# Ectons in a vacuum arc

G. A. Mesyats
*Institute of Electrophysics, Ural Mountain Branch of the Russian Academy of Sciences, 620219 Ekaterinburg, Russia*

(Submitted 30 August 1994)
Pis'ma Zh. Eksp. Teor. Fiz. **60**, No. 7, 514–517 (10 October 1994)

A new mechanism for the operation of a cathode spot in a vacuum arc, based on ecton processes, is proposed. An ecton is formed by the explosion of the tip of a jet of molten metal as it interacts with plasma. It is suggested that the time over which an ecton functions is limited by the thermal conductivity of the liquid metal. Theoretical expressions are derived for the specific amount of mass removed, for the ion erosion, for the current, and the for the diameter of the craters for a copper cathode. The results agree satisfactorily with experimental data. © *1994 American Institute of Physics.*

It has been established that microscopic explosions at a cathode cause an explosive emission of electrons.[1] This emission occurs in distinct, brief events, which we call "ectons."[2] The duration of the flow of electrons in each event is determined by the time required for the emission center to cool down, with the result that the explosive electron emission is cut off. This effect is widely used to produce intense pulsed beams of electrons. Ectons also play a fundamental role in the initiation of vacuum discharges, in the conversion of glow discharges into arcs, in pseudosparks, in the deviation from the scaling law on the right and left branches of the Paschen curve and near its minimum.

In this letter we show that ectons are present in each cycle of a vacuum arc. Ectons are responsible for the emission of electrons from the cathode, for the removal of mass, for the appearance of cathode ions, for oscillations of the potential in the cathode region, and for other effects.

We start from Kesaev's idea[3] that a cathode spot consists of distinct cells, from which a current $i_m$ flows; this current is equal to twice the threshold current for the arc, $i_n$. An ecton forms as the result of an interaction of a jet of molten metal with plasma. Such jets are created by virtue of the high pressure in the vicinity of the microscopic explosion; this pressure ranges up to[2] $10^4$–$10^5$ atm. At a current above the threshold, a jet of liquid metal forms a droplet. Even before detaching, this droplet leads to an intensification of the current density of ions moving out the plasma at the junction point of the jet and the droplet. This effect leads to a high concentration of energy at the junction and to the formation of an ecton by virtue of Joule heating of the junction.[1]

We assume that an arc cycle consists of two processes. The first, which lasts $t_e$, is the operation of an ecton. The second, lasting $t_i$, results from the flow of ion current in the cathode region. Over the time $t_i$, the formation of a new jet of liquid metal is completed, with the result that a new ecton is formed. The process thus becomes self-sustaining.

If a new ecton is formed upon the detachment of a droplet, the condition for self-sustenance of an arc cycle can be written

$$\gamma_k t_c i_m \geqslant 1, \tag{1}$$

where $\gamma_k$ is the number of droplets during the flow of one coulomb of charge, $t_c = t_e + t_i$ is the duration of an arc cycle, $i_m = 2i_n$ is the minimum current of a cell, and $i_n$ is the threshold current of the arc.

We thus assume that a conical jet of liquid metal with a vertex angle $\theta$ is formed as a result of the operation of the arc. The length ($r$) of the generatrix of the cone at which a certain temperature $T$ is reached is then determined from the model of Joule heating of the cone. If we are interested in the temperature $T = T_B$, which is equivalent to explosion of the cone, we have[1]

$$r = \left( \int_0^t i^2 dt / 16\pi^2 \bar{h} \sin^4 \frac{\theta}{4} \right)^{1/4}, \tag{2}$$

where $\bar{h}$ is the specific action characterizing the explosion of the metal. We assume that explosive emission comes to a halt at the radius $r = r_\lambda$, where $r_\lambda$ is the thermal-conductivity radius. If $i = i_m$ and

$$r_\lambda = 2(at)^{1/2}, \tag{3}$$

where $a$ is the thermal conductivity and $t$ is the time, we find from (2) and (3) that the ecton functions for a time

$$t_e = i_m^2 / 256\pi^2 a^2 \bar{h} \sin^4(\theta/4). \tag{4}$$

The length of the generatrix of the cone corresponding to this time is

$$r_e = i_m / 8\pi (a\bar{h})^{1/2} \sin^2(\theta/4). \tag{5}$$

The mass of metal removed in the course of the explosion is $m_e = 4\pi \sin^2(\theta/4) r_e^2 \rho/3$, i.e.,

$$m_e = 4\pi\rho i_m^3 / 384\pi^2 (a\bar{h})^{3/2} \sin^4(\theta/4), \tag{6}$$

where $\rho$ is the density of the metal.

The charge of electrons carried off during a cycle is $q_c = i_m t_c$, and the specific removal of mass is $\gamma_m = m_e / q_c$. Using (6), we find

$$\gamma_m = 2\rho(1-\alpha) a^{1/2} / 3\bar{h}^{1/2}, \tag{7}$$

where $\alpha = t_i / t_c$ is the fraction of the time in the cycle corresponding to the ion process.

Research on vacuum discharges has shown that the explosion of microscopic tips is accompanied by emission of a cathode plasma, which moves toward the anode at a velocity[1] $v > 10^6$ cm/s. This effect gives rise to a current of positive ions moving toward the anode. According to (7), the fraction of the total arc current represented by this ion current is

$$\gamma_i = 2ez\rho(1-\alpha) a^{1/2} / 3A\bar{h}^{1/2}, \tag{8}$$

TABLE I.

| $A$, $10^{-22}$ g | $i_m$, A | $a$, cm$^2$/s | $\bar{h}$, $10^9$ A$^2\cdot$s/cm$^4$ | $\rho$, g/cm$^3$ | $z$ | $t$, $10^{-9}$ s |
|---|---|---|---|---|---|---|
| 3.07 | 3.2 (Ref. 3) | 0.41 (Ref. 4) | ~1 (Ref. 5) | 8.9 | 0.55 (Ref. 6) | ~25 (Ref. 1) |

where $z$ is the degree of ionization of the plasma, $e$ is the charge of an electron, and $A$ is the atomic weight of the cathode metal.

By the end of the operation of the ecton, the current density is

$$j_e=i_m/4\pi r_e^2 \sin^2(\theta/4)$$

or, if we use (5),

$$j_e=16\pi a\bar{h} \sin^2(\theta/4)/i_m. \qquad (9)$$

In Eqs. (4)–(9), the quantities $a$ and $\bar{h}$ must be used for liquid metals at temperatures $T\geqslant T_{\text{melt}}$.

A comparison of theory and experiment was made for an arc with copper electrodes. Table I shows thermal and other properties used below. The average cycle duration $t_c=25$ ns was estimated from the potential oscillations at the cathode of the copper arc at a current of 4 A (Ref. 1). It was assumed that abrupt changes in the potential correspond to the ion phase. It follows from Ref. 1 that we have $t_i\ll t_e$ (i.e., $\alpha\ll 1$) on the average, but it is difficult to find an accurate estimate of $t_i$.

We first work from Eqs. (7) and (8) to estimate the ratio of the ion current to the arc current and the specific removal of mass. It was shown in Ref. 5 that we have $\gamma_i\approx 0.08$ for many metals. In our model, we can find this value of $\gamma_i$ by setting $\alpha=0.18$. In this case the specific removal of mass is $\gamma_m\sim 1\times 10^{-4}$ g/C. The experimental data[1,7] on $\gamma_m$ lie in the range $(0.4-1.15)\times 10^{-4}$ g/C. Our calculations agree best with the measurements of Kimblin,[6] who found $\gamma_m=1.15\times 10^{-4}$ g/C.

For further estimates we need to know the cone angle $\theta$. If $\alpha$ and $t_c$ are known, we can find $t_e$ and then $\theta$, from Eq. (4). In our case we find $\theta\approx 0.74$. We can also find $\theta$ if we know the specific number of droplets, $\gamma_k$, emitted by a cathode spot of the arc. For silver, for example, we have[9] $\gamma_k\approx 1.4\times 10^7$ C$^{-1}$. According to Eq. (1), at a current $i_m=3.2$ A the time $t_c$ is $\approx 22$ ns; this result is close to the result found experimentally from potential oscillations. For the general case, using $\sin(\theta/4)\approx\theta/4$, and substituting (1) into (4), we find

$$\theta^4\approx i_m^3\gamma_k/\pi^2(1-\alpha)a^2\bar{h}. \qquad (10)$$

Let us estimate the arc current density. This current density will differ at different times. Upon the initiation of an ecton, the current density is found from the relation[1] $j_{\text{init}}^2 t_{\text{ex}}=\bar{h}$. Since we have $\bar{h}=10^9$ A$^2\cdot$s/cm$^4$, and the delay of the explosion is $t_{\text{ex}}\approx 10^{-9}$ s, we find $j_{\text{init}}\approx 10^9$ A/cm$^2$. When the ecton stops functioning, the current density is found from expression (9); it is $j_e\approx 2.2\times 10^8$ A/cm$^2$. This result corresponds to the conclusions reached by many investigators.[1,3,10] Ordinarily, however, the current density is estimated from the measured radius of a crater ($r_{\text{cr}}$) on the surface of the cathode and from the current flow. If we estimate the crater radius from $r_{\text{cr}}=2(at_c)^{1/2}$, we find

$r_{cr} = 2 \times 10^{-4}$ cm. This result corresponds to the data of Ref. 8 at arc currents $i < 10$ A. In this case the apparent current density is $i_m / \pi r_{cr}^2 = 2.7 \times 10^7$ A/cm$^2$. This figure is close to the value found experimentally in Ref. 8 for tungsten, although it is unrelated to the actual current density.

In summary, we have proposed a new model for the operation of a cathode spot in a vacuum arc, in which ectons play a fundamental role.

[1] G. A. Mesyats and D. I. Proskurovskiĭ, *Pulsed Electric Discharges in Vacuum* [in Russian] (Nauka, Novosibirsk, 1984).

[2] G. A. Mesyats, "Ectons in electric discharges," JETP Lett. **57**, 95 (1993).

[3] I. G. Kesaev, *Cathode Processes in Electric Arcs* [in Russian] (Nauka, Moscow, 1968).

[4] V. E. Zinov'ev, *Thermophysical Properties of Materials at High Temperatures* [in Russian] (Metallurgiya, Moscow, 1989).

[5] Yu. A. Kotov *et al.* "Action integral and energy in the electrical explosion of conductors," Preprint 41, Tomsk Polytechnical Institute, Tomsk, 1986.

[6] C. W. Kimblin, J. Appl. Phys. **44**, 3074 (1973).

[7] J. E. Daalder, J. Phys. D **8**, 1647 (1975).

[8] V. F. Puchkarev and A. M. Murzakayev, J. Phys. D **23**, 26 (1990).

[9] T. Utsumi and J. H. English, J. Appl. Phys. **46**, 126 (1975).

[10] G. W. McClure, J. Appl. Phys. **45**, 2078 (1974).

Translated by D. Parsons