Investigation of Droplets Evaporation in Vacuum Arc Plasma [1]

S.A Popov, D.I. Proskurovsky, A.V. Kozyrev, A.V. Batrakov,
A.N. Shishkov, and E.L. Pryadko.

*Institute of High Current Electronics SB RAS, 2/3 Akademichesky Avenue,Tomsk 634055, Russia,
Popov@LVE.hcei.tsc.ru*

Abstract - A method of cleaning of vacuum arc plasma from droplet fraction of cathode erosion by means of arrangement of conditions for igniting and operating of "droplet spots" has been proposed. Such conditions are realized at reflective arc discharge burning. The plasma of this discharge has substantially higher temperature and concentration of particles. The experiments performed have shown that, compared to usual vacuum arc, arc of reflective discharge provides multiple decrease of number of droplets, not evaporated on their way through plasma. The experiment results have been discussed in the term of heat exchange between droplets and surrounding plasma. The proposed method opens up new opportunities for cleaning of vacuum arc plasma from droplets.

1. Introduction

The availability of big portion of droplet fraction in vacuum arc plasma [1,2] substantially confines the possibilities of the use of such plasma in technologies. Theoretical analysis of droplet heating and evaporation in vacuum arc discharge [3-5] predicted their insignificant evaporation. Purposeful experimental investigation of droplet evaporation during their motion through vacuum arc plasma has not been performed.

It was recently revealed by our group that plasma clots are formed around some droplets leaving the cathode during arcing [6-8]. We have named the aggregate composed of a droplet and surrounding plasma clot as a "droplet spot". Appearance of such "droplet spots" is explained by high temperature of the droplets [6-10]. Intensive thermo-electron emission from the droplet surface leads to vanishing of droplet negative floating potential. In so doing, intensiveness of its bombarding by plasma electrons (energy flux from plasma onto the droplet) is rapidly increased, that is accompanied with rapid increase of droplet material evaporation rate. Ionization of metal vapor by plasma electrons leads to formation of vapor-plasma cloudlet around the droplet. Getting the energy from the surrounding discharge plasma, the "droplet spot" can operate up to complete evaporation of the droplet. Taking into consideration the droplet spot, the problem of the evaporation of droplets in vacuum arc plasma requires further investigation.

The objectives of this research are to investigate experimentally the droplet fraction evaporated during their motion through plasma, to clarify the role of droplet spots in droplet evaporation, and to study the possibility of practical significant cleaning of vacuum arc plasma from droplets.

2. Experimental procedure

The procedure of evaporated droplet estimation consisted in comparative analysis of droplet sediments, formed in two modes on substrates, placed at some distance from the cathode spot. In the first mode usual vacuum arc was used, i.e. with no special efforts taken to evaporate droplets. In the second mode an additional region of metal plasma of relatively higher density and temperature was formed on the droplet path to the substrate. In this case, high current reflective arc discharge was used. In so doing, change from the first mode to the second one was realized by placing of the discharge cell into external magnetic field.

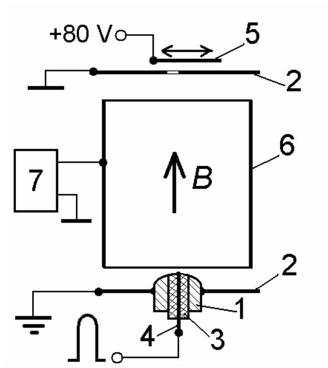

Fig. 1. Experiment scheme.

The experiment scheme is given in Fig.1. Cathode spot was initiated on the made of different materials (Zr, Cu, Ti) insert **1** of one of the planar cathodes **2**

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which were earthed**.** The initiation was performed by breakdown along the ceramic surface **3** with the use of the auxiliary tungsten electrode **4,** through which high-voltage (5-10 kV) initiating pulse was delivered. There was a hole in the opposite cathode **2** with a movable substrate **5** behind it to collect droplets. Positive voltage pulses of 0,5 Hz were delivered from the high-voltage generator **7** to the ring-shaped anode **6,** which was 2,5 cm in diameter and 3 cm in length. The generator **7** provided current surge in the beginning of pulses to purposefully produce a lot of droplets exactly in the first moments of discharge current flow. Discharge current amplitude I_d was regulated in the range 50-150 A, pulse duration τ- in the range 300-900 μs. Magnetic field of up to 130 mT was established by Helmholtz coils (not shown in Fig.1). Measurement of plasma parameters was performed by the probe method, with the droplet collection substrate **5** being used as an electrostatic probe. In this case, sinusoidal voltage of ≅3 kHz produced by special generator was applied to the latter in order to perform total probe characterization during the pulse. Experiments were carried out in the oil-free vacuum under residual pressure of ~10^{-7} Torr. Electrochemically polished Mo foil strips were used as substrates for droplet collection. The positive voltage bias of 80–100 V was applied to the substrate **5** to prevent deposition of the cathode erosion ion phase on it. It was enough to apply several (3-6) thousand discharge pulses to collect necessary droplet sediment. The substrates with the sediments were studied by scanning electron microscope SEM-515. Then, with the use of obtained images and an original method of droplet size analysis, the droplet size distributions were plotted.

3. Results and discussion

In Fig. 2 typical images of discharge glow are shown. In the absence of magnetic field, usual arc discharge is realized between the cathode **1** and the anode **6**, with no discharge in the cell volume (Fig. 2, a). In the presence of magnetic field in the cell, and at the same arc current, bright reflective discharge burns in vapors of cathode material, resulted by the cathode spot (Fig. 2, b).

Parameters of discharge plasma in the plane of the second cathode **2** for both discharge burning modes are summarized in the Table. The discharge currents and pulse durations presented in Table for Cu and Zr cathodes are related to extremely small and great values provided by the generator **7**. It is easily seen that change to the reflective burning mode under the same current value provides significantly higher values of concentration and temperature of plasma electrons.

Typical images of sediments are given in Fig. 3. Droplet diameter distributions are given in Fig.4 (droplet number was normalized to 1 Coulomb of charge transferred through cathode circuit and to solid

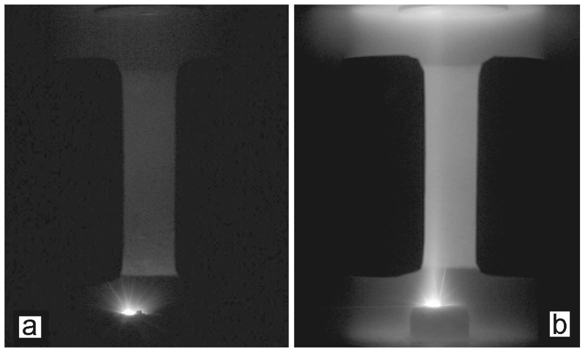


Fig. 2. Discharge glow, image obtained through a longitudinal slit in the anode at B =0 (a, brightness is increased by 50%) and B = 130 mT(b); Zr cathode.

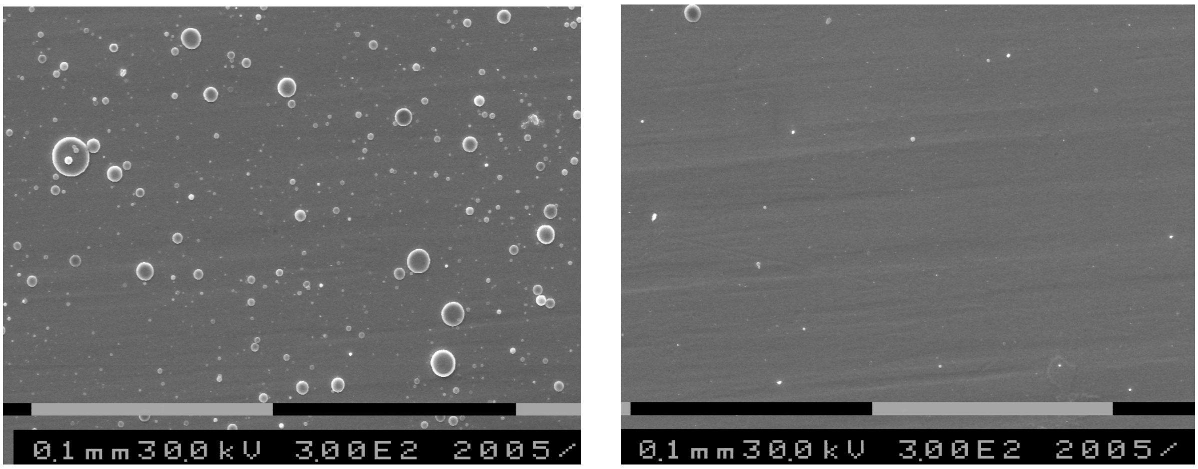
Table. Plasma parameters and changes in droplet sediment under change from usual arc mode to reflective discharge mode

	I_d=60 A, τ=300 μs		I_d=150 A, τ=900 μs	
B, mT	n_e, cm^{-3}	kT_e, eV	n_e, cm^{-3}	kT_e, eV
0	(6-8)×10^{11}	3-4	(4-6)×10^{12}	3.5-4.5
80-130	(3-4)×10^{12}	6-8	(2-3)×10^{13}	8-10
Cu	Sediment is not changed sufficiently		3-5-times reduction of droplet amount	
Zr	4-6-times reduction		10-20-times reduction	
Ti			3-5-times reduction	

angle unit). Generalized data of sediment analysis are also included into Table. It is evident from the data obtained, that change to reflective discharge burning mode and increase of arc current and pulse duration lead to noticeable decrease of number of droplets, flew through the plasma column, as well as their maximum size. Most pronounced effect among three used cathode materials was revealed for Zr cathode.

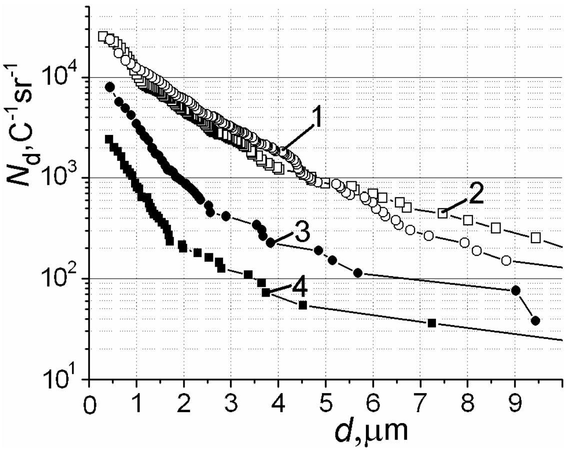
Theoretical model of heat exchange between the droplet and non-equilibrium plasma was used for the calculations of droplet evaporation [9, 10]. In the model, a system of three differential equations was solved self-consistently. 1) Equation of charged particle flow balance described the dynamics of droplet floating potential. 2) Equation of energy flow balance described dynamics of droplet temperature. In doing so, electron heat flow, heat and directed flows of ions from plasma to a droplet, as well as flows, taking away the energy from the droplet (flows of thermoemission electrons and evaporating atoms, as well as radiation losses, i.e. losses due to droplet radiation) were taken into account. 3) Equation of droplet size evolution considered flow of ions falling on the droplet and heat atom evaporation.

Figure 5 presents calculated dependences of stationary droplet temperature on the electron density of plasma. The upper (high temperature) branch of the



a) b)

Fig. 3. Typical images of sediments on substrates, obtained under burning of discharge with the use of Zr cathode at $B = 0$ (a) and $B = 85$ mT (b). Amplitude and current duration were 150 A and 900 μs, correspondingly.



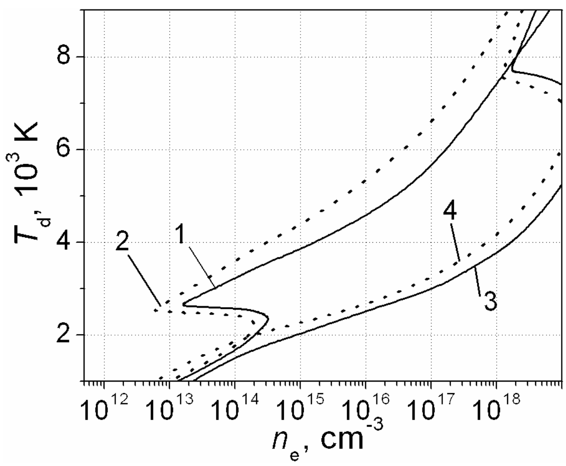


Fig. 4. Typical droplet diameter distributions on substrates for Zr cathode: 1, 2 – B=0, 3 – B=130 mT, 4- B=85 mT, 1, 3- I_d =60 A, τ=300 μs, 2, 4 – I_d =150 A, τ=900 μs.

Fig. 5. Calculated dependences of the stationary droplet temperature T_d on the plasma density n_e, at different electron temperature kT_e: 1, 2 – Zr; 3, 4 – Cu; 1, 3 – $kT_e = 4$ eV; 2, 4 – $kT_e = 8$ eV.

curves in Fig. 5 corresponds to ignition of thermionic-emission spot on the droplet (droplet spot). The conditions for droplet spot igniting on Zr droplets are realized down to plasma density $n_e \sim 2\times10^{13}$ cm^{-3} at $kT_e = 4$ eV, and down to $n_e \sim 5\times10^{12}$ cm^{-3} at $kT_e = 8$ eV, while on the Cu droplets a droplet spot can be ignited only under plasma density more than 10^{18} cm^{-3}.

In [11] the dynamics of changes of temperature and droplet radii in both discharge burning modes were calculated. It was suggested, that a droplet with the initial temperature T_0, equal to melting temperature, starts from a distance of r_0=100 μm from the cathode and moves through plasma. It was also suggested, that electron density of plasma changes according to the law $n_e \sim n_{e0}/(1+ r^2/r_0^2)$ for the first mode, where $n_{e0} = 10^{17}$ cm^{-3}, and $n_e \sim n_{e0}/(1+r^2/r_0^2)+n_{ed}$ for the second mode, where $n_{ed} = 10^{13}$ cm^{-3} is the density of additional plasma, formed in the plasma column under reflective discharge burning. Experimentally measured values of electron temperatures $kT_e = 4$ eV and $kT_e = 8$ eV for the first and the second modes correspondingly were also used in the calculations. The results of calculation for Zr and Cu droplets of 1 μm in diameter are presented in Fig. 6. For Cu droplet, in both discharge modes, the droplet spot can not to be ignited, although some part of droplet material is evaporated nearby the cathode, where the plasma density is at the level of 10^{16}-10^{15} cm^{-3}. For Zr droplet, the plasma parameters obtained in our experiment are close to necessary ones for ignition of droplet spot. At a reflective arc discharge operation, on entire path of droplet motion, the conditions for the droplet spot burning are performing (curve 1, Fig. 6, a). At an usual vacuum arc operation, the rapid transition into the low-

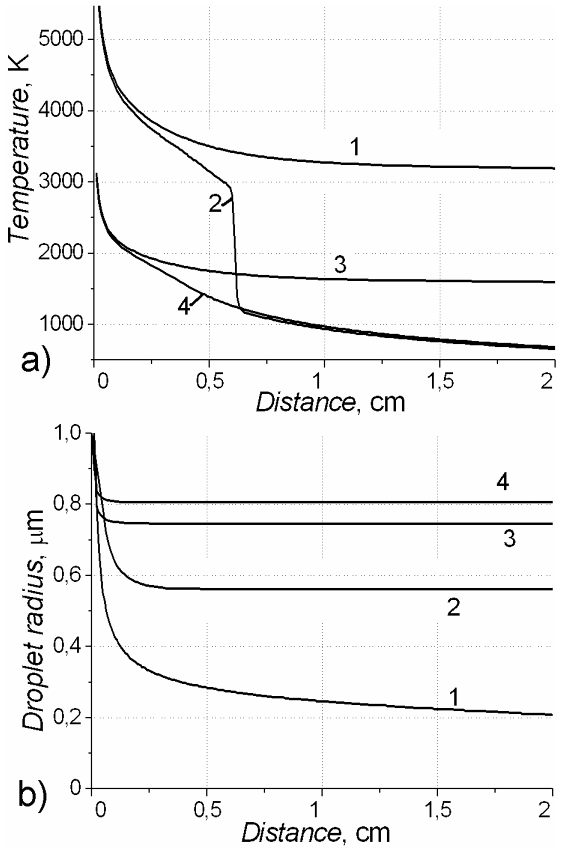


Fig. 6. Dynamics of changes of droplet temperature and radius during their motion through plasma. 1, 2 – Zr, 3,4- Cu. 1, 3 – reflective discharge mode, 2, 4 – vacuum arc mode.

temperature regime at a distance from the cathode of more than 0.5 cm occurs (curve 2, Fig. 6, a). Thus, the changes of plasma parameters, in which the droplets move, affect the evolution of refractory Zr droplets in a great extent (it follows from the experiments [6, 7] also, that droplet spots are easier formed on refractory materials).

Thus, the calculation results are in qualitative agreement with experimental data. The calculations confirm the fact that evaporation of droplet of relatively more refractory Zr due to burning of droplet spots on them turns out to be more intensive compared to evaporation of Cu droplets at the same discharge conditions. However, experimental data demonstrate noticeably higher effectiveness of discharge plasma cleaning from droplets, than it was shown in the model calculations. Apparently, the main disadvantage of model calculations is that they were performed without taking into account the influence of evaporated droplet material on the local density of surrounding plasma. In fact, it follows from the calculations, that during droplet motion in reflective discharge plasma column, its temperature is maintained at the level of 1600-1800 K for Cu and of 3200-3400 K for Zr. Equilibrium density of neutral vapors at mentioned temperatures is $>10^{15}$ cm^{-3} [12]. Such a level of neutral vapor density around droplets was earlier measured by our experiments [8]. If it is supposed that at least ~1 % of evaporated atoms are ionized, then the local plasma density around droplets turns out to be several times higher than the discharge plasma density used in calculations. However, self-consistent taking into account of vapor ionization is a very complicated problem, which is not solved yet.

4. Conclusions

It was determined, that most effective evaporation of droplets takes place in the case of thermo-emission droplet spot ignition on them. To increase the probability of droplet spot ignition and burning, high-current reflective arc discharge, providing formation of more powerful plasma, was suggested and realized. Effect of decrease of droplet number was observed for cathode materials with different thermal-physic and emission properties under burning of this type of discharge. The results obtained give opportunities for significant decrease of pollution of vacuum arc plasma with droplets due to their evaporation during motion through plasma.

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