Optical diagnostics of a dielectric surface discharge in the triggered vacuum gap using various dielectric materials

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Abstract. High-speed imaging and visible light stereomicroscopy were applied to do researches, which allowed us to find out differences in a dielectric surface discharge behavior in the triggered vacuum gap, when various dielectric materials (mica, muscovite and corundum-type ceramics) were used. Images of the discharge and the erosion in the electrode systems were analyzed to reveal that at the discharge on the ceramics surface a material of electrodes was mostly involved as a plasma-forming matter and on the mica it is the dielectric material.

1. Introduction

An effect of arc discharge in a vacuum initiated by a dielectric surface discharge has long been widely used in X-ray tubes, neutron tubes and vacuum gaps [1]. Such a useful combination of these two discharge types helps make a generation of the electric arc controlled, with a time accuracy of about ten nanoseconds. Specifications of tools based on this effect (a delay time, a trigger voltage, a stable trigger voltage, switched-current) are certainly related to features in a behavior of the initiating dielectric surface discharge. Parameters of the discharge are much affected by the dielectric material along which it flows. Therefore, an objective of the paper is to single out differences in the behavior of the dielectric surface discharge in the triggered vacuum gap using various dielectric materials.

2. Experiment

The triggered vacuum gap is mostly a system comprising three electrodes: a cathode, an initiating or igniting electrode and an anode located in the vacuum volume under pressure of residual gases at least $10^3$ Pa. The cathode and the igniting electrode are separated from each other through a dielectric material and constitute an igniting system of the spark gap. The anode is partitioned from the cathode by a vacuum gap [1]. The cathode is earthed, the anode is under a positive potential of several kilovolts, to initiate the toll triggering. In order to generate the electric arc in the gap between the cathode and the anode, an actuating pulse of positive voltage with respect to the cathode is applied to the igniting electrode.

Since the subject of the research is a dielectric surface discharge, experiments use only the igniting system of the spark gap, which is an electrode system formed by the magnetron sputtering of a thin-film metal coating on the surface of the dielectric substrate, as shown in figure 1.
The types of dielectric material most commonly exploited in vacuum gaps for the substrate are ceramics and mica. The dielectric gap is 140–160 μm wide, the sputtered coating is 2 μm thick, the coating material is titanium.

As a voltage pulse is generated, there is a discharge between the cathode and the igniting electrode on the dielectric surface. The pulse voltage of a breakdown, at which the discharge occurs, is 3 kV, a discharge duration is 30 ns, a maximum discharge current in case of ceramics as dielectric substrate is 3.6 A and 6 A, if it is mica.

High-speed imaging takes place with a digital CCD camera, which allows us to take images of the spark at the wavelength from 190 to 1100 nm with a spatial resolution of 1928×1448 pixels and a minimum exposure time of 60 μs. A special mandrel, illustrated in figure 2a, which makes it possible to accommodate the tested igniting system within the camera coverage (figure 2b) and provide a reliable electric contact, is used for imaging.
The analyzed images reveal a number of features, which distinguish the discharge on ceramics from one on mica:

- For the discharge on the mica surface, there is a single compact glowing area with a middle matching the dielectric gap; in case of ceramics two glowing areas are observed to be formed, which coincide with the cathode spot (on the cathode) and the anode spot (on the igniting electrode);
- The dielectric surface discharge on the mica propagates together with multiple bright images of glowing tracks of microparticles (droplets of liquid metal, which is the cathode material); on ceramics there are no tracks of microparticles;
- A glow intensity for ceramics is significantly higher than for the mica, despite identical pulse breakdown voltages and a higher discharge current in case of mica.

4. Comparative analysis of images of erosion in igniting systems

After imaging we analyzed an erosion in igniting systems affected by the dielectric surface discharge under a stereomicroscope. Images of erosion in electrode systems on the surface of mica and ceramics are shown in figures 4a and 4b, respectively.

The images point out that a scale of erosion in electrodes subjected to the discharge is much extensive for the igniting system on ceramics as compared with the mica, where a narrow edge of electrodes is solely eroded. It is also apparent that an erosional boundary is flatter for the mica than for ceramics.

5. Results and discussions

Such different observed images of erosion in igniting systems and the dielectric surface discharge of two dielectric materials can be explained as follows.

Ceramics is a refractory material with a melting point at 2047 °C and a sublimation temperature of 2980 °C. The ceramics surface is porous. The pores have a certain amount of the occluded gas. As the
discharge propagates along the ceramics surface, the matter leaves pores because of heating. The temperature of electrons while the cathode layer is built up, is about 15 eV or slightly higher, which is sufficient for the effective gas ionization. At the above temperature of ions from the cathode material, their average thermal velocity will be \(8 \times 10^3\) m/s. Plasma expands from the center of explosive emission to \(~10^{-3}\) m for 10 ns and generates a conductive channel \(~100\) µm thick and as long as the dielectric gap, which is equal to \(~140\) µm, above the dielectric surface. As a result, the channel should pass a current of \(~4\) A. If the surface is as rough as \(~2.5\) µm, about \(3 \times 10^{11}\) particles can be occluded on the whole surface due to its porosity. As the particles arrive to the discharge channel, they form plasma with the concentration of charged particles equal to \(10^{23}\) m\(^{-3}\) [2, 3]. A current drift velocity of electrons is \(~3 \times 10^9\) m/s, which is higher an average thermal velocity of ions, and, as a result, much higher that of the ion sound. It leads to the so-called ion sound instability, which makes electrons lose energy not only during paired collisions with ions but through swinging fluctuations. Given that a mean free path of particles in the spark is \(\lambda \approx 10^{-4}\) m, which is too high (to heat the gas in pores) for gas molecules to escape pores, the dielectric material needs to be heated. Ceramics will warm up to a depth of \(1\) µm for 30 ns (an order of current pulse width) and therefore only a part of molecules, will be desorbed on the surface, it means that conditions for the current flow may be worse than expected. The lack of charged particles in the current channel can be compensated solely by the erosion in the material of electrodes (the cathode and the igniting electrode) and then it will be possible for the spark to change into a short-circuit mode.

We can observe a different situation with the discharge on the mica surface. The mica almost completely dehydrates, swells at 700 °C and a water vapor is released outside. The mica is warmed up to a depth of \(0.2 \times 10^{-6}\) m for the time as long as a current pulse. It melts at 1145–1400 °C and at 1997 °C SiO\(_2\), one of the basic mica components, starts decomposing (the lowest recorded temperature of the matter in vicinity of the cathode spot is 0.8 eV [4]). Thus, the mica, from the very scratch of the spark, might have been a source of gaseous products from erosion, which flow into the current channel (it is apart from the gas desorbed from the surface). When the concentration of particles is about \(10^{12}–10^{23}\) cm\(^{-3}\) in a solid, one can obtain an order of \(10^{13}–10^{14}\) particles in the current channel above the dielectric surface. It will increase the concentration of particles and deaccelerate a current drift velocity of electrons. The required current drift velocity of electrons is \(10^2–10^3\) m/s at the full ionization, that will be less than the sound velocity in plasma, and, hence, there will be enough particles in a spark to change into an arc.

For plasma to be initially well-conducting at the discharge over the mica surface, a narrow edge of electrodes should only take part in the discharge (figure 4a). Here it is essential that a plasma-forming matter arrives from the dielectric surface. For the discharge on the ceramics surface, an insignificant amount of discharge carriers, which flow into the plasma from the dielectric surface, will result in the need to involve a larger area of the electrode surface (figure 4b).

The discussed mechanism probably explains the dielectric surface discharge localization in different points when various dielectric materials are used. For the mica, the discharge glow is localized above the surface of the dielectric gap, since the conductive medium of the spark is generated from erosion products of the dielectric gap on the mica. In case of ceramics, the discharge glow is localized above the surfaces of the electrodes due to the fact, that they are the main sources of the matter for creating a conductive medium of the dielectric surface discharge.

6. Conclusion
Images show, that a source of the conductive medium at the discharge on the mica surface is primarily the dielectric material, and on the ceramics surface it is the material of the electrodes. The indicated conditions stipulate a drastically different picture of the erosion in the electrodes and the dielectric materials.

References
[1] Dolgov A N, Davydov S G, Kozlov A A and Yakubov R Kh 2021 Nanoindustry 14 407–13
[2] Mesyats G A 2011 *Explosive Electronic Emission* (Moscow: Publishing House of Physical and Mathematical Literature) 280 p

[3] Kumada A 2018 *The 28th International Symposium on Discharges and Electrical Insulation in Vacuum* (ISDEIV) (Greifswald, Germany) 307–12

[4] Lyubimov G A and Rakhovskii V I 1978 *Sov. Phys. Usp.* 21 693–745