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ON ANALYSIS OF PHYSICAL PROCESSES ON THE ELECTRODE SURFACE IN A RAIL LAUNCHER

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This paper analyzes some physical effects that occur on the electrode surface in plasma-armature rail launchers when the linear current density is higher than critical value. It is shown that under typical experimental conditions, Rayleigh–Taylor and Kelvin–Helmholtz instabilities and magnetohydrodynamic instabilities, which arise from the interaction of the current with the self-magnetic field, can develop over times much smaller than the launcher operation time and can be responsible for the entry of the electrode material into the discharge. Flash radiography of the electrode surface confirmed the presence of inhomogeneities and ejection of the material from the surface. Under certain conditions, the emergence of conducting metal jets from the electrode surface was detected.

INTRODUCTION

Over the past 15–20 years, considerable attention has been given to the study of electromagnetic methods of solid body acceleration to high velocities. It was expected that the use of electromagnetic forces would make it possible to attain velocities far exceeding the experimental values obtained previously. Much hope was pinned on the acceleration of dielectric solids in rail launchers (RL) using a plasma armature (PA). In particular, there have been projects aimed at attaining velocities of 12, 15, 25, and 50 km/sec, and higher [1]. However, experimental studies performed in many laboratories showed that the indicated projects did not consider a number of physical processes due to the interaction of the plasma armature with the walls of the railgun channel (primarily with the electrode surface).

Experiments and simple estimations show that in RL of small length, effective acceleration of plasma and solids can be attained if the linear current density I/b far exceeds the critical current density $(I/b)_{\rm cr}$ for which the electrode-surface temperature at a chosen point reaches the melting point of the electrode material (generally, the melting point of the railgun-channel walls) over the time of passage of the plasma armature through this point [2]. Layers of molten metal and insulator material form on the surfaces of the electrodes and insulators, respectively. Under the action of electromagnetic and other forces, this melt in the form of drops (vapor or plasma) can enter the discharge gap and have a significant influence on discharge parameters.

The analysis of the forces acting on the melt in powerful arc discharges has been given considerable attention in the literature but no unified explanation of the ejection and drop formation phenomena is not available because of the complexity and variety of the processes considered [3].

Obviously, there may be different manifestations of the effect of the erosion mass, depending on the time when the erosive mass entered the RL channel. If the entry of erosion products occurs almost instantaneously, with a delay of a few microseconds, this leads immediately to changes in voltage, current-density distribution, the friction force exerted on the PA by the channel walls, and, hence, in acceleration. If the entry of the erosive mass occurs with a delay of tens and hundreds of microseconds, this can lead to formation of secondary breakdowns if the PA is inside the RL channel at that time. At even larger delay times (hundreds of microseconds), it becomes possible to eliminate the effect of erosion on the RL operation. Exactly this is the goal work on designing erosion-resistant materials and multi-section RL.

The present paper reports results of studies of the traces remaining on the electrode surface after interaction with a plasma armature and results of flash radiography of the electrode surface during electric discharge.

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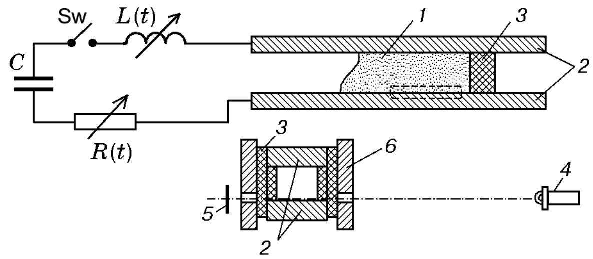

Fig. 1

EXPERIMENTS

The experiments described here were performed under conditions of a magnetically pressed (H-pressed) discharge close to the conditions of railgun operation in the initial stage of solid body acceleration.

A diagram of the experiment is given in Fig. 1, where 1 is a plasma armature, 2 are copper electrodes, 3 are insulators, 4 is an x-ray tube, 5 is an x-ray film, and 6 is a steel band. The x-ray tube was located so as to record the surface of one of the electrodes. The region recorded on the film is shown by a dashed line.

The capacitance of the capacitor bank was $3.4 \cdot 10^{-3}$ F, and the working voltage was up to 5 kV. The maximum discharge current was varied between 200 and 400 kA. The RL models used in the experiments had channel dimensions of 2×3 and 8×8 mm.

Two series of experiments were performed. In the first series, using an optical microscope, we analyzed the traces left on the electrode surface after interaction with the plasma armature. In the second series of experiments, the state of the electrode surface during discharge was studied by flash radiography using a PIR-100 flash radiograph.

The high discharge chamber pressure does not permit the use of insulators of small thickness. In the experiments, the total thickness of the fiber-glass plastic insulators was 10 mm. Under these conditions, it is possible to record the image of a copper wire 0.15 mm in diameter.

RESULTS OF EXPERIMENTS

Investigation of the Electrode Surface after Interaction with an *H*-Pressed Discharge Plasma. After each experiment, the electrode surface was examined under an optical microscope. Next, the electrodes were cut into microsections, and their microstructure and microhardness were studied.

The absence of motion of the dense plasma along the electrode surface and fast cooling of the melt enable the relief to be retained after the experiment. The traces from the action of the PA on the electrode surface were conditionally divided into regions with dimension equal to the cross-sectional dimension of the channel. The following pattern of thermal action on the electrode is observed.

In region Nos. 1–5, melting of the surface is recorded with a typical depth of the molten layer of 50 μm.

In region Nos. 1–3 a wave structure forms which has a wavelength of about 1 mm and wave crests parallel to the magnetic field (Fig. 2).

In region Nos. 2–3, maximum fracture of the electrode surface occurs (region of maximum thermal action); here a great number of large drops is detected and the wave structure is replaced by a “star-like” structure with rays in the shape of rolls converging to the central bulge.

In region Nos. 4–5, the melt solidifies in the form of fine ripple (10 crests per 1 mm) and the wave pattern (Fig. 3) is similar to the flow of a liquid film along an inclined plane in a gravity field [4].

In region Nos. 6–10 there is change in the color of the surface due to thermal action, and the structure of the electrode material is close to the original one.

With change in discharge energy, the thermal action pattern does not change qualitatively.

The numerous drops-bulges on the copper electrode surface (observed primarily in region Nos. 2–3) can be divided into four groups:

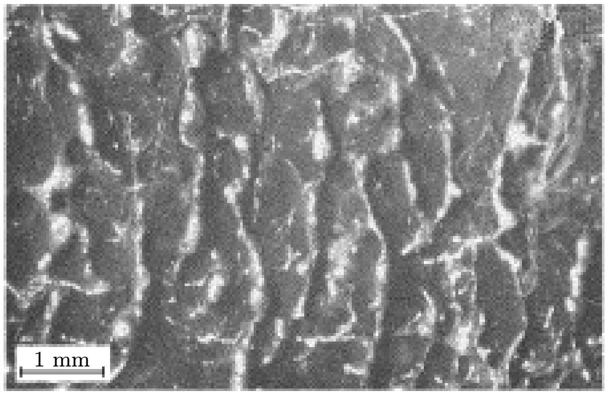

Fig. 2

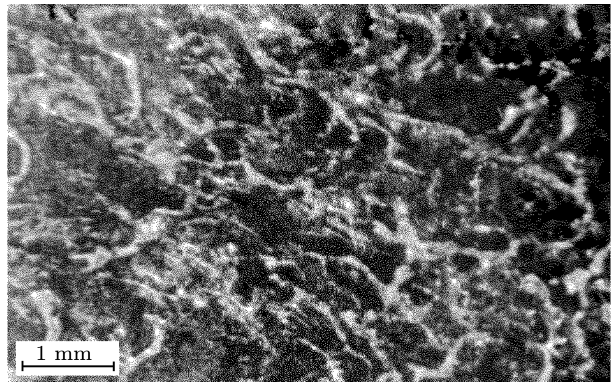

Fig. 3

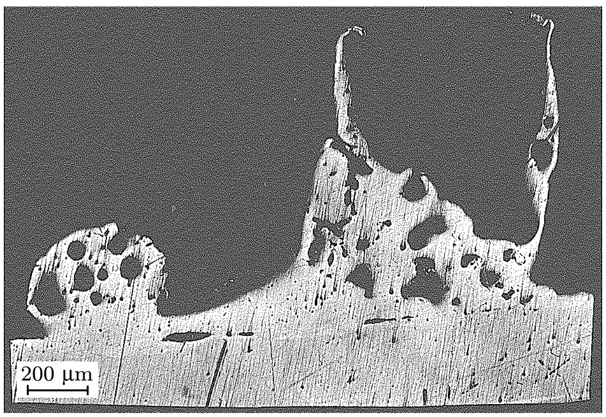

Fig. 4

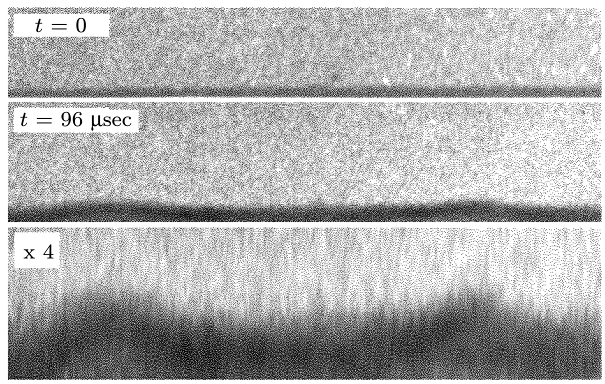

Fig. 5

1) splashes-drops of the melt without pores and gas emission;

2) bubble-saturated drops attached to the surface;

3) drops having limited contact with the surface;

4) hollow formations (closed and open), having the shape of a cylinder or a sphere; the height and diameter of the bulges reach 1 mm (Fig. 4).

As the discharge energy increases, drops with a size of a few millimeters (which is comparable to the channel size) appear on the melt surface.

Thus, an analysis of the traces due to the interaction of the plasma with the electrode surface leads to the following conclusions:

— the great number of pores and hollow structures indicates the processes of boiling and gas emission;

— flow of the melt over the material surface is observed;

— the presence of a wave structure whose wavelength and orientation depend on the magnetic field shows that electromagnetic forces influence the formation of the surface relief.

The formation of waves, bulges, and drops can affect both the service life of the facility (possibility of reusing the electrodes) and the processes occurring during discharge if the bulges form rather rapidly.

To determine the time of material ejection and relief formation, we performed flash radiography of the electrode surface during electric discharge.

Flash Radiography of Melt Ejection from the Electrode Surface in a Stationary *H*-Pressed Discharge. Flash radiography was performed at various times at an average current density of $j = 4 \cdot 10^9$–8×10^9 kA/m^2.

By the moment the current reaches the first maximum ($t = 48$ μsec) in the 2×3 mm channel, the surface of the copper electrode becomes rough, and one can see separate inhomogeneities 0.1–0.2 mm high. At $t = 96$ μsec

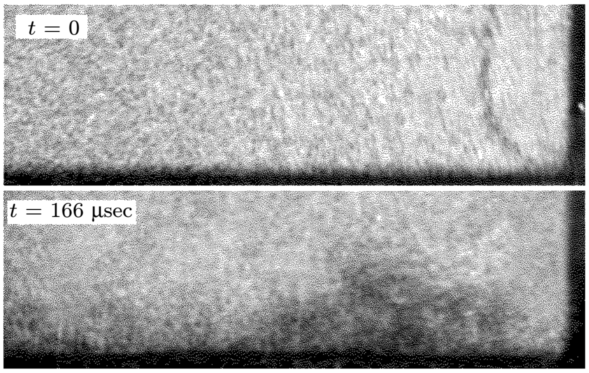

Fig. 6

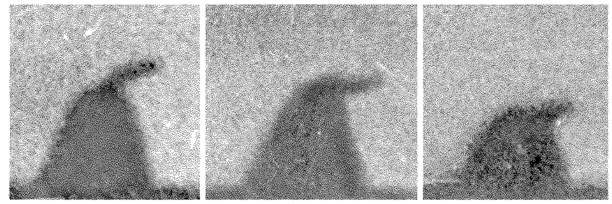

Fig. 7

(at this moment, the current is equal to zero), the surface becomes wavy. Two crests with a height of 0.2 mm and a wavelength of 5–6 mm can be seen (Fig. 5). At the moment the current is minimal ($t = 166$ μsec), one can see ejections of material with dimensions of 0.5–1.0 mm in the region of the wave crest (Fig. 6). The ejection is recorded as a cloud with diffused boundaries, which does not permit one to conclude unambiguously on the state of the material in this ejection. Large drops with a size of about 1 mm are observed on the electrode near the site of the ejection.

In the experiments with radiography of the flat electrode surface in a stationary H-pressed discharge, the following results were obtained:

1. Near the maximum discharge current ($t \approx 50$ μsec), inhomogeneities appear on the electrode surface which are 1 mm apart and have amplitude less than 0.1–0.2 mm. Ejection of the material was not detected.

2. The dimensions of the inhomogeneities do not change until $t = 90$–100 μsec.

3. Later (at about at $t \approx 90$ μsec for the 2×3 mm channel and at $t \approx 170$ μsec for the 8×8 mm channel), besides small-scale instability, a wave structure with a wavelength of 5 mm and a height of 0.2 mm appears.

4. At the moment the minimum current is attained (at $t \approx 170$ μsec in experiments with the 2×3 mm channel,), ejection of material occurs in the neighborhood of the wave crest, and the dimensions of the ejection reach 1 mm. After the experiment, drops of about 1 mm diameter appear in this region.

5. In experiments with the 8×8 mm channel, drops of 1 mm diameter form at about $t \approx 400$ μsec. When the time of RL operation is less than 400 μsec, such drops do not influence the acceleration in the RL but they can determine ablation of the surface and the multishot life of the channel. The governing mechanism of drop formation and removal of the melt from the surface is the boiling of the overheated melt or the boiling of the melt and expansion of the pores with pressure drop in the RL channel.

To increase the current density at the same discharge chamber pressure, we performed experiments with an artificially produced copper bulge in the form of an ellipsoid of revolution with semiaxes $a = 2.5$ mm and $b = 1$ mm. This bulge was located on the surface of the copper electrode in the 8×8 mm channel. At the vertex of the ellipsoid, the current density is about $6 \cdot 10^9$ A/m^2. At $t = 56$ μsec, we recorded ejection of the electrode material in the form of a jet about 2 mm long from the vertex of the ellipsoid (Fig. 7a). In Fig. 7b and c, one can see ejections obtained at later times in similar experiments. In all experiments, the jet is deflected in the direction of action of the electromagnetic force. This suggests that a current flows in the jet, i.e., the material is ejected in a conducting state. The jet velocity is estimated at $V \gtrsim 40$ m/sec.

DISCUSSION OF RESULTS

The experimental data given above show that during discharge, instabilities develop on the electrode surface, which can lead to the entry of the electrode material into the launcher channel. Let us estimate the wavelength $\lambda_{\max}$ and the characteristic rise time τ for the most rapidly developing perturbations of some types of instabilities for a melt layer 50 μm thick and surface tension of the melt $T = 1.1$ N/m.

Rayleigh–Taylor Instability. Assuming that during launcher operation, the electrodes move at an acceleration $g \approx 4 \cdot 10^6$ m/sec^2 [5], it is easy to obtain estimates $\lambda_{\max} = 7 \cdot 10^{-5}$ m and $\tau =$ 2–3 μsec, which is about two orders of magnitude smaller than the characteristic time of operation of a rail launcher.

Helmholtz–Kelvin Instability. Using the well-known formulas [4] for a plasma of density $\rho \approx 1$ kg/m^3 moving at velocity $v = 10^3$ m/sec parallel to the interface between the plasma and a medium of density $\rho_2 = 9 \cdot 10^3$ kg/m^3 (melt), we obtain estimates for the wavelength $\lambda_{\max} = 10^{-5}$ m and the characteristic time of instability development $\tau < 1$ μsec.

"Necking" Instability of a Conducting Liquid Surface under the Action of a Highly Skinned Electric Current. We restrict ourselves to qualitative estimates for an electrode of a cylindrical shape. According to [6], we analyze the development of instability of a conducting liquid cylindrical layer on the surface of a conducting solid rod which is in the magnetic field of the current flowing along the conductor. Electric current flows in the liquid layer and part of the solid rod. The liquid was considered inviscid and incompressible, and surface tension and inertia of the liquid were taken into account. An analysis of the dispersion relation obtained shows that in the case of a thin melted layer, the presence of a solid rod leads to a sudden decrease in the increment and a shift of its maximum toward shorter wavelengths compared to the case of a liquid cylinder. At the same time, a decrease in the depth of penetration δ of the electric current leads to a sudden increase in the increment.

For a conductor radius $r_0 = 3 \cdot 10^{-3}$ m, $\delta = 5 \cdot 10^{-4}$ m, and $I/b = 10^7$ A/m, the wavelength $\lambda_{\max} \approx$ 0.25 mm and the characteristic rise time is $\tau \approx 10$ μsec. As I/b decreases to 10^6–$2 \cdot 10^6$ A/m, the wavelength $\lambda_{\max}$ increases to values of about 1 mm, and the characteristic time of perturbation growth τ increases to several hundred microseconds. The obtained estimates of the wavelength are close to those observed in experiments.

Instability of a Liquid Conducting Surface with Passage of an Electric Current trough It. An analysis in [7] showed that when an electric current flows through an interface between two media with markedly different conductivities (the melt on the electrode surface and the plasma), this interface can be unstable. Estimates show that for a current density $j = 5 \cdot 10^9$ A/m^2, the wavelength $\lambda_{\max} = 0.5 \cdot 10^{-3}$ m and the characteristic time $\tau = 50$ μsec. Because in the RL, the local current density can be beyond the average density, the development of this type of instability can also affect the acceleration process.

Thus, the electrode material can enter the discharge in times much smaller than or comparable to the time of launcher operation.

The studies performed showed that in estimating the potentials of acceleration of solids in plasma-armature RL, it is necessary to take into account complex physical processes and phenomena that occur in the RL channel when the plasma armature interacts with the electrode surface.

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