The sequence of processes in the ecton cycle of a vacuum arc

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The sequence of processes in the ecton cycle of a vacuum arc

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Abstract. The paper deals with the temporal structure of the explosive electron emission cell of the vacuum arc cathode spot. Essential features of the cathode spot cells operation - the ignition, burning and extinction have been considered in frames of the ecton model.

The processes that occur in the cathode spot (CS) of a vacuum arc are known to be cyclic in nature [1]. The CS ejects plasma bunches that we name ectons [2]. The sites of their origin are called cathode spot cells [3]. The period of time in which a cell operates is called an ecton cycle. An ecton is formed due to the electrical explosion of a liquid-metal jet that occurs when the jet interacts with plasma [1–4]. The cell processes are responsible for the principal vacuum arc phenomena, such as the emission of electrons and ions and the formation of liquid-metal jets and droplets, and determine the arc characteristics, such as threshold current, ion charge states, cathode fall potential, arc lifetime, etc. The cells and their cycles are investigated by observing the CS traces (craters) on the cathode surface, the luminescence in the cathode–anode gap, the electromagnetic radiation, the arc voltage pulsations, etc.

Figure 1. Waveform of the voltage across a vacuum gap with copper electrode at an arc current of 4 A. The right end of the waveform indicates the decay of the arc (see the interval between points 6 and 7 in figure 2).
Let us consider the observation of arc voltage pulsations in more details by examining the arc voltage waveforms obtained in a study of the structure of an arc cycle [5]. An illustrative waveform fragment given in figure 1 shows triangular voltage pulses against the background of a voltage equal to the cathode fall potential $U_0$. The discharge operated at a current of 4 A, which is close to the cell current for copper electrodes $i=2i_0=3.2$ A. To account for the occurrence of these pulses, we consider a single-cell arc operating in the simplest one-loop circuit.

Denote the voltage applied to the electrode gap by $U$, the circuit resistance by $R$, the resistance in the cathode region by $R_c$, and the time-varying arc resistance by $R(t)$. Recall that $R_c$ is defined as

$$R_c = \frac{U_0}{2i_0}. \quad (1)$$

For a copper arc, we have the cathode fall potential $U_0=16$ V and the threshold current $i_0=1.6$ A, and hence $R_c=5$ Ω. In the experiment [5], $U$ was 300 V, $R$ was 75 Ω, and hence $R_c \ll R$. For the circuit under consideration, the arc voltage is determined as

$$U_a = U - iR, \quad (2)$$

where $i$ is the current in the circuit. It follows that the arc voltage decreases with increasing current, and vice versa.

![Figure 2. Sketch of the arc voltage variation during the ecton cycle of a cathode spot cell in a vacuum arc: $t_h$ – heating time, $t_c$ – cooling time, $t_e$ – total cycle duration, and $U_0$ – cathode fall potential.](image)

Let us consider the behavior of the arc voltage using its schematic waveform (figure 2). It can be seen that $U_a$ increases in the interval between points 0 and 1; that is, the arc current $i$ decreases. This seems to be caused by a decrease in emission current resulting from the cooling of the cell due to liquid metal splashing from the cathode surface under the action of the plasma pressure and due to heat removal by conduction. The decrease in arc voltage in the interval between points 1 and 2 is due to an increase in arc current. The increase in arc current is related to explosive electron emission (EEE) which is induced by the electrical explosion of liquid-metal jets. The jets are ejected from a melt pool formed on the cathode surface overheated by the discharge plasma. The interval between points 2 and 3 corresponds to an operating arc. The voltage increases again in the interval between
points 3 and 4, like in the interval between points 0 and 1. In the interval between points 4 and 5, a liquid-metal jet explodes due to EEE. The arc is operating again in the interval between points 5 and 6. Subsequently, if the jet and plasma parameters are inadequate to provide conditions for a new explosion, the arc current will cut off [5].

Thus, the operating cycle of a vacuum arc cell includes its heating during a time interval $t_h$ (points 1-2), burning during $t_b$ (points 2-3), and cooling during $t_c$ (points 3-4). The cycle time, in which an ecton is formed and emitted from the cathode, is

$$t_c = t_h + t_b + t_c.$$

(3)

In the experiment [5], $t_c$ was estimated to be about 30 ns, and $t_b$ and $t_h$ to be no more than 3 ns each. More exact estimates could not be obtained because of the limited resolving power of the oscilloscope.

Let us consider in more details what occurs with a cell in different cycle periods. At point 1, a previously operated cell dies out, and a new one starts forming. The liquid-metal jet having appeared in the period 0–1 starts exploding. For conventional EEE at which the emitter tip explodes due to Joule heating, the criterion for the explosion is similar to that for the explosion of a wire [6]:

$$J \int_{0}^{t_e} j^2 dt = h,$$

(4)

where $J$ is the current density in the wire, $t_e$ is the explosion time, and $h$ is the specific current action. Assuming that $t_e = t_h \sim 3 \cdot 10^{-9}$ s and taking into account that for copper $h = 4 \cdot 10^{-2}$ $A^{-2} \cdot s \cdot cm^{-4}$ [6], we obtain that the current density is about $10^{-9}$ $A/cm^2$.

However, in an electric arc, the plasma-induced explosion of a liquid-metal jet occurs not at the jet tip but throughout its surface. In this case, Joule heating does not play a dominant part. The ignition of an arc on a cathode subject to the action of plasma is a well-known phenomenon [1, 3]. Its mechanism has been investigated experimentally and by numerical simulation. For instance, the running up of copper plasma on a copper cathode being at a potential of 25 V was simulated [7]. The plasma parameters were varied over wide limits. In particular, for a plasma of density $10^{18}$ $cm^{-3}$, mean ion charge 2, ion temperature 2 eV, and electron temperature 5 eV, the explosion of a cathode microprotrusion was predicted to occur in $2 \cdot 10^{-9}$ s. The simulation took into account the Joule heating of the cathode surface and its bombardment with electrons, ions, and neutrals. In the experiment [8], new explosions were observed at a distance of 5 µm from the plasma source. The plasma density in this region reached $10^{20}$ $cm^{-3}$. Thus, an explosion on the surface of a metal cathode may occur at certain values of the plasma parameters and cathode potential. As soon as these critical values are reached, the vacuum arc becomes self-sustaining. The occurrence of arc voltage pulses (see figure 1) is indicative of self-induced cyclic processes caused by surges of the cathode potential. If the critical parameters are not reached, the arc will decay (see figure 2, interval 6-7).

Let us estimate the parameters of an operating arc (interval 2-3) assuming, based on experimental data on exploding conductors [9, 10], that at a current density of $10^6-10^7$ $A/cm^2$, the exploded metal approaches its critical point [11]. For copper, we have the following values of the critical point parameters: temperature $T_c = 8.39 \cdot 10^3$ K and pressure $P_c = 7.46 \cdot 10^3$ bar [12]. Let the emission be thermionic in nature, so that the current density is determined by the Richardson-Schottky formula (5):

$$j = AT^2 \exp \left( -\frac{\phi - \Delta \phi}{kT} \right),$$

(5)

where $A = 120.4$ $A/cm^2 \cdot K^{-2}$, $\phi$ is the work function of the cathode metal, $\kappa$ is Boltzmann’s constant, and $\Delta \phi$ is the Schottky correction given by

$$\Delta \phi = aE^{1/2},$$

(6)

where $a = 3.79 \cdot 10^{-4}$ eV/(V·cm)$^{-1/2}$ and $E$ is the electric field at the cathode.
The plasma pressure on the cathode, $P$, and the current density $j$ are related by the Tanberg formula [13] refined by McClure [14]:

$$j = \frac{2\rho}{\gamma v}, \quad (7)$$

where $\gamma = 39 \cdot 10^{-6}$ g/C is the specific erosion for copper [15] and $v = 1.3 \cdot 10^6$ cm/s is the velocity of motion of copper ions [16].

For the critical point conditions, formula (7) yields for copper $j \approx 2.9 \cdot 10^8$ A/cm$^2$. Substituting this current density value in (5), in view of (6), we find the critical electric field at the cathode, $E = 2.5 \cdot 10^7$ V/cm.

Next we estimate the emitting area $S_{em}$. As the cell current is twice the threshold current $i_0$ [3], we have

$$S_{em} = \frac{2i_0}{j}. \quad (8)$$

For a copper cathode, we have $i_0 = 1.6$ A, and thus $S_{em} = 1.1 \cdot 10^{-8}$ cm$^2$ and the emitting area radius $r_{em} = 0.6 \cdot 10^{-4}$ cm. This radius should be smaller than the radius of the crater on the cathode surface, $r_c$ (about $2 \cdot 10^{-4}$ cm for a copper cathode [17]), which is generally used to estimate the current density in an arc. However, in view of the rim formed by the molten metal around the crater, this is an overestimated value of the crater radius. To obtain a more correct radius of the melt zone (pool) in a cell, a system of two-dimensional heat equations taking into account Joule heating and magnetic field diffusion was solved in cylindrical coordinates. Empirical relations were used for thermal conductivity, resistivity, and product of density by heat capacity as functions of temperature. The radii of isotherm curves for melting were plotted versus time for a cell current of 3.2 A. It was obtained that at the end of the cycle (~30 ns), the isotherm radius $L_1$ was $1.2 \cdot 10^{-4}$ cm, which is twice the radius of the emitting area, $r_{em}$.

Let us estimate the time for which the liquid metal is expelled from the pool. Assume that if the liquid metal is expelled a distance $L_0$, the arc will start decaying. This will occur in a time equal to $L_0/v_1$, where $v_1$ is the velocity of motion of the liquid metal in the cell. The velocity $v_1$ can be estimated by the velocity of the scattering droplets. For instance, the highest velocities observed for Au and Pd are $4 \cdot 10^4$ and $4.5 \cdot 10^4$ cm/s, respectively [18]. Close velocity values were obtained using a hydrodynamic simulation for the liquid metal splashing in a vacuum arc [19]. Thus, the droplet scattering time is about 3 ns. It is likely that this time corresponds to the interval between points 3 and 4 (see figure 2); that is, it is consistent with our estimate above.

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