The mechanism of formation of the droplets on the electrodes under the impact of the high power density streams

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Abstract. The article contains a brief description of functioning principles of the device for creating ultradispersive powders of metals under the impact of electrically charged streams with power density about 10⁸ W/cm². The results of atomic forced microscopy (AFM) measurements of surfaces of the electrodes exposed to dispergated the microdroplets, which allowed to study the droplets formation steps are presented. The results of AFM surfaces of the substrate surfaces to be inflicted by the dispergated droplets are presented. The dependency of the particles sizes on the distance between the electrode and substrate allows to consider the main mechanism of division the dispergated from the electrode surface droplets the Rayleigh instability.

Nanomaterials and coatings based on these materials tend to find increasingly expanding cases of use in different areas of science and technics [1, 2]. It is widely known, that nanoparticles may act as the catalysts, the coatings of these materials may be used for disinfection, or to dissipate the electromagnetic waves or as a structural strengthening phase. Every year the areas of applying of those materials increase. Though the most of the methods of their production are based on the chemical reactions, while using ones, the complicated fractal structures of the materials appear. Further those structures might be delivered to the surfaces to be used with the nanoparticles. But they could still tend to aggregate there and in consequence of that, loose their useful properties. The alternative methods of producing ultradispersive (smaller than 100 nm) particles, are the physical ones, based on the influences of powerful streams of energy on dispergated materials, are still in the phase of development [3–5].

One of the examples of the physical methods is the device for producing the ultradispersive materials is being realized in the laboratory of “Electric impulsive technologies” SPb ETU [6, 7].

A brief description of the device’s working principles:

1. The addictive sparking discharge of the atmospheric pressure, which is initialized by impulsive high voltage transformer through high voltage addictive electrodes, initializes the ignition of the main discharge. This discharge initializes the release of the energy, previously stored in the capacitive batteries, which are connected to the main electrodes with the co-axial cable;

2. After the ignition, the discharge exists in the evaporations of the electrodes material. Under the influence of power, appearing while the magnetic field of currents on the electrodes and plasma, the discharge starts to move along the rails from the point of connection of the electrodes;
3. During a short period of time (100 μs) the huge energy input (1500 J) with high power densities \((10^8 \text{ W/m}^2)\) takes place in the discharge plasma and, consequently, high temperature of plasma and electrodes and big currents (up to 50 kA) appear. The average time of the contact of discharge and the point on the electrode is no longer than 10 μs. During this time the surface of the electrode heats up, melts, partly evaporates and disperges (part of the material leaves the electrode surface as a microdroplet phase);

4. The droplets, moving influenced by vapor pressure from the evaporated electrodes and the electric field, rapidly start to move to the substrate. The droplets, that reached the substrate and held on there, get frozen as discrete particles.

The droplets formation lasts for couple microseconds. Its size reaches couple microns, the temperature – about 5000 degrees. The process of formation of these droplets is very complicated. The ways of experimental studying of the process in such conditions are also very complicated and expensive [8]. Though they can’t give the answers about the microdroplet formation process, which is key in our case.

Having in mind the complexity of theoretical and experimental research of the processes, we used the method of indirect measurements. In terms of this method we judged about the processes to take place on the electrode by the trails, left by running discharge. The problem is that the discharge moves along the extended electrodes surface making it melted on couple microns deep. When the discharge leaves the area on the electrode, it rapidly cools down and many droplets, which were in the process of formation, get frozen as they were in the area of the discharge. That’s why to find out the physical mechanisms of the droplets formation, it’s necessary to measure the electrodes surfaces, finding out the characteristic areas on it and also to research the changes in the particles dispersions on the substrate depending on the distance to the electrodes.

Sizes of the particles, which form on the electrodes and get caught on the surface of substrate change from couple nm to couple um. That’s why to measure the surfaces of electrodes and substrates, we used atomic-forced microscope (AFM) Certus in tapping mode.

The measurements of surfaces of electrodes and substrates with the particles coatings, received while using different modes of working of the technological device (voltage, capacitance, gap between electrodes and substrates, etc.). Firstly, the surface of the unused electrode was measured (figure 1).

![Figure 1. The surface of unused electrode measurement result.](image)

It’s easy to see that the surface is mostly flat. There’re no significant altitudes over or under the main surface, even of the sector of 100 μm. The height of arbitrary located irregularities does not exceed 3–4 μm.

Scanning of the electrodes in different areas after using them appeared that for different stages of the discharge movement the surfaces of the electrodes have different structure (figures 2, 3) [9].
Figure 2. The images of the surfaces of the electrodes after their use in different points: (a) – in the middle of the discharge trail (the surface is still pretty flat, though slightly more rough than unused); (b) – at the end of the trail (we can see the droplets forming on the surface of the electrode).

Figure 3. The photo of the electrode with the discharge trail.

For the images, created with scales of 100×100, 50×50 and 15×15 μm, different characteristic regions were allocated, where surface roughnesses had same diameter and different altitude. Those areas are marked and zoomed in figure 4.

Figure 4. The images of forming of the droplets on the surface of the electrodes on different stages of forming: (a) – three-dimensional pictures; (b) – two-dimensional pictures of the droplets, where we can see the forming of the secondary, much smaller droplets.
The scales for all coordinates kept same for all three cases. Obviously, these roughnesses have a shape of a piece of sphere, about the same diameter, and different height. We consider these spheres as frozen on different stages of forming microdroplets.

The droplets of a much smaller size also can be found on the measured surface. From the surfaces of big droplets, sized about 2 μm the droplets of 200 nm separate. Most likely this process is a result of the Rayleigh instability.

The results of measuring the surfaces of substrates, covered by particles for the different cases of heights over the electrode are shown on the figure 5. The material of the electrodes was steel, the voltage was 3 kV, capacitance 500 μF. Obviously, the created particles depending on the substrate removal from the electrodes tend to have different sizes and distance between each other. This gives the opportunity to say, that while reaching on to the substrate the droplets keep on dispersing, becoming smaller while the removal from the electrodes.

![Figure 5](image)

**Figure 5.** The results of measurements of the surfaces of the substrates at different distance from the electrode (left 5,5 cm, right – 7,5 cm, at 3 kV and 500 μF).

Particularly, on the distance of 5,5 cm from the substrate, most of the droplets have a size about 150–180 nm, the size of particles is going to be 100 nm. At the 7,5 cm from the electrode the size decreased to 50–120 nm (figure 6). The number of particles grows significantly. Though the summary volume keeps almost unchanged.

![Figure 6](image)

**Figure 6.** The results of mathematical processing of the pictures of the substrate on different distances from the electrodes.
Conclusions
The measurements created with AFM of the electrodes of the system for producing ultradispersive coatings, allowed to investigate and capture the phases of forming of the droplets under the affection of powerful charged energy streams.

The results of AFM measurements created using different parameters of the technological device and on the different distance from the electrodes allow to claim, that the division of the droplets still continues while their flying in the plasma of the vapors of evaporated material of the electrodes.

On the assumption of the produced researches, we can suggest that the main mechanism of the droplets formation on the electrodes and their division in the discharge plasma is Rayleigh instability.

References
[1] Kostrin D K and Lisenkov A A 2016 Materials Science Forum 843 278–83
[2] Vetrov N Z, Kostrin D K, Lisenkov A A and Popova M S 2015 Journal of Physics: Conference Series 652 012032
[3] Zabrodsky A G, Gurevich S A, Kozhevin V M, Astrova E V, Nechitailov A A, Sresely O M, Terukov E I and Compon M E 2007 International Scientific Journal for Alternative Energy and Ecology 2
[4] Russkikh A G, Oreshkin V I, Labetskiy A Yu, Tchaikovsky S A and Shishlov A V 2007 Journal of technical physics 5 35–40
[5] Goncharov V D and Samsonov D S 2015 Journal of technical physics 5 37–42
[6] Samsonov D S, Goncharov V D and Fiskin E M 2011 Patent RU 2471884
[7] Goncharov V, Samsonov D, Fiskin E and Kalinin S 2014 Proceedings of the international scientific colloquium Modelling for electromagnetic processing (Hannover) (Moscow: Spektr Publ. House) pp 277–81
[8] Zhykov B G, Kurakin R O, Sakharov V A, Bobashev S V, Ponyaev S A, Reznikov B I and Rosov S I 2013 Letters to JTP 23 58–62
[9] Goncharov V D, Kalinin S A and Yashkardin R V 2015 Proceedings of Saint-Petersburg state electrotechnical university «LETI» 5 3–7