Investigation of the aluminum electrodes erosion of a plasma gun during the operation of a high-current vacuum arc discharge

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Abstract. The aim of this work was to obtain magnitude quantitative estimates of the "closed-type" plasma gun aluminum electrodes erosion that occurs during the course of a high-current vacuum arc discharge. The experimental setup consisted of two current generators. The first generator capable of generating a current with an amplitude of up to 450 kA and a rise time of 500 ns was used as a current source for a plasma gun. The second one was used as an X-ray radiograph to visualize the object under study in the soft X-ray range ($h\nu \approx 0.5–3$ keV). Quantitative distributions of the plasma linear mass are obtained both along the radius and along the length of the jet at different times. It was shown that the erosion properties of the electrode material are related to the current characteristics of the arc discharge current.

1. Introduction

Among the numerous applications of the vacuum arc discharge, the use of the evaporated material of the cathode and anode as a source of material for the formation of Z and PZ pinches seems to be very interesting [1, 2]. One of the main parameters that determine both the pinch implosion dynamics and the X-ray radiation yield is the substance mass participating in the pinch compression. The traditional Z-pinch mass estimation uses a zero-dimensional calculation based on the known current values through the pinch and the time of the pinch compression. Unfortunately, in the case of plasma-metal liners, there is an uncertainty in the estimate of the pinch mass due to the fact that the initial diameter of the imploding Z-pinch and the initial radial distribution of the material are unknown.

On the other hand, it is possible to estimate the plasma gun electrodes material mass evaporated by a high-current arc discharge. In works [3, 4] it was shown that for this purpose it is possible to successfully use the radiographic method [3-5]. In this work, we studied a plasma jet formed by a gun with an "open" cathode. In the design of this gun, the cathode and anode were at the same level and were separated by an annular insulator, on the surface of which the arc discharge was initiated. It was shown that the rate of cathode erosion in a high-current vacuum arc is a function of the charge passed through the cathode. However, the design of a plasma gun with an "open" cathode turned out to be unsuitable for the formation of plasma Z-pinches. As shown in [4], a feature of the operation of a gun with an "open" cathode is the entrainment of gun current together with the evaporated substance in the direction of the jet spreading, as a result of which an azimuthal frozen-in magnetic field is formed.
around the jet (the jet is a structure in the form of a narrow column [3]). The latter circumstance can prevent the formation of a plasma liner.

The so-called "closed" type plasma guns have shown themselves much better in this regard. In this case, (see figure 1) the plasma flows out into the high-voltage gap of the main generator through a hole in the anode. It was shown in [6] that the arc discharge current flows only inside the cavity separating the cathode and anode. In other words, in that part of the plasma that flows out of the hole in the anode, the arc discharge current does not flow.

The objective of this work was to determine the mass of the evaporated substance from the electrodes of a "closed" type gun by a direct method based on pulsed X-ray radiography, which we successfully implemented earlier.

2. Experimental setup

The experimental setup consisted of two current generators. The first generator (IMRI-5, capable of generating a current with an amplitude of up to 450 kA and a rise front of 500 ns in a short-circuited load mode) [7] was used as a plasma gun. The second generator (XPG, 250 kA, 220 ns) [8] was used as a pulsed X-ray radiograph to visualize the object under study in the soft X-ray range \( h\nu \approx 0.5–3 \) keV. The XPG generator was loaded with an X-pinched, which was used to form a pulsed soft X-ray source \( \sim 1 \) µm in size [9, 10]. The X-pinched consisted of two molybdenum conductors with a diameter of 25 µm, which were twisted in the shape of the letter "X".

The sketch of the plasma gun installed in the high-current generator IMRI-5 load is shown in figure 1. The end face of the aluminum cathode of the plasma gun was deepened into the insulator and was located at a distance of 3 mm from the hole in the anode electrode. A vacuum arc discharge was initiated upon a breakdown along a 3 mm long polyethylene insulator separating the end of the plasma gun cathode and the adjacent anode. The diameter of the aluminum cathode was \( d_c = 3 \) mm. The plasma jet, forming in the interelectrode gap of the plasma gun, flowed into the vacuum chamber of the IMRI-5 generator through a cylindrical channel in the anode, the diameter and length of which were 4 mm and 3 mm, respectively.

![Figure 1. Experimental arrangement. RC is a Rogowski coil.](image)

The current in the X-pinched and the arc current were measured with Rogowski coils. The X-pinched X-ray pulse was recorded using a vacuum X-ray diode (XRD) with an aluminum cathode located behind a 6 µm thick polypropylene filter at a distance of 30 cm from the X-pinched. The XRD sensitivity lies in the photon energy range \( h\nu = 100 \) eV to 5 keV. The time delay between the IMRI-5 and XPG was adjusted using an external digital pulse generator (DPG) with a time step of 25 ns. Typical oscillograms of the arc and X-pinched current pulses, as well as the XRD signal, are shown in figure 2.

As mentioned above, the jet plasma mass was determined by the direct radiographic method, when an image of the object of study (jet) and a step wedge made of the same material as the gun cathode are recorded on one photograph. This method for determining the mass is described in detail in [3].
The scheme for obtaining radiographic images of a plasma jet is shown in figure 3. The magnification factor of the radiographic scheme was 1.5.

In the experiment, the image of the plasma jet was recorded on a Mikrat-ORTO photographic film. To protect the photographic film from the visible radiation of the X-pinch and the studied plasma jet, an aluminum filter with a thickness of 0.4 μm, which is not transparent for visible radiation, was used, deposited on a kimfoil film with a thickness of 4 μm. The step wedge was fabricated by magnetron sputtering of several layers of aluminum onto a 6 μm thick polypropylene film. The wedge stages were 0.25, 0.5, 0.75, 1 and 1.25 μm thick.

3. Experimental results

The figure 4 (right) shows an example of an X-ray image of a plasma jet outflowing from a hole in the gun anode, which was obtained 1115 ns after the start of the current of the IMRI-5 generator. For better visualization the white dashed lines show the approximate boundaries of the jet. This figure also shows the values of the mass thickness of the $R_{SW}$ layer for each stage of the aluminum attenuator. The calibration range of the surface density was set by the minimum and maximum $R_{SW}$ values for the step attenuator and was 60–340 μg/cm$^2$. The figure 4 (left) shows the distributions of the mass thickness of the plasma layer $R(x)$ over several sections of the jet made at different distances $H$ from the outer surface of the gun anode.

The linear mass for each cross section of the plasma jet was estimated by integrating the surface density distribution along the $r$ axis:

$$m_p = 2 \int_{-\infty}^{\infty} R(x) \, dx. \quad (1)$$
Figure 4. Radiographic image of the plasma jet, obtained 1115 ns after the onset of the IMRI-5 current pulse (right) and the distribution of the surface density $R(x)$ over sections at distances $H$ from the outer surface of the anode (left).

The figure 5 shows an example of the plasma envelope linear mass determining when scanning an image obtained at the time $t = 978$ ns. It can be seen from the graph above that the plasma flow has a significant mass gradient along the $Z$ axis. The presence of such a gradient is a consequence of the rapid increase in the arc current (and, accordingly, the erosion of the electrodes) over time. In real experiments, the presence of such a mass gradient is not a negative phenomenon, since with an increase in the distance from the plasma gun, not only does the mass of the matter decrease, but also the radius of plasma expansion increases. As a result, a plasma that begins to contract from large radii and has a lower mass can reach the center in the same time as a large mass starting from smaller radii.

Figure 5. Linear mass of the plasma sheath obtained at time $t = 978$ ns.

The obtained linear mass distributions along the $Z$ axis were numerically integrated over the jet length in order to determine the total jet plasma mass $m_{pj}$ at different times [3]. The time dependences of the plasma jet mass, as well as the IMRI-5 current pulse, determined in this way are shown in
figure 6. In this case, the error in measuring the total mass of the plasma jet, $m_{pj}$, was determined by the manufacturing accuracy of the step wedge and amounted to approximately 20%.

![Graph showing IMRI-5 current and jet plasma mass](image)

**Figure 6.** Time dependences of the IMRI-5 current and the jet plasma mass ($m_{pj}$ and $m_I$ are experimental and approximated, respectively).

Analyzing the experimental values of the evaporated mass $m_{pj}$ as a function of time and current, it can be concluded that the evaporated mass does not depend on the flowing charge density (as was obtained in [3] for an "open type" plasma gun), but is numerically proportional to the arc current discharge:

$$m_j \approx kI.$$  \hspace{1cm} (2)

The $m_I$ approximation plot corresponding to the coefficient $k = 0.45$ is shown in figure 6. At this point in time, the reason for just such a dependence of the gun electrodes evaporated mass on the arc current has not yet been explained. We will investigate this phenomenon in further experiments and planned theoretical calculations. Note, however, that the arc discharge current evaporates both the cathode material and the anode material. It is possible that such an unusual behavior of the evaporated substance dependence on time is a consequence of the electrodes substance erosion properties superposition on the plasma flow hydrodynamic characteristics, in which the temperature and pressure of the substance in a rather narrow channel through which the plasma flow outflows into the vacuum chamber of the IMRI device play an important role.

**4. Conclusion**

As a result of the aluminum plasma jet studies, quantitative distributions of the substance linear mass were obtained both along the radius and along the length at different times. The absolute values of the total mass of the substance evaporated by a high-current arc discharge were obtained at different times, which reached values (150-200) $\mu$g in the experiment at the maximum arc current. The studies carried out and the results obtained made it possible to relate the erosion properties of the electrode material with the current characteristics of the arc discharge current. The obtained erosional properties of electrodes in combination with optical and electrical measurements will make it possible in the future to simulate the operation of high-current plasma guns.

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