Analyzing Spotless Mode of Current Transfer to Cathodes of Metal-Vapor Arcs

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Abstract- **The diffuse, or spotless, mode of current transfer has been observed on cathodes of vacuum arcs under conditions where the average cathode temperature was high enough, about 2000 K. It has been known for many years that none of the known mechanisms of current transfer to cathodes of vacuum arcs and, in particular, of the electron emission is capable of producing the current densities of the order of 10^5 - 10^6 Am^{-2} deduced from the experiment. A fresh attempt to clarify this question is made in this work. Cathodes made of chromium are considered, on which the most of the experiments have been performed. It is shown that an account of the difference between values of thermionic and photoelectric work functions given in the reference literature allows one to significantly reduce the deviation between the theory and the experiment. Unfortunately, data on thermionic work function available in the literature refer to the cathode surface temperatures below 1400 K, which is significantly smaller than measured temperatures of the chromium cathodes of vacuum arcs operating in the spotless mode. Therefore, further experimental data are needed in order to clarify this effect.**

I. INTRODUCTION

It is well known that current transfer to cathodes of arc discharges in ambient gases may occur in the spot mode, where the most of the current is localized in a narrow domain, or current spot, occupying a small fraction of the cathode surface, and in the diffuse, or spotless, mode, where the current is distributed over the front surface of the cathode in a more or less uniform way. The diffuse mode is favored by small cathode dimensions: if the cathode is small, it is easier to heat it up to temperatures necessary for the diffuse operation; a feature well familiar to designers of ambient-gas arc devices.

Spots on cathodes of vacuum, or metal vapor, arcs are known equally well. The spotless mode of current transfer to cathodes of vacuum arcs seems to be known not so well, however its existence has been firmly established by now [1-7]. Similarly to the diffuse mode on cathodes of ambient-gas arcs, the spotless mode on cathodes of vacuum arcs occurs in cases where the average temperature of the cathode surface is high enough. Values of the cathode surface temperature necessary to this end are typically around 2000 K and can be achieved by placing the (evaporating) cathode into a thermally insulated crucible made of a material for which a vacuum arc would burn at a higher voltage than for the cathode material. Characteristic features of this discharge are a relatively low current density at the cathode, which is of the order of 10^5 - 10^6 Am^{-2}, and the ability to generate steady highly ionized plasma containing no microdroplet fraction. The latter feature may be attractive for applications; e.g., [7]. Note that the above-described vacuum arc discharge with a diffuse cathode attachment should not be confused with the so-called thermionic vacuum arc discharge [8], which can be ignited in high vacuum conditions between a heated cathode operating as an electron gun and an evaporating anode placed in a tungsten crucible and heated to a high temperature by the electron beam.

From the point of view of theoretical description the spot mode is more challenging than the spotless mode, since an additional question of determination of shape, dimensions, and positions of the spots arises. As far as cathodes of ambient-gas arcs are concerned, this question has been answered by means of treating spots as self-organization phenomena. With the use of this approach, the understanding of both diffuse and spot modes on cathodes of ambient-gas arcs was significantly improved, relevant simulation methods developed, and a relation with spots and patterns in DC glow gas discharges established; e.g., reviews [9, 10] and references therein. In particular, axially symmetric and three-dimensional stationary and transient spots on cathodes of arcs in ambient gases can be self-consistently simulated as a matter of routine nowadays.

Recently, the same approach was applied to simulation of stationary spots on cathodes of vacuum arcs [11]. (There is also a variety of other approaches in the literature; e.g., [12] and references in [11].) However, understanding of the spotless mode on cathodes of vacuum arcs remains elusive: it was concluded in the pioneer work [1] that none of the known mechanisms of current transfer to the cathode surface and, in particular, of the electron emission is capable of producing the above-mentioned current densities, and this conclusion still stands. Given that the effort invested by different groups in the experiment and its theoretical analysis has been quite significant [1-7, 13-15] and that the spotless arc attachment to cathodes of vacuum arcs, being in essence a one-dimensional and stationary phenomenon, represents a much simpler

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object than cathode spots, this state of the art is rather surprising and detrimental not only to potential technological applications of spotless vacuum arc discharges, but to the vacuum arc physics in general.

A fresh attempt to elucidate basic mechanisms of the spotless vacuum arc attachment to cathodes is undertaken in this work.

II. Analysis

The cathode material on which the most experiments have been performed is chromium with most detailed data having been reported in [6]. The arc current in these experiments varied from 30 to 250 A, the arc voltage from 25 to 12 V, and the cathode temperature T_w from 1800 to 2100 K. Since the cathode radius was 9.5mm, the above current range corresponds to current densities of the order 10^5 - 10^6 Am^{-2}. The bulk of the results [6] conforms to [1]; an important fact supporting the credibility of both works.

While analyzing the experimental data, the authors [6] assumed the value of 4.58 eV for the work function A_f of chromium. Thermionic emission current density estimated in terms of this value with the use of the Richardson formula is shown in Fig. 1a. One can see that it attains the value of 10^5 Am^{-2} at the cathode surface temperatures T_w exceeding approximately 2850 K, which is much higher than the measured temperatures of 1800 – 2100 K. Of course, the Richardson formula does not represent a good approximation for the current density on cathodes of vacuum arcs: one must take into account contributions of currents of the ions and plasma electrons, as well as the Schottky effect and eventually the thermo-field emission. To this end, a complete model of the near-cathode plasma layer of vacuum arcs is needed, which would adequately describe, in particular, the near-cathode space-charge sheath and balance of the evaporated metal atoms with their eventual return to the cathode surface after having been ionized in the sheath. Results of such calculations performed by means of the model [16] are also shown in Fig. 1a. One can see that the density of current of ions coming to the cathode surface from the near-cathode space-charge sheath slightly exceeds the electron emission current density. The electric field at the cathode surface is not high enough for the thermo-field electron emission mechanism to come into play and the electron emission is of thermionic nature. Therefore, the electron emission current density j_{em} shown in Fig. 1a, which in the framework of the model [16] is evaluated by means of the Murphy and Good formalism, is very well represented by the Richardson-Dushmann formula. On the other hand, j_{em} exceeds the Richardson values j_R, hence the Schottky correction to the work function is significant. The current of fast plasma electrons capable of overcoming the retarding electric field of the space-charge sheath and reaching the cathode surface is negligible in these conditions and not shown on the graph.

Although the density j of net electric current at the cathode surface exceeds the Richardson value j_R by about a factor of 3, this difference is insufficient to bring the estimates close to the experiment: j attains the value of 10^5 Am^{-2} at T_w exceeding approximately 2700 K, which is still much higher than the measured temperatures.

A natural question is if the value A_f = 4.58 eV of the work function of chromium, assumed in [6] and used also in calculations shown in Fig. 1a, is adequate under conditions being considered. In [6], this value was given with a reference to the general physics reference book [17]. Indeed, the work function for polycrystalline chromium surface found in [17] (table 25.1, p. 568 of the Russian edition) is 4.58 eV, the source being the well-known reference book on emission properties by Fomenko [18]. One can verify that 4.58 eV indeed represents the value of the work function for polycrystalline chromium surface recommended by Fomenko ([18], p. 26). A similar value of 4.5 eV obtained by means of the method of photoelectric effect is cited in the general physics reference book sometimes nicknamed the 'Rubber Bible' ([19], p. 12-124), the source presumably being the recommendation given in [20].

On the other hand, in addition to the recommended value equal to 4.58 eV, the reference book [18] cites a vast set of raw data on the work function for polycrystalline chromium surface, ranging from 3.57 to 5.05 eV and mostly obtained by the method of photoelectric effect or estimated theoretically. The only work function value from this set that refers to relatively high cathode surface temperatures is the one from the paper [21], which equals 3.90 ± 0.04 eV and was obtained by thermionic method in the temperature range 1100 - 1400 K for 99.99% pure Cr surfaces. It should be stressed that the author [21] was conscious that this value was in serious disagreement with the other measurements values, so the experiments [21] have been repeated under a variety of heat treatment and outgassing conditions.

Furthermore, the Smithells Metals Reference Book [22] makes an explicit distinction between thermionic and photoelectric work functions; cf. Table 18.1 on p. 18.2 and Table 18.5 on p. 18.4, respectively. For chromium, the value of 3.90 eV is given in [22] for the thermionic work function with the reference to [21] and the value of 4.4 eV is given for the photoelectric work function.

This reasoning suggests that 3.90 eV is a more suitable value for the work function for chromium under conditions of the spotless cathode vacuum arc attachment than values of around 4.5 eV used by previous researchers. Results of calculations with the former value are shown in Fig. 1b. One can see that the deviation from the experiment is indeed significantly smaller than in Fig. 1a. Given that the value A_f = 3.90

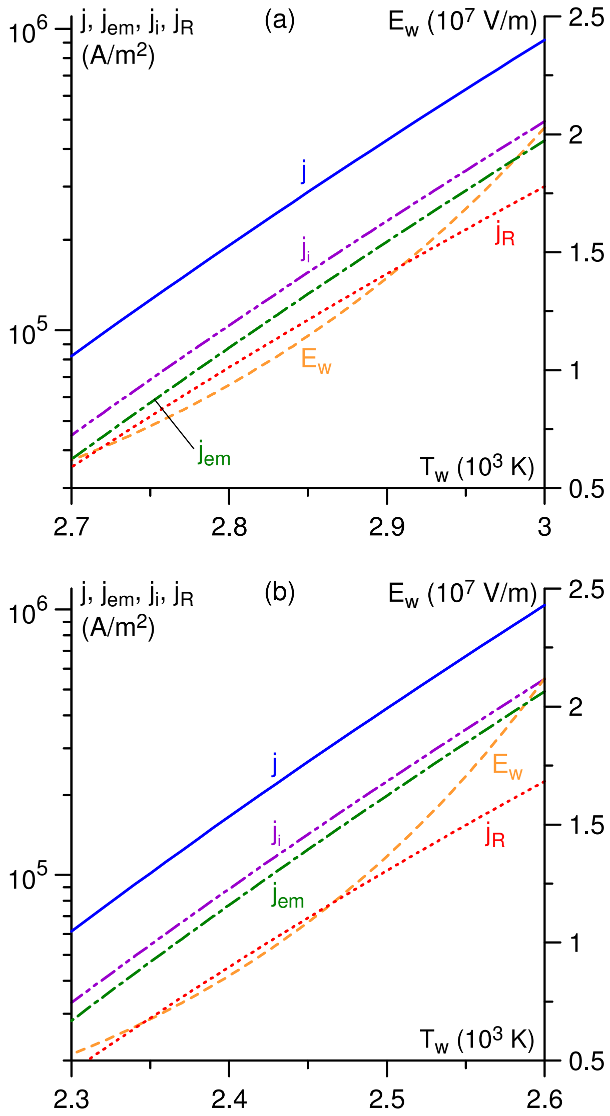

Fig. 1. Computed characteristics of near-cathode layer of vacuum arc. Chromium cathode, near-cathode voltage 20 V, work function 4.58 eV (a) and 3.90 eV (b). j_i: density of ion current at the cathode surface. j_{em}: density of electron emission current. j: net current density. j_R: electron emission current density evaluated by means of the Richardson formula. E_w: electric field at the cathode surface.

eV was measured in the temperature range 1100 – 1400 K and that values of thermionic work function A_f in the range T_w = 1800 – 2100 K may be still smaller, it is possible that the difference between thermionic and photoelectric work functions may indeed provide an explanation of high values of current density in the spotless cathode vacuum arc attachments found experimentally.

III. Conclusions

An account of the difference between values of thermionic and photoelectric work functions given in the reference literature allows one to significantly reduce the deviation between the theory and the experiment on spotless attachments of vacuum arcs to chromium cathodes. Unfortunately, data on thermionic work function available in the literature refer to the cathode surface temperatures below 1400 K, which is significantly smaller than measured temperatures of the chromium cathodes of vacuum arcs operating in the spotless more (1800 - 2100 K). Therefore, further experimental data are needed in order to clarify this effect.

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