Electrode Erosion in a Pulsed Plasma Accelerator

I. Anode

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Electromagnetic acceleration to $10^6$–$10^7$ cm/sec occurs in the discharge column in a pulsed plasma accelerator, which in this way differs from ordinary pulsed vacuum discharges (spark working of metals, pulsed light sources, etc.). This affects the electrode erosion. A study has been made of the anode damage in pulsed plasma accelerators with rail geometry.

APPARATUS

Figure 1 shows the apparatus. The working pressure was about $10^{-5}$ mm Mg. Eight MBGV capacitors, each 100 $\mu$F at 800 V, were used. The discharge was aperiodic and lasted 30 $\mu$s (the end of the discharge was taken as the point at which the current was 0.1 of the maximum current). The rate of rise was about $2 \cdot 10^9$ A/sec (Fig. 2). The capacitor voltage and discharge current were recorded by an OK-17M oscilloscope. The peak discharge current was 22 kA. The discharge was also recorded by an SFR-L high-speed camera. The accelerator electrodes were attached directly to the vacuum leads and allowed any gap between 10 and 120 mm to be used. The electrodes were 150–500 mm long. The anode was of copper, aluminum, or molybdenum. Most of the tests were done with electrodes 200 mm long, which were mechanically polished to a mirror finish immediately before use. If an oxide film was present, the electrodes were briefly etched with a mixture of nitric and hydrochloric acids. The sides and outer surfaces of the electrodes were covered with plates of nonconducting material to prevent discharges there.

RESULTS

The surface of the anode after a single discharge was examined with MIM-7 and MIM-8 metallurgical microscopes at magnifications of 100, 600, and 1000.

Most of the surface remained undamaged, and the discharge left a track 2–3 mm wide near the end. The tracks on the cathode under these conditions ran throughout the length, so it could not be assumed that the discharge arose at once at the ends of the electrodes after the striker had acted. This anode track in all cases consisted of numerous small craters (pits) separated by distances of 2–4 diameters or more; a single anode crater was not produced. The diameter, depth, and degree of melting in the microcraters were dependent on the material. There was no relation between crater disposition and surface defects. No craters were produced at the anode when the electrode length was increased to 500 mm.

Fig. 1. Circuits: 1) striker unit; 2) SFR control unit; 3) high-speed camera; 4) OK-17M oscilloscope; 5) Rogowski loop; 6) voltage divider; 7) capacitors; 8) striker; 9) accelerator electrodes; 10) high voltage source.

Fig. 2. Discharge current (upper curve) and voltage (lower curve).

Craters in Al (Fig. 3) had prominent relief, with a ring of melted metal around the edge and a small cone at the center. About 90% of the craters in aluminum were 0.05–0.1 mm in diameter (a few were 0.15 mm), while the depths were 0.02–0.05 mm, increasing with the diameter.

The effects for Cu were much more superficial and we observed flat pits 0.1–0.3 mm in diameter, sometimes with dendrites at the bottom produced by solidification of liquid (Fig. 4a). The shape of the dendrites were characteristic of rapidly growing crystals. Cu also gave another type of effect: circular spots without appreciable melting surrounded by broad rings of oxide (Fig. 4b).

Mo gave three types of track: 1) craters up to 0.3 mm in diameter and 0.05–0.07 mm deep, with a ridge of melted metal at the edge (Fig. 5a); 2) flat, slightly melted pits about 0.05 mm in diameter (Fig. 5b); and 3) small craters (diameter 0.05 mm or less) in groups of 4 or 5 (Fig. 5c).

The regular shape of the craters showed that the discharge spot remained fixed throughout the discharge.
time (~20 μsec). This was confirmed by estimates of the time needed to produce a single crater.

In the rare cases where the spot did migrate, the craters were joined by a characteristic thermal track (Fig. 3a).

The SFR-L camera was used to examine the discharge from the end and from the side. The discharge near the anode was mainly diffuse and distributed over much of the surface, without any signs of contraction, which was observed only in frames showing emergence of the discharge at the end. Three simultaneous processes could thus be correlated: formation of anode craters, production of a vapor jet from the anode, and contraction of the discharge near the anode. The SFR data gave the speed of the jet as about 5–10⁵ cm/sec, which agrees well with the results [3, 4] from fixed high-current pulsed discharges. The mean current density in the luminous channel near the anode was also of the same order as in experiments with discharges which have no acceleration of the plasma in the positive column [5-7], namely 40–60 kA/cm², or 200 kA/cm² if allowance is made for splitting into separate channels and production of microcraters.

The extent of the erosion was determined by weighing, the losses being (in μg/Cu) 30, 6, and 5 for Al, Cu, and Mo. The weighing was performed after 1000 shots at the rate of 10 per minute.

DISCUSSION

One of the most interesting results is that there are no craters over much of the length of the anode, with preferential formation at its end. This may occur because: 1) the discharge gap in the accelerator is exposed to the strong magnetic field produced by the discharge current, and 2) there is a special mechanism for heat transfer to the electrode. Charge transport near the anode is provided almost entirely by electrons [8]. The electron concentration nₑ is low in the striking discharge, so the current density at the initial part of the anode is small:

\[ j_e = e n_e v_e, \]

in which \( v_e \) is the electron velocity.

Increase in \( n_e \) near the anode occurs as the discharge current rises mainly as a result of ionization of vapor from the cathode and insulator, since there is no supply of material from outside and also no appreciable evaporation from the initial part of the anode under these conditions; \( n_e \) and \( j_e \) increase with the total number of electrons near the anode, in view of the restricted transverse size of the anode.

The relatively low \( j_e \) at the initial part of the anode agrees with the diffuse (uncontracted) light emission near the anode. The discharge current and magnetic field are relatively low during the first 1 or 2 μsec, so the electrons pass freely to the anode, and we may assume that the anode potential drop \( U_a \) is only 7–10 V [6], as for a fixed high-current discharge.

The heat flux at the anode is

\[ q = f_e (\varphi + U_a), \]

in which \( \varphi \) is the electron work function.

We take \( j \) at the initial part of the anode as less than that for the contracted part of the discharge by 1–2 orders of magnitude [6], and \( U_a \) as 7–10 V, while the electron binding energy in the lattice is 3–4 eV [9].

Also, the region of the discharge near the anode moves with a speed equal to that of the plasma in the accelerator, so 2–3 atomic layers of metal are evaporated from the anode, which is undetectable by ordinary methods even for a polished surface.

Motion of the plasma along the electrodes is accompanied by increase in the discharge current and magnetic field, which reach maximum values at the end of the electrode. Field increase causes \( \omega_e \gamma_e \) (the Hall parameter) to become much greater than one. Current continuity at the anode can then be maintained only by an appropriate increase in \( U_a \), which may rise to 100 V at the end of the electrode [11]. Then (2)