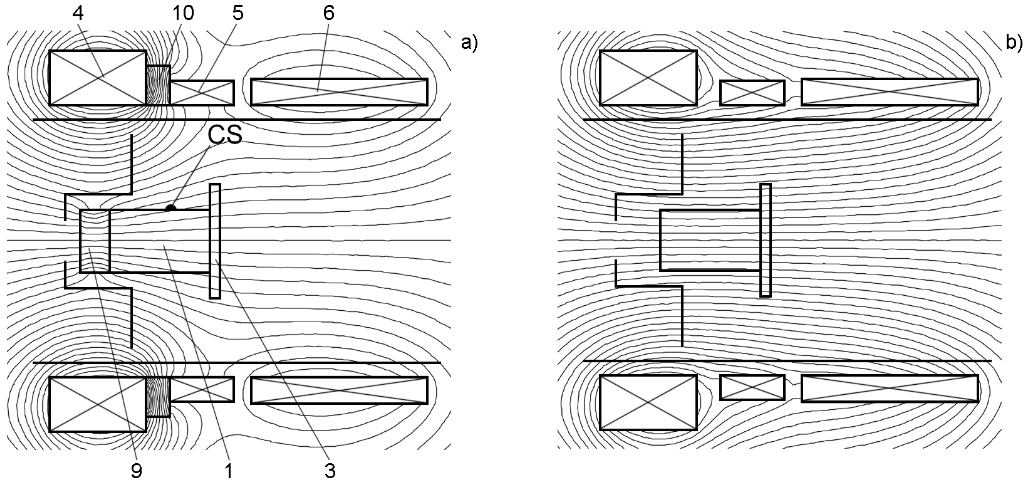

Fig. 2. Magnetic fields in presence of concentrators *9* and *10* and counter-energized coil *5* (a), the same in absence of concentrators and concordant energization of all coils (b).

When a starting pulse is applied to the triggering unit, an arc discharge appears in the gap between the cathode and the anode. An electronic control system (not shown) provides automatic submission of the starting pulse after any spontaneous decay of the arc. Under action of the magnetic field longitudinal component $H_z$, the CS moving chaotically over the cathode surface gets also an ordered velocity component directed across the magnetic field in "anti-ampere" direction (the known phenomenon of CS "retrograde" movements in vacuum), and moves around the cathode axis. At the same time, under action of a magnetic field inclined to the electrode surface, the spot, according to the known "rule of an acute angle", drifts towards the free cathode butt face (with the shield *3*), and under action of its own magnetic field, it is displaced in the opposite direction, towards the current feeder. Finally, the zone of the spot annular movement takes a certain position on the cathode side surface where actions of external and own magnetic fields are counterbalanced. The optimum conditions for pushing the CS out of its initiation zone onto the cathode working surface are provided by counter-energizing of the coil *5* and also by magnetic concentrators *9* and *10* [6]. Thus, a magnetic field is formed in the triggering zone (Fig. 2a) with the lines inclined optimally for "pushing out" the CS as compared to the case where the concentrators are absent and at concordant energizing of all coils (Fig. 2b). The CS travel onto the cathode butt face is prevented by the shield 3: when the spot comes onto the shield ledge, it is returned back onto the cathode cylindrical surface by action of own magnetic field (towards the current feeder). Thus, area of stable CS existence is the part of the cathode side surface between the triggering device and the shield *3*. Being in this area, the CS generates a plasma stream moving towards the anode (along the radius). The magnetic field turns the stream by 90° towards the output butt face of the anode. (The mechanism of a magnetic field influence on partially magnetized plasma in a vacuum arc is described elsewhere (see, e.g., [1]). Thus, ions and electrons are arriving to the source output, while heavy low-charged MPs do not interact with either magnetic or electric fields and, moving rectilinearly from the place of their origin, hit the anode or the ledge of the shield *3*. Some MPs, being in solid state, may ricochet and thus get to the exit of the source and substrate. Traps shaped as a set of thin baffles (*11*) are used often to suppress rebounding MPs (Fig. 2).

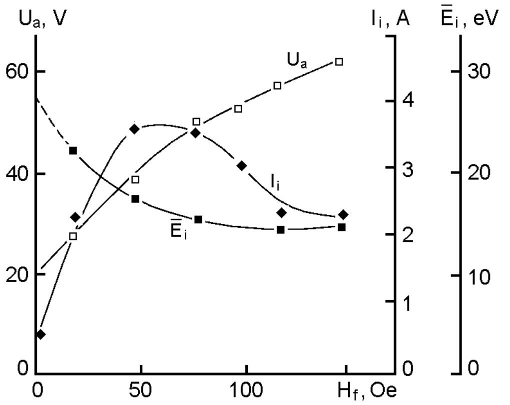

Fig. 3. Output ion current ($I_i$), arc voltage ($U_a$), and average energy of ions ($\bar{E}_i$) depending on a focusing field in the anode ($H_f$); $z = 1$ cm.

The ion component $I_i$ of the output plasma stream was measured using a flat collector of 200 mm diameter. The ion current density $J_i$ distribution over the output plasma stream diameter and along the system axis was determined using a flat probe of 1 cm$^2$ area movable along $x$ (across the stream) and $z$ axes. The average energy of ions was measured by a multigrid electrostatic probe [7]. The relative content of ions with various charges in plasma was determined using the technique described elsewhere [8]. Graphite was used as the cathode material. Preliminary experiments on optimization of the source design were carried out with a titanium cathode because this material provides more stable arc burning of than graphite.

The measured values of the output ion current $I_i$, the arc voltage $U_a$ and average energy of the directed movement of carbon ions $\bar{E}_i$ depending on magnetic field $H_f$ generated at the system axis by the coil *6* are presented in Fig. 3. The magnetic field intensity in the center of coil *4* was 180 Oe, the arc current $I_a$ was supported at 110 A. The dependence of $I_i$ on $H_f$ has a maximum in the 50–70 Oe range. In optimum conditions, the output ion current is about 3.7 A, that corresponds to efficiency factor of the source $\eta = I_i/I_a = 3.4$ %. The increase in the output ion current according to the left part of curve $I_i(H_f)$ is caused by decreasing level of the losses caused by plasma diffusion across the growing magnetic field having a "single bottle neck" geometry (curve *1* in Fig. 4). The current re-

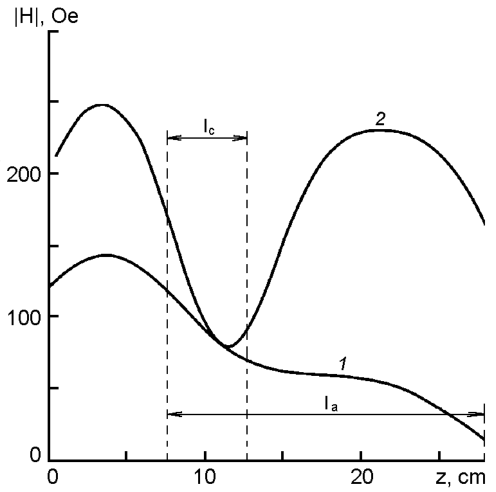

Fig. 4. Distribution of magnetic field intensity along the source at 6 cm distance from its axes (calculation) for an ascending $I_i$. ($H_f$) (*1*) and for descending one (*2*).

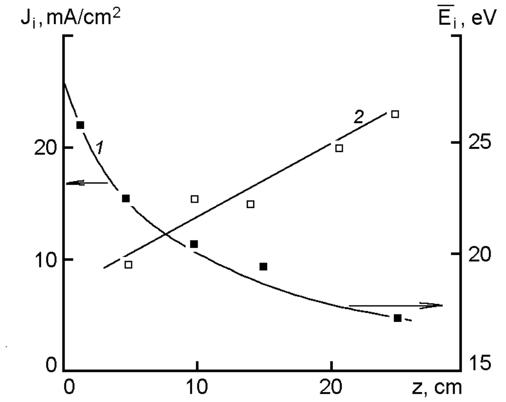

Fig. 5. Ion current density (*1*) and average energy of ions (*2*) depending on distance ($z$) to the output butt face of the plasma source.

duction after the maximum seems to be caused by partial reflection of the stream from the magnetic mirror formed in front of the cathode at a further strengthening of magnetic field (curve *2* in Fig. 4). In the source under study, as well as in other plasma generators with magnetic focusing, the arc voltage rises with $H_f$ increase, with the only difference that this rise occurs with some slowing down. Such a character of $U_a(H_f)$ dependence is caused by presence of zone with a minimum of a magnetic field in the area of current transfer (Figs. 2 and 4). Formation of this minimum is realized by means of ferromagnetic elements 9 and *10* and/or by counter-energizing of coil 5. An appreciable reduction of average ion energy approximately from 24 down to 15 eV was observed with strengthening of magnetic field from 20 up to 70 Oe. That dependence of $\overline{E}_i$ on $H_f$ can be explained by the fact that the angle between the ion velocity vector and the system axis at which the ions can still pass through the anode without contact with the walls, increases with growing magnetic field intensity. The amount of such ions increases with strengthening of magnetic field and average energy of the directed movement of ions decreases with increase of α, since $\overline{E}_i \sim \cos 2\alpha$.

At the same time, the average energy of ions rises monotonously with increase in distance (up to 25 cm) from the output butt face of the source (Fig. 5) because less and less of ions, for which the angle α differs essentially from zero, and longitudinal movement energy from its maximal value, are remaining at the axis of the plasma stream with increasing distance from the source. The ion current density at the system axis decreases exponentially with distance from the source exit: from 22 mA/cm$^2$ at $z$ = 2 cm down to 4 mA/cm$^2$ at $z$ = 25 cm. The steep lowering of the ion current density with distance from the source exit is explainable by the divergence of plasma stream, where the electron component is "rigidly adhered" to a bunch of magnetic lines [1] which quickly diverge outside of the anode.

The measurements have shown that the ion component of the carbon plasma generated by the investigated source, comprises 94 % of singly-charged ions and 6 % of doubly-charged ones. The increased concentration of the doubly-charged ions (as compared to the plasma generated by other sources [9]), seems to be explainable by increased voltage drop in the interelectrode plasma (30–40 V). This circumstance in combination with magnetization of electrons, that causes their movement along intricate trajectories, favors increased probability of additional ionization of the single-charged ions C$^+$ with formation of doubly-charged ions C$^{2+}$ according to the scheme

$$\mathrm{C}^{+} + e \rightarrow \mathrm{C}^{2+} + 2e.$$

Fig. 6 shows the ion current density distributions across the output plasma stream. The condensate deposition rate at the same time is about 35 μm/h within a spot of about 12 cm in diameter. (For comparison, the radial distribution curve of the ion current density at the exit of Boercker's device

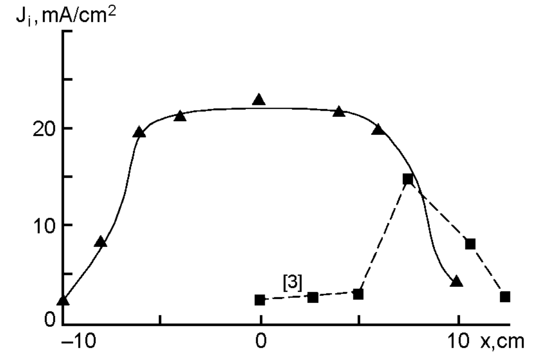

Fig. 6. Distribution of ion current density across the output plasma stream: $x$, distance from the stream symmetry axis; $z$ = 1 cm.

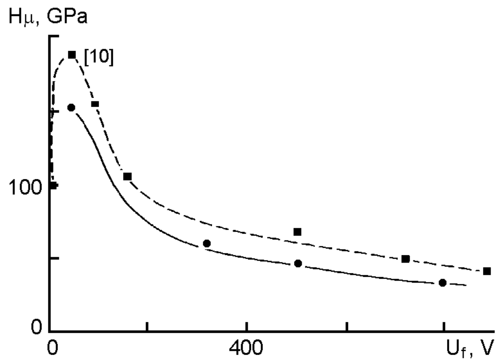

Fig. 7. Microhardness of carbon condensate ($H_\mu$) as a function of HF amplitude ($U_f$) of potential at the substrate.

[3] with a copper cathode is shown in the same Figure). The data cited illustrate a high distribution homogeneity of both $J_i$ and $V$ across the plasma stream. The obtained carbon films are characterized by high microhardness (Fig. 7) though they yield in this parameter to the films deposited using plasma sources with traditional "toroidal" filter [10].

During experiments, a strong inhomogeneity of cathode erosion was observed when it was made of graphite. This is connected, first of all, with low CS traveling speed over the surface of such cathode: the time between two spontaneous decays thus becomes commensurable with the spot detour time around the cathode. As a result, during a significant part of total of arc burning time, the CS is in the area adjoining to the triggering zone where the maximal "burning out" of the cathode occurs. The erosion inhomogeneity, in turn, is a factor defining decreased useful utilization coefficient of the cathode material. With regard to all the said, it seems to be expedient to continue the improvement of the considered plasma source to increase arc stability and useful utilization factor of the cathode material.

To conclude, the studied source is characterized by a high efficiency factor (about 3.5 %) and homogeneous distribution of ion current density across the output plasma stream of up to 12 cm diameter. The source provides deposition of superhard carbon coatings with homogeneous distribution of thickness in the condensation spot of the same diameter. Thus, the main parameters of the source correspond to the best modern level, and the novel device surpasses in design simplicity the conventional plasma sources of similar destination. The cathode erosion inhomogeneity (in case of a graphite cathode) is a disadvantage of the new plasma source. The further optimization of a source is expedient to increase the arc stability and increase in useful utilization factor of the cathode material.

Technical preparation of the equipment for experiments and conducting of all measurements were carried out with participation of V.G.Bren‘.

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# Вакуумно-дугове джерело плазми з прямолінійним фільтром для осадження функціональних покриттів

**І.І.Аксьонов, Д.С.Аксьонов**

Описано будову та принцип дії вакуумно-дугового джерела фільтрованої ерозійної плазми. Очищення плазми від макрочастинок здійснюється перетворенням радіальних потоків плазми, що емітуються катодними плямами дуги на боковій поверхні циліндричного катода, в аксіальний потік за допомогою "однопробкового" магнітного поля. Коефіцієнт ефективності джерела становить близько 3,5 %. Вихідний потік плазми в оптимальних умовах характеризується високою рівномірністю розподілу густини іонної компоненти за перерізом потоку діаметром близько 12 см. Швидкість зростання товщини покриття у плямі того ж діаметра сягає 35 мкм/г при мікротвердості конденсата до 150 ГПа.