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The "hunting effect" in the cathode region of a vacuum arc

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The interaction of liquid-metal droplets with plasma jets in the cathode region of a vacuum arc is considered based on the ecton model of a cathode spot. It is shown that the heating of a droplet which is in the zone of operation of a cathode spot can result in the transition of the droplet into the plasma state.

1. Introduction

When investigating the parameters of the cathode plasma with the use of fast laser diagnostics, *Batrakov* and co-workers [1] detected dense plasma blobs at distances of several micrometers from the cathode surface. The plasma density in these blobs was $\sim 10^{20}$ cm^{-3}, which is close to that immediately in cathode spots. We believe that the appearance of plasma blobs at a cathode is related to the interaction between the plasma jets and droplets ejected by the cathode spot of a vacuum arc.

It is well known that the cathode spot of a vacuum arc ejects plasma jets whose velocity is $\sim 10^6$ cm/s and liquid-metal droplets flying with a velocity of $\sim 10^4$ cm/s [2, 3]. These plasma jets are formed due to a high energy density in cathode microvolumes heated by the Joule mechanism by a high-density current. The high energy density leads to explosion-like disintegration of the cathode, accompanied by explosive electron emission. The liquid metal is splashed off the cathode spot region in the form of droplets and jets under the action of the reactive force occurring upon the ejection of high-velocity plasma jets. The droplet sizes depend on the arc current. For copper, gold, and palladium, at currents close to the arc threshold current i_{thr}, the droplet size distribution has a maximum at about 0.1–0.2 μm and the number of droplets leaving the cathode per unit charge is $\sim 10^7$ C^{-1} [4]. An increase in current increases the droplet size; thus, for $i \gg i_{thr}$ droplets of size up to ten micrometers are observed. Almost 90% of the droplet mass leave the cathode at an angle < 20° to the cathode plane with a velocity of $\sim 10^3$–10^4 cm/s [2, 3].

A cathode spot has an internal structure which shows up in the existence of individual cells, the lifetime of each cell being $\sim 10^{-8}$ s [2]. In this connection, the operation of a cathode spot is accompanied by cyclic ejection of plasma jets and liquid-metal droplet. Besides, the cathode spot itself is in continuous chaotic motion. The great difference in ejection velocities between the plasma and the droplets may give rise to a situation where a cathode plasma jet hits a droplet. This resembles a shot of a hunter at a flying bird; therefore, we have called this phenomenon the "hunting effect".

2. Interaction between plasma jets and droplets in the cathode region of a vacuum arc

Let us consider a noncharged droplet in a flow of quasi-neutral plasma ejected by a cathode spot. For the energy flux density P_i transferred to the droplet per unit time by plasma jet ions we can write

$$P_i = \frac{j_i\left(\overline{E}_i + \overline{U}_i - Z\varphi\right)}{eZ}, \qquad (1)$$

where j_i is the ion current density; Z and $\overline{E}_i$ are the ion average charge and energy, respectively; φ is the work function of an electron; $\overline{U}_i = \sum_i f_i U_i$ is the average ionization potential, and f_i is the fraction of the ions of charge multiplicity i.

Upon interaction with a droplet, electrons transfer to the droplet their kinetic energy and the energy equal to their work function:

$$P_e = \frac{j_i\left(2kT_e + \varphi\right)}{e}, \qquad (2)$$

where T_e is the electron temperature.

An investigation of the ion flow from the plasma of a vacuum arc has shown that the ion current toward the anode is proportional to the arc current I with a factor $\alpha \approx 0.1$ [5]. Correspondingly, for the ion current density we can write

$$j_i = \frac{\alpha I}{S}, \qquad (3)$$

where S is the cross-sectional area of the plasma jet at the site of its interaction with a droplet.

In view of relations (1)–(3), the expression for the specific energy w received by a droplet of radius R_d from a plasma jet has the form

$$w = \frac{3\alpha It\left(\overline{E}_i + \overline{U}_i + 2ZkT_e\right)}{4SZR_d\rho e}, \qquad (4)$$

where ρ is the density of the cathode material. Note that, according to (4), the specific energy is inversely proportional to the droplet radius.

Let us use the ecton model of a vacuum-arc cathode spot [2] to analyze the plasma jet parameters involved in equation (4). According to the ecton model, a cathode spot consists of individual cells, each emitting a portion of electrons – an ecton. The current of a spot cell is about twice the threshold current of the arc operation. As the arc current is increased, the spot cells are grouped in the close vicinity of one to another since, in this case, conditions are realized which are more energetically profitable for the repetition of ecton processes. As this takes place, the plasma parameters are established due to the operation of an individual cell of the spot upon explosion-like disintegration of a portion of the cathode under the action of a high-density current. A simulation of the ecton processes has shown that the ionization processes occur within a narrow (of the order of a micrometer) region near the cathode and further the charge state of the arc plasma remains practically unchanged [6]. The ions, under the action of the electron pressure gradient, acquire directional velocities of the order of 10^6 cm/s within distances as small as several micrometers. Taking this into account, to estimate the ion flow parameters $\overline{E_i}$ and $\overline{U_i}$ involved in equation (1), we can use their values measured away from the cathode. Let us consider a cathode made of copper, the material most extensively studied from the viewpoint of cathode phenomena and arc plasma properties. The kinetic energy of ions and the average ionization potential for Cu are, respectively, 56 eV and 20.4 eV [7, 8]. The electron temperature near the cathode is ~ 3–4 eV [6]. Correspondingly, for a copper cathode, the energy transferred to a droplet by ions and electrons (bracketed term in (4)) is ≈ 90 eV.

The droplet fraction of the cathode erosion plays an important role in the self-sustaining of an arc discharge [2]. As a droplet breaks off a cathode, a thin bridge is formed. The ion current from the cathode plasma, which closes on the droplet, flows through the bridge. Since the ratio of the droplet surface area to the bridge cross-sectional area may be great, the current density in the bridge may reach high values sufficient for the bridge to explode and an ecton to appear. The characteristic time of the ecton process is ~ 20–30 ns [2]. With a velocity of 10^4 cm/s, a droplet will move off the cathode surface for a distance not over 2–3 μm. If a droplet of diameter 0.1–0.2 μm, having broken off the cathode, is in the region of propagation of a plasma jet formed during the operation of an ecton, then, according to (4), for an ecton current of 3.2 A, $w > 10^4$ J/g is achieved within 20–30 ns even if the plasma expansion is spherically symmetric, i.e., $S = 2\pi r^2$, where r is the distance from the cathode. This specific energy corresponds to a droplet temperature higher than 2 eV and, as revealed in a study of the electrical explosion of conductors and the initiation of explosive electron emission [2], it is suffice for a material to go from the condensed to the plasma state.

We have shown above that a dense plasma can be generated during the operation of an individual cathode spot cell. An increase in current increases the number of ectons and makes the droplet larger. When a spot moves to a new site and the droplet formed during the operation of the previous spot appears in the zone of its action, coarse plasma blobs may appear at a certain distance from the cathode surface. This process is quite probable since the velocity of motion of the spot over the cathode surface (~ 10^4 cm/s) is comparable to the velocity of flight of the droplet.

Let us consider the interaction of a droplet with a collectivized plasma jet produced by an ensemble of simultaneously operating ectons. To estimate the ion current density, we use the data of *Daalder* [9] according to which, for a current of 100 A, the cathode spot diameter is 10 μm. In this case, for a droplet of radius R_d = 0.5 μm being 5 μm away from the cathode surface and a plasma jet with an expansion angle of 60° [10], at t = 30 ns the specific energy is over 10^4 J/g.

3. Conclusion

Thus, the above analysis based on the ecton model has demonstrated that dense plasma blobs can be formed near a cathode due to the interaction between the plasma jets and droplets ejected by the vacuum arc cathode spot.

4. Acknowledgement

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5. References

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