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Splashing conditions for a liquid metal in vacuum arcs: Cyclic processes in a cathode spot

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Abstract. Molten metal extrusion from craters that form on the cathode during vacuum arc burning is considered. Using the hydrodynamic similarity principle, this process is compared with the well-studied splashing process that can develop within the impact of drops impinging one by one on a solid surface (the arc cycle duration is identified with the inverse frequency of the drop train). Based on this analogy, the conditions under which the regime of spreading of a liquid over the cathode surface will change into the splashing regime (accompanied by the formation of microjets and droplets) are analyzed. As it turns out, the conditions realized in vacuum arc cathode spot at near-threshold currents are close to the splashing threshold of liquid metal. This gives grounds to relate the existence of a threshold arc current to the existence of a threshold for the process of liquid metal jet formation.

1. Introduction

As is known [1], a burning of vacuum arc discharge is accompanied by the crater formation on the cathode with the diameters of the order of several micrometers. This process was simulated numerically in recent papers [2–4]. The photographs of cathode surfaces [5–7] show the “crown-like” patterns formed when the molten metal is ejected from craters under the action of the cathode plasma pressure. The liquid-metal microjets appear around the crater that, as noted in [8–13], resembles the patterns, which can be seen in hydrodynamic experiments on liquid drop impact on a solid surface (see, for example, [14]).

Mesyats [1] proposed that hydrodynamic processes play a key part in self-sustainment of arc discharges: the appearance of microinhomogeneities of the cathode surface due to the formation of jets creates the conditions for initiation of explosive electron emission and, consequently, for self-sustainment of vacuum arc discharge. According to the ecton model of the cathode spot (CS) [1, 15, 16], the time of the current flowing through a single crater (the arc cycle duration $T_{cs}$) is limited and is of the order of dozens of nanoseconds. Electric current through the crater is limited from below; its threshold value is $I_c \approx 1.6$ A for copper and tungsten cathodes [1,17]. The total arc current consists of currents that flow through individual craters (cells of the cathode spot in terms of [17]), so that the vacuum arc cannot be ignited if $I < I_c$. Characteristic currents, flowing through the individual crater, lie in the range from one to two threshold currents [1], i.e., $I \approx (1–2)I_c$. 

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In [8], a new approach to investigation of liquid metal motion in the cathode spot of vacuum arc was proposed. It was based on the assumption that this situation is broadly similar to the classical hydrodynamic problem of a drop impact on a surface. The basis for such analogy is the hydrodynamic similarity principle: the processes will proceed in a similar way in geometrically similar systems with different spatial and time scales. The obvious advantage of this approach is the following: on the one hand, the characteristic times of hydrodynamic processes in the cathode spot are a few or dozens of nanoseconds and the characteristic scale is a few microns, which complicate their observation in dynamics. On the other hand, the typical time and spatial scales in the problem of drop impact on a surface are as a rule milliseconds and millimeters, respectively. As a consequence, for the latter case, there are a lot of experimental data on a fluid behavior and, particularly, on splashing conditions.

The analysis of [8–13] allowed to put forward a hypothesis that the existence of threshold current of the discharge may be conditioned by the hydrodynamic processes in the cathode spot: for $I < I_c$, the jets formation does not occur during the molten metal extrusion. In the mentioned papers, the authors limited themselves to comparison with the most well-studied problem of single drop collision with a surface [14]. It should be noted that, along with this, the investigations were carried out on a periodic fall of drops, in which a new parameter, the frequency of the process, appeared. Since the process of self-reproduction of microinhomogeneities on the cathode surface is cyclic, it makes sense to compare it with such a situation. Indeed, it can be seen from the photographs of [5, 7] that new craters form on the site of old ones: they partially or fully overlap (see also [18]). Such a picture is close enough to one that arises in the case of periodic drop collision with a solid surface.

As a drop collides with a solid surface, there are two main possible regimes of liquid motion: the splashing one, which is accompanied by the formation of jets and secondary droplets, and the spreading one, which is not. It was demonstrated in [19] that, in the case of the drop train, the transition between these regimes is convenient to analyze in terms of the following non-dimensional numbers: the capillary number $Ca$ and the non-dimensional “viscosity length” $\lambda_\nu$. These numbers are defined as follows:

$$Ca = \rho U \nu \sigma^{-1}, \quad \lambda_\nu = \sigma f^{-1/2} \nu^{-3/2} \rho^{-1},$$

where $U$ is the velocity of drops, $f$ is the frequency of the drop train, $\rho$ is the fluid density, $\sigma$ is the surface tension coefficient, and $\nu$ is the kinematic viscosity. The experiments conducted in [19] allowed (for more details, see sections 2 and 4) to find the boundary between splashing and spreading regimes on the parametric plane $Ca$–$\lambda_\nu$.

In the present work, we will estimate $Ca$ and $\lambda_\nu$ numbers for molten metal (for estimations, we will take a tungsten cathode) in the cathode spot of a vacuum arc. This will allow us to determine (on the basis of the comparison with the results of hydrodynamic experiments [19]) which regime of liquid motion will be realized. As will be shown below, the conditions in the cathode spot at near-threshold currents ($I_c \leq I \leq 2I_c$) refer to the boundary between splashing and spreading regimes. This result justifies the conclusion of [8] that the existence of threshold current of the discharge may be related with the existence of splashing threshold for a liquid phase in the cathode spot.

2. Liquid splashing criterion

Let us discuss the liquid behavior in the case of impact of drop trains on a flat solid surface. On the basis of the obtained experimental data [19] relating to the following range of $Ca$ and $\lambda_\nu$ numbers:

$$0.1 \leq Ca \leq 8, \quad 3 \leq \lambda_\nu \leq 900,$$

a liquid splashing criterion was formulated. It has the form

$$Ca \geq C \lambda_\nu^{-3/4}.$$
Here $C$ is the constant, which was determined as $C \approx 16.9–18.1$.

The physical meaning of the criterion is as follows: if the inequality (3) holds, the drops collision with a wall leads to the formation of jets and secondary droplets. Otherwise, if the inequality does not hold, the liquid just spreads over the surface without splashing.

Substituting the definitions (1) for $Ca$ and $\lambda_\nu$ numbers into (3), we get the splashing criterion in the dimensional form:

$$ U \geq C\sigma^{1/4}f^{3/8}\nu^{1/8}\rho^{-1/4}. $$

This criterion contains the frequency of the drop train $f$ (the time interval between impacts of separate drops is $1/f$). As applied to the dynamics of molten metal in the cathode spot, an analog of such an interval is an arc cycle duration $T_{cs}$. This time was estimated as $T_{cs} = 25–50$ ns in [5] for a tungsten cathode by using the directly recorded oscillograms. It corresponds to the frequencies $f_{cs} = 20–40$ MHz. For comparison, in the case of hydrodynamic experiments [19], the frequency of drop train was $f \approx 20$ kHz, i.e., it differs from the characteristic arc cycle frequencies by three orders of magnitude. Also, there is an essential difference in the characteristic spatial scales of the problems (one-two orders of magnitude). On the one hand, in [19] the diameters of falling drops were in the range of 70–340 $\mu$m. On the other hand, for the threshold current, the characteristic size (diameter) of the cathode craters was $\sim 4$ $\mu$m [5, 20].

Nevertheless, despite this difference in characteristic time and spatial scales, these processes can be compared on the basis of the hydrodynamic similarity principle. This is due to the fact that, firstly, the geometries of the systems are generally similar and, secondly, as will be shown below, the non-dimensional numbers $Ca$ and $\lambda_\nu$ for the problems are comparable.

The feature of the liquid splashing criterion (4) that distinguishes it from other criteria for the fall of single drops [14] is its independency from the drop sizes. The basic scale of the problem is determined as $U/f$ and corresponds to the distance, to which a liquid moves during the cycle. However, as applied to the problem of interest to us concerning the liquid extrusion from the crater, the condition (4) includes the crater size implicitly. In the next section, we will show that the molten metal velocity depends on it essentially. This distinguishes our problem from the single drop collision with the wall, where the drop velocity is an independent parameter.

3. Molten metal dynamics in the cathode spot

In addition to the parameters of a liquid (the surface tension $\sigma$, viscosity $\nu$, and density $\rho$), the splashing criterion also includes the frequency of the cyclic process $f$ and the fluid velocity $U$. For the processes in the vacuum arc cathode spot, as it has been already pointed out, the frequency may be taken directly from the experimental data [5] ($f = 1/T_{cs}$). Along with this, determining the characteristic velocity of molten metal $U_{cs}$ (it can be matched with the velocity of falling drops $U$) requires some preliminary calculations.

To find the velocity $U_{cs}$ of the fluid extrusion from the crater, we will use the technique that was proposed in our recent work [10]. Let a molten metal initially occupies a hemispherical depression of radius $R$. The action of the expanding cathode plasma on the liquid can be described in terms of the pressure $P$ exerted by the reactive force (thrust) $F$ acting on the liquid (on an area of $\pi R^2$):

$$ P = F/(\pi R^2). $$

In its turn, the force $F$, according to [1, 21], is linearly related to the current $I$ flowing through a crater:

$$ F = Iu_i\gamma_i, $$

where $u_i$ is the characteristic velocity of the ions and $\gamma_i$ is the ion erosion rate (mass removed per unit charge). Here we considered that the ion velocity is directed normally to the cathode surface.
Let us assume for simplicity that the pressure outside the crater equals zero, i.e., the fluid accelerates only inside the crater and moves by inertia at the periphery. The momentum imparted to the liquid for the time $t$ is estimated as $Ft$. Dividing it by the total liquid mass $2\rho \pi R^3/3$, we obtain the rate $u(t) \approx 3Pt/(2\rho R)$, i.e., the rate linearly increases with time while the fluid is in the crater. The moment, when the liquid leaves the crater, is estimated from the condition $\int_0^{t_R} u(t)dt = R$ that gives $t_R = R\sqrt{4\rho/3P}$ and, consequently, we have for the fluid velocity

$$U_{cs} = u(t_R) \approx \sqrt{3P/\rho}. \quad (7)$$

Note that in [8] the extrusion rate was estimated from the Bernoulli law as $U_{cs} \approx \sqrt{2P/\rho}$. However, Bernoulli’s equation is valid only for stationary flows. The process under study is substantially nonstationary that, as can be seen by comparing with (7), gives an increase in the velocity estimate in $\sqrt{3}/2 \approx 1.22$ times. Taking into account (5) and (6), we finally find the expression for the liquid metal velocity that is acquired under the cathode plasma pressure,

$$U_{cs} = \sqrt{3Iu_i\gamma_i/\rho \pi R^2}. \quad (8)$$

Our reasoning in many respects was based on the results of experimental work [5], in which the vacuum arc burning was investigated at near-threshold currents for a tungsten cathode. So, we will make our estimations for this cathode material considering that its temperature is a little above the melting point. According to [22], under such conditions, tungsten has a surface tension $\sigma = 2.48$ N/m, density $\rho = 16.7 \times 10^3$ kg/m$^3$, and kinematic viscosity $\nu = 4.13 \times 10^{-7}$ m$^2$/s. According to the reviews [15, 23], the vacuum arc discharge burning on the tungsten cathode is characterized by the following parameters: ion velocity $u_i = 1.05 \times 10^4$ m/s, ion erosion $\gamma_i = 62 \mu g/C$, and threshold current $I_c = 1.6$ A. As it was established for tungsten cathode [5], the most probable diameter of the crater in the range of arc currents from a few to a few dozen amperes weakly depends on current. It is possible to take $R = 2 \mu m$ for near-threshold currents. Now we can estimate the range of fluid velocities for permissible (according to [1]) current interval from 1 to 2 threshold currents ($I \approx 1.6–3.2$ A):

$$U_{cs} \approx 122–173$ m/s. \quad (9)$$

It should be noted that the values (9) are in agreement with the results of numerical simulations [2, 24, 25] and with the experimental data [26].

Substituting the arc cycle duration $T_{cs} = 25–50$ ns and our estimations for the fluid rate (9) into (1), we get the following ranges for the capillary number and non-dimensional “viscosity length”:

$$Ca \approx 0.33–0.48, \quad \lambda_\nu \approx 88–125. \quad (10)$$

It is important that these values fall into the experimentally investigated in [19] range (2) of Ca and $\lambda_\nu$ numbers. This gives us grounds to compare processes occurring during the operation of vacuum arc cathode spot (they were not observed in situ up-to-date) and during the drop train collision with a solid surface (there exist a lot of experimental data on it). We can do it by using the hydrodynamic similarity principle despite of essential differences in temporal and spatial scales for these processes (see section 2). Particularly, this allows us to apply the splashing criterion found in [19] to describe the process of molten metal extrusion from the cathode craters.

4. Results and discussion

In figure 1, on the parametric $Ca$–$\lambda_\nu$ plane, the border between the regions, in which different regimes of liquid motion (splashing or spreading) are realized, is shown. The estimated ranges
Figure 1. Solid curves give the boundary between the spreading and splashing regimes of liquid motion according to data of [19]. Two curves characterize the scatter of the experimental data. The points correspond to our estimations for molten metal parameters in the cathode spot at near-threshold currents.

(10) for Ca and $\lambda_\nu$ numbers that correspond to the threshold conditions of vacuum arc operation are shown too. One can see that corresponding Ca and $\lambda_\nu$ values lie near the boundary between spreading and splashing regimes.

It follows from the definition (1) of the capillary number Ca that $Ca \propto U_{cs}$. In its turn, the molten metal velocity is directly proportional to the square root of current and inversely proportional to the crater radius: $U_{cs} \propto \sqrt{I/R}$ (see equation (8)). As it was mentioned, at relatively small discharge currents, the radius $R$ practically does not depend on the current $I$. Then, we can assume the radius $R$ be constant. In this case, up to several threshold currents, the following relation will be valid:

$$Ca \propto \sqrt{I},$$

i.e., the number Ca increases with increasing current $I$. It means that, at relatively high currents, we fall into the upper region of the parametric plane $Ca-\lambda_\nu$ (figure 1), where splashing of molten metal occurs accompanying with jets formation. The formation of such microprotrusions on the cathode surface provides the conditions for the initiation of explosive electron emission [15] and, consequently, for self-sustaining of vacuum arc discharge. Instabilities of individual liquid-metal jets in electric and magnetic fields that lead to their disintegration were studied in papers [27–29].

On the contrary, when decreasing the current $I$, we fall into the lower region of the parametric plane, where the regime of molten metal spreading over the cathode surface is realized. In this regime, microprotrusions on the cathode do not develop and, as a consequence, the arc extinguishes. The transition through the boundary between spreading and splashing regimes occurs at some critical discharge current which can be matched with the threshold current of the vacuum arc $I_c$. 

$$\lambda_\nu^{0.75} Ca = 16.9-18.1$$
5. Conclusions
In the present work, liquid splashing (i) during the drop train impact on a flat solid surface and (ii) in the vacuum arc cathode spot were compared on the basis of the hydrodynamic similarity principle. It was established that, at near-threshold discharge currents, $I_c \leq I \leq 2I_c$, the conditions realized in vacuum arc cathode spots are close to the threshold conditions for splashing of the molten metal. Non-dimensional parameters $Ca$ and $\lambda_\nu$, which characterize the molten metal motion in the cathode spot, fall close to the border between the regions that correspond, according to [19], to splashing and spreading regimes (figure 1). This counts in favour of the supposition that hydrodynamic processes are responsible for the threshold character of vacuum arc burning.

In the previous work [8], the liquid phase behavior in the vacuum arc cathode spot was compared with the behavior of the liquid in the single drop collision with a solid wall. The important feature of the present work is the use of experimental data on splashing conditions for periodic drop impact at the given time interval $1/f$. This allowed us to include in the analysis the arc cycle duration $T_{cs}$, which is an important parameter for understanding the mechanisms of vacuum arc operation. This magnitude, which is identified here with the interval between drop impacts ($T_{cs} = 1/f$), defines the characteristic time of microprotrusions self-reproduction on the cathode due to the liquid metal jets formation. Electric explosion of such microinhomogeneities provides the vacuum arc operation [1,15]. At below-threshold currents, $I < I_c$, microjets do not form and, as a consequence, spontaneous extinction of the discharge occurs.

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