PROPAGATION OF ION PLASMA FLOW OF CATHODIC ARC DISHARGE IN HOLLOW CATHODE (STUDY AND THE FIRST RESULTS)

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It is shown that the ion plasma flow originated from cathodic spots of vacuum arc discharge, at its propagation through cylindrical electrode with proper voltage bias, initiates hollow cathode discharge, which is self-sustained and continues its glow after the ion plasma flow blow out. At that, the hollow cathode discharge plasma features (electron density and temperature) are mainly determined by work gas pressure and supplied electrical power. Achieved discharge power and duration could be sufficient for efficient evaporation of microdroplets in the ion plasma flow from vacuum arc discharge without significant loss of ion fraction of the flow.

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INTRODUCTION

Dense metal ion plasma flows, generated by vacuum arc discharges, are a subject of detailed studies due to their ability to provide high rates of various coating deposition with relatively low production cost. However, serious restriction in implementation of such technology consists in a presence of microdroplet fraction which follows the ions flow and degrades the coating quality. For removal of the droplets, usually different filters and separators are used, which deflect ion flow from the droplet one by means of magnetic fields. However, use of the filters often results in significant losses of ion fraction of the filtered flow. At the same time, in a number of practical applications there is no necessity to achieve complete droplet removal from the plasma, and it is sufficient to remove from it major portion of the droplets with dimensions exceeding predetermined limit. Due to that, development of simpler methods of macroparticle removal, which provide orders of magnitude higher rate of coating deposition without complete removal of the microdroplets from the plasma flow, is of essential practical interest. One of such approaches is based on droplet evaporation in the plasma of discharge device which is installed in series with the vacuum arc. For that purpose different discharges are used including reflective arc discharge [1], discharges in crossed electric and magnetic field with closed electron drift inherent to plasma lens configuration [2] and more. Main peculiarity of used discharge types is high plasma density ($n_e \approx 10^{12} \ldots 10^{13}$ cm^{-3}) and moderate effective electron temperature $T_e \approx 4 \ldots 10$ eV.

At the same time, modeling of the microdroplet heating process (see e.g. [3]) has shown that in case of certain materials (Zr, Ti) temperature of the microdroplets essentially depends on T_e. It enables use of discharges with lower plasma density, but with high T_e for heating and evaporation of the microdroplets. The original approach [2] is based on application the cylindrical plasma lens configuration for introducing at volume of propagating along axis's dense low temperature ion plasma flow convergent radially energetic electron beam generated self-consistently by ion-electron secondary emission from electrodes of plasma optical tool. However, this approach implies magnetic field use. To make the design simpler, one can apply hollow cathode discharge for which the presence of fast electrons is natural.

This work presents the results of studies of the hollow cathode discharge (HCD) ignition and glow processes, as well as the influence of the device parameters on the discharge plasma characteristics at the use of vacuum discharges with Ti and Cu cathodes. Choice of the HCD is defined by fact that inherent peculiarity of such discharge plasma is a presence of large number of electrons having energy of tens eV.

1. SET-UP WITH Ti VACUUM ARC

1.1. SET-UP DESCRIPTION AND EXPERIMENTAL METHODS

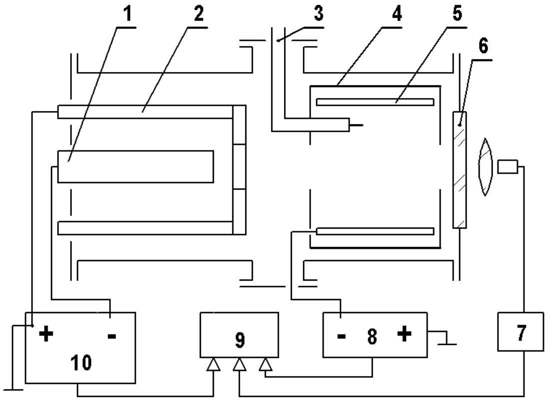

Fig. 1. Block diagram of the experimental set-up. 1, 2 - cathode and anode of vacuum arc discharge, respectively; 3 - probe; 4 - housing at floating potential; 5 - hollow cathode; 6 - window made of quartz KU-1; 7 - CCD-spectrometer SL40-2-2048USB; 8 - power supply of hollow cathode discharge; 9 - control and monitoring unit; 10 - vacuum arc discharge power supply

Block diagram of the set-up used at performing the researches is shown in Fig. 1. Arc discharge current was 40… 250 A with the arc voltage of 30…35 V. Duration

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of arc discharge could be varied in a range of 0.1… 1.0 ms with pulse repetition rate of 0.2… 10 Hz. Maximum density and temperature of electrons in the plasma flow from arc discharge at 25 mm distance from anode 2 were $\approx 4 \cdot 10^{12}$ cm^{-3} and $\approx$ (5… 7) eV, respectively, and at 150 mm distance $\approx 3 \cdot 10^{11}$ cm^{-3} and $\approx$ 3 eV, respectively. The hollow cathode (HC) 5 was made of stainless steel tube having either 120 mm or 66 mm internal diameter and 220 mm length. The cathode was located inside quartz tube 4 with its ends being closed by metal apertures having openings with 30 mm diameter, at that the apertures were under floating potential. Arc discharge anode served simultaneously as the one of HC discharge and was located at 25…50 mm distance from the aperture plane. Pulse shaped as a sine negative half-wave with utmost -10 kV idle voltage amplitude and $\approx$ (3… 4) ms duration at half extremum was supplied to the cathode 5. Maximum discharge current was 5 A. The system of arc discharge ignition synchronization allowed voltage supply to cathode 5 at predetermined timing with respect to arc discharge current pulse position.

Measurements of the plasma density and electron temperature were performed by means of single Langmuire probe, which was unmovably installed in medium plane of the HC at a half of its radius.

The set-up chamber was vacuumed by means of oil vapor pump with liquid nitrogen cooled trap down to a pressure of $\approx 4 \cdot 10^{-5}$ Torr. Pressure of working gas argon in the chamber was varied in a range from $3 \cdot 10^{-4}$ to $2 \cdot 10^{-3}$ Torr.

1.2. RESULTS AND DISCUSSION

Typical time dependencies of hollow cathode discharge voltage U_{HC} and current I_{HC} in case of HC having 120 mm internal diameter (bHC means big HC) are presented in Fig. 2. The discharge in the HC is ignited only at the rear fall of vacuum arc current pulse. The discharge glow occurs in two stages – at first, pre-discharge with $\approx$ 0.2…0.3 ms duration is ignited, and after that “true” hollow cathode discharge is developed.

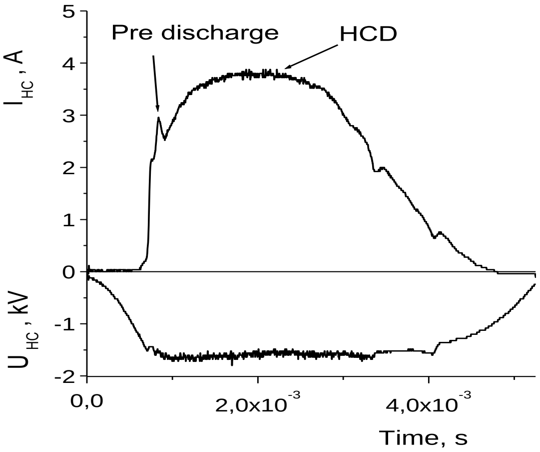


Fig. 2. Time dependencies of bHC discharge current I_{HC} and voltage U_{HC}. Argon pressure P=3e-4 Torr

One can see in the figure that from about 1 till 4 ms of the discharge glow U_{HC} is practically independent on the discharge current, which gives evidence to fact that we indeed observe the discharge with hollow cathode effect (that is, “true” HCD). And dynamic current-voltage characteristic presented in Fig. 3 also clearly confirms this conclusion.

Studies of such discharge system have shown that the discharge voltage value U_{HC} (and, consequently, the plasma density and electron temperature) essentially depend on geometry of certain parts of the system, as well as on argon pressure inside the hollow cathode.

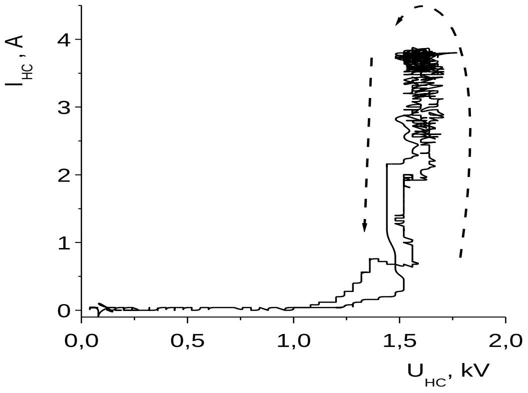


Fig. 3. Typical dynamic current-voltage characteristic of bHC discharge. Argon, P= 3e-4 Torr

In the bHC discharge at $3 \cdot 10^{-4}$ Torr argon pressure maximum U_{HC} values could reach 2.4… 2.6 kV with the discharge current $I_{HC} \approx 5$ A. The plasma density and temperature of major portion of electrons were at that $\approx 10^{11}$ cm^{-3} and $\approx$ (25… 30) eV, respectively. Increase of argon pressure up to 10^{-3} Torr at the same current $I_{HC} \approx 5$ A resulted in U_{HC} decrease down to $\approx$ (1.2… 1.4) kV. At that, electron temperature decreased down to $\approx$ 15 eV whereas the plasma density changed inessentially. Specific power W_d introduced into the discharge in case of bHC was about 2…3 W/cm^3.

Decrease of the hollow cathode internal diameter down to 66 mm (with the same its length of 220 mm) (sHC means mall HC) provided the discharge specific power increase up to 6… 7 W/cm^3. It enabled us to increase the plasma density up to (2… 3)$\cdot 10^{11}$ cm^{-3}. At that, electron temperature changed inessentially and was $\approx$ (20… 25) eV and $\approx$ (12… 15) eV at argon pressure $3*10^{-4}$ and 10^{-3} Torr, respectively.

2. HOLLOW CATHODE AND Cu VACUUM ARC

Also, we have studied the possibility of hollow cathode discharge ignition with plasma flow from vacuum arc discharge with Cu cathode. The setup has mainly the same design as one described above. Scheme of the setup is shown in Fig. 4. We have the source of the arc plasma flow 1-3 and hollow cathode 4.5 in the vacuum chamber 6 with transparent window 7. The plasma flow source uses the cathode made of Cu, which is isolated from igniter by the polymer. The anode has a hole with 6 cm diameter with a grate. The source operates in pulse-periodical regime with repetition rate from 0.1 to 5 Hz. The arc current is up to 280 A and the arc voltage is about 30 V. The discharge pulse is created by means of pulse forming network and decoupling transformer, at that the arc plasma source is not grounded. The hollow cathode has 6 cm diameter and 42 cm length. From the plasma source side, HC has the aperture with 3 cm diameter. From the other side, the hollow cathode is closed with a grate, which is electrically isolated from HC and can be either grounded or float. The transparent window at the vacuum chamber allows the optical measurements.

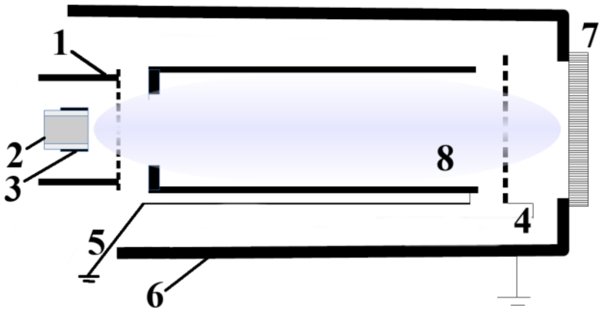
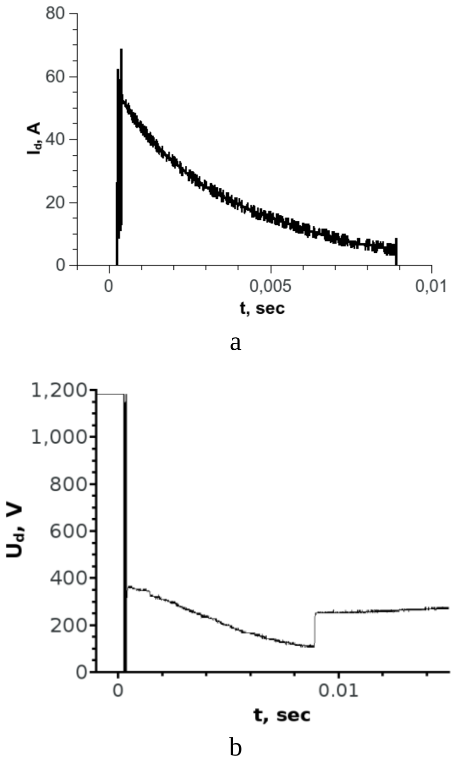


Fig. 4. Scheme of the setup with Cu cathode and the hollow cathode. 1 – anode of arc discharge; 2 – cathode of arc discharge; 3 – igniter of arc discharge; 4 – grate of hollow cathode; 5 – main electrode of HC; 6 – vacuum chamber; 7 – transparent window; 8 – plasma flow

The setup has the measurement circuits with interface to the oscilloscope. The digital oscilloscope with data storage memory and USB interface is used for recording the parameters of each pulse.



a

b

Fig. 5. The typical view of discharge diagrams. The duration of arc pulse is 600 μs, I_d=250 A

As well as in the Ti arc system, with proper design of HC geometry and power supply, we observe HC discharge ignited by the plasma flow in pressure range from $3\cdot10^{-4}$ to 10^{-3} Torr.

The power for HC operation is supplied from 125 μF capacitor via 25 Ohm current limiting resistor, at that the capacitor was permanently charged by high voltage DC source. The power supply circuit allows to apply up to 5 kV of electrical potential to the anode of HC. The arc discharge anode also serves as the anode of HC. The work gas is argon. The background pressure is $(1…2)\cdot10^{-5}$ Torr. The work pressure is $(5…8)\cdot10^{-4}$ Torr.

At higher pressure, permanent HC discharge glows without the plasma flow. Typical kinetics of with HC discharge parameters are shown in Fig. 5.

The arc pulse duration is 600 μs. It is shown that the HC discharge duration can reach 10 ms. The HC discharge is ignited at the second half duration of the arc pulse and glows after arc pulse extinguishing. In this case we have the sharp breakdown with very short transition time and high current value. And after that, relatively stable discharge in argon glows until its completion. In this case we can observe only In this case we can observe only reverse part of current-voltage characteristic since its forward part appears as the fast transient due to quick application of the whole discharge voltage from the capacitor. In subsequent, due to the capacitor discharge, the discharge current decreases, as well as the discharge voltage does until its extinguishing. At this point voltage applied to the discharge system is restored to certain level determined by residual charge in the capacitor. Dynamic current voltage characterstic in this case is similar to one presented in previous section, however, with essentially higher current and lower voltage. Nevertheless, the power introduced into the discharge is big enough.. The dynamic current-voltage characteristic is presented in Fig. 6.

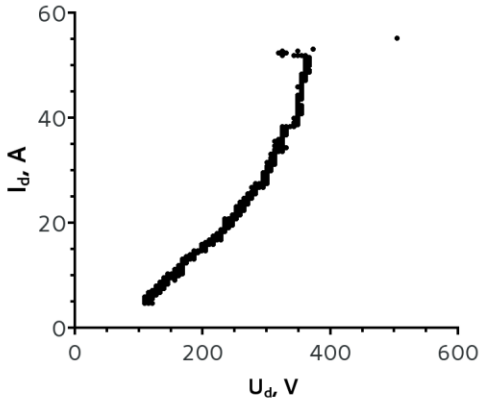


Fig. 6. The typical dynamic current-voltage characteristic of discharge with plasma flow from arc discharge with copper cathode

The discharge exhibits uniform glow across the hollow cathode cross section. It can be ignited starting from idle voltage of about 0.8 kV, however, the most stable operation is observed at the voltage above 1 kV. With the increase of this voltage, the initial discharge current value after its ignition grows up as well. The discharge voltage at steady state of the discharge is practically independent on initial idle voltage of the capacitor.

Typical value of the HC discharge voltage is about 400 V. The discharge current after the discharge ignition weakly depends on applied voltage. As a result, use of excessive initial potential value does not make sense. At the same time, increase of power introduced into the discharge results in electron temperature increase in the HC discharge plasma.

CONCLUSIONS

In this study we demonstrate experimentally the propagation of high density low energy ion plasma flow in pulse-periodical regime through the hollow cathode discharge arrangement. It is shown that propagation of this plasma flow ignites the hollow cathode type discharge, which is self-sustained and continues its glow after the ion plasma flow blow out. The hollow cathode discharge operation is realized with the use of both refractory (Ti) and moderate melting point (Cu) metal as the arc discharge cathode material at work gas pressure below 10^{-3} Torr.

This work is in progress. We plan further research of this discharge effect on microdroplet elimination from high density plasma formed by erosion plasma sources like vacuum arc and laser produced plasma.

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РАСПРОСТРАНЕНИЕ ИОННО-ПЛАЗМЕННОГО ПОТОКА ИЗ КАТОДНО-ДУГОВОГО РАЗРЯДА В ПОЛОМ КАТОДЕ (ИССЛЕДОВАНИЕ И ПЕРВЫЕ РЕЗУЛЬТАТЫ)

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Показано, что ионно-плазменный поток из вакуумно-дугового разряда при его прохождении через цилиндрический электрод, к которому приложено необходимое напряжение, инициирует самостоятельный разряд с полым катодом, который продолжает гореть после прекращения ионно-плазменного потока. При этом свойства плазмы разряда с полым катодом (плотность и температура электронов) определяются, главным образом, давлением рабочего газа и вкладываемой электрической мощностью. Достигнутые мощность и длительность разряда могут позволить его эффективное использование для испарения микрокапель в плазменном потоке из вакуумно-дугового разряда без существенных потерь ионной фракции потока.

РОЗПОВСЮДЖЕННЯ ІОННО-ПЛАЗМОВОГО ПОТОКУ З КАТОДНО-ДУГОВОГО РОЗРЯДУ В ПОРОЖНИСТОМУ КАТОДІ (ДОСЛІДЖЕННЯ ТА ПЕРШІ РЕЗУЛЬТАТИ)

В.Ю. Баженов, А.М. Добровольський, О.А. Гончаров, В.О. Хомич, І.В. Найко, В.М. Піун, І.М. Проценко, В.В. Ціолко

Показано, що іонно-плазмовий потік з вакуумно-дугового розряду при його проходженні через циліндричний електрод, до якого прикладена необхідна напруга, ініціює самостійний розряд з порожнистим катодом, який продовжує горіти після припинення іонно-плазмового потоку. При цьому властивості плазми розряду з порожнистим катодом (щільність та температура електронів) визначаються, головним чином, тиском робочого газу та вкладеною електричною потужністю. Досягнуті потужність та тривалість розряду можуть дозволити його ефективне використання для випаровування мікрокрапель в плазмовому потоці з вакуумно-дугового розряду без суттєвих втрат іонної фракції потоку.