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Cathode Erosion due to Evaporation in Plasma Arc Cutting Systems

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Abstract Erosion of a hafnium cathode in Plasma Arc Cutting torch using oxygen as plasma gas is considered. It is shown that approximately 0.001 fraction of the evaporated particles participate in a net erosion, the rest of the evaporated particles return back to the cathode after spending some time in a near-cathode plasma. Along with erosion rate, the suggested equations allow one to the calculate current density at the cathode, the cathode temperature inside the arc attachment and the electron temperature at the cathode-plasma boundary. Comparison of the obtained values with the available information on these parameters shows a reasonable agreement.

Keywords Plasma arc cutting · Electrode · Hafnium · Erosion rate

Introduction

Cathode erosion in PAC systems is inevitable but very undesirable phenomenon. It is known, that erosion takes place when the arc current is kept constant (constant current erosion), and during switching the arc on and off (cycling erosion). While the nature of the cycling erosion is not completely understood, see papers [1] and [2], the nature of the constant current erosion is clear: it is evaporation of the cathode.

Calculation the rate of the erosion due to evaporation consists of two steps. First, one should calculate the flux of the evaporating particles. This can be easily done if the cathode temperature and the corresponding vapor pressure of the cathode material are known. The Hertz–Knudsen formula provides the flux density of the evaporating particles:

$$G_0 = p(T_c)\sqrt{\frac{M_c}{2\pi k T_c}} \tag{1}$$

Here, M_c is the mass of the cathode material atom, k is the Boltzmann constant, T_c is the cathode temperature, and $p(T_c)$ is the corresponding vapor pressure. However, not all of the

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evaporated particles participate in the erosion. Some of them return to the cathode after spending some time in the near cathode plasma. The second step in calculating the erosion rate is to evaluate the amount of these returning atoms.

It is important that due to their relative low ionization potential, evaporated atoms become ionized practically instantly. Two major competing forces act on the evaporated atom/ion: electric field pulling it back and plasma flow drag pushing it away from the cathode. In the near-cathode plasma, the strong electric field exists within a relatively narrow layer where ionization equilibrium is broken. Being very strong at the plasma-sheath boundary, this field fades off further from the cathode. On the contrary, plasma flow drag is very weak close to the cathode but increases at further distances from the cathode. There is, therefore, a specific point where pulling back action of the weakening electric field is balanced by the pushing away action of the plasma flow drag. This point has been named as a point of no return. According to the concept developed in our previous works [3, 4], if an evaporated atom reaches this point, it looses the possibility to return back to the cathode. One can see that the net erosion rate is determined by location of point of no return. To calculate the net erosion rate it is, therefore, necessary to consider distributions of the main plasma parameters within ionization non-equilibrium layer along with consideration of the plasma flow close to the cathode. It would be better to have these calculations to be performed in the same work, however, as a first approximation, the plasma dynamic part of information could be taken either from experiments or from a separate work.

In paper [5], this approach has been used to calculate the erosion rate of a tungsten electrode in a free-burning arc in argon atmosphere. This type of arc, being used in GTAW welding process, is well explored both theoretically and experimentally. Calculated erosion rate showed good agreement with the available experimental data.

In this paper, we use the method developed in [5] to calculate erosion rate of the electrode in PAC. The calculations are performed for hafnium cathode in Oxygen atmosphere: the cathode material—plasma gas composition, which have been used in the paper [6], where the experimental data on cathode erosion have been taken from.

The Hf-O_2 emitter-plasma gas combination used in Plasma Arc Cutting systems for steel cutting is substantially more difficult to model than the W–Ar combination used in GTA welding systems and other applications. Arcs with tungsten electrodes burning in argon gas have experimentally been explored in hundreds and hundreds of papers whereas experimental data on electrodes in PAC is very limited. As a result, while in the case of GTAW the emitting material (tungsten) has very well known electrical, thermal, chemical and emitting properties, the corresponding properties of Hf in PAC systems are much less known. It is important, therefore, that in this paper, in addition to modeling the erosion processes we obtain some information on such parameters of the electrode and near-electrode plasma as electrode and plasma temperatures, arc current density, and the effective work function of the electrode.

The paper is organized as follows. A brief review of formulae from [5] is given in the next section 2. Then, the experimental data on external parameters: cathode temperature, plasma temperature and current density are analyzed and discussed. Finally, the comparison of the results of calculations and experimental data is given in the last section.

Method of Calculations

The flux density of the evaporated particles, G, as shown in [5], can be presented in the following form

$$G = -D_c \nabla N_c + N_c V_{pl} - D_c N_c \frac{\nabla n_e}{n_e} \tag{2}$$

Here D_c and N_c are the effective diffusion coefficient and density of the evaporated particles, and n_e and V_{pl} are electron density and plasma flow velocity. The meanings of these terms are: diffusion flux density, drag due to plasma flow. The last term represents the action of the electric field, which pulls the ion back to the cathode.

The density of the evaporated hafnium particles is described by the continuity equation:

$$\nabla G = 0 \tag{3}$$

Boundary conditions for this equation are as follows. At X_b, at the point of no return, one can set zero condition:

$$N_c(X_b) = 0. \tag{4}$$

At the inner boundary of the layer (at the sheath-plasma boundary), we assume that flux of the returning particles obeys the Bohm criterion:

$$G = G_0 - N_c(0)\bar{v}_c, \tag{5}$$

where G_0 is the flux of the evaporating particles, $N_c(0)\bar{v}_c$ is the flux of the returning particles, and $\bar{v}_c$ is their thermal velocity. The ratio G/G_0 is called the escape factor. It shows by how much the net erosion rate is less than the evaporation rate.

In the most general consideration, all unknowns (n_e, V_{pl}, N_c, G) should be obtained simultaneously. Here, we, as in [5], split the whole problem into separate ones: First, $V_{pl}(x)$, distribution of the plasma velocity we take from others' works on modeling of the plasma flow inside the plasma chamber. (We are not aware of any measurements of the plasma velocity INSIDE the chamber.) Second, $n_e(x)$, D_c we obtain considering the near-cathode plasma while neglecting evaporated particles. Finally, having $V_{pl}(x)$, $n_e(x)$ and $D_c(x)$ known, it is possible to solve Eqs. (2, 3) for density of the evaporated particles. This allows us to calculate the flux density of the eroding particles, and to obtain the escape factor.

Without going into detail, below we present the equation to solve the second part from the above list. Namely, the equation that describes the electron density distribution is

$$\frac{d}{dx}\left(D_{pl}\frac{N_0}{n_a + n_e}\frac{dn_e}{dx}\right) + (N_0 - 2n_e)n_e\frac{\beta N_e^2}{N_0 - 2Ne} - \beta n_e^3 = 0 \tag{6}$$

Here D_{pl} is coefficient of the ambipolar diffusion of the ions of the main gas, $n_e(x)$ and $n_a(x)$ are the electron and neutral atom densities of the this gas, N_e and N_0 are the ionization equilibrium electron and the total plasma particles densities, respectively. β is the three-particles recombination coefficient.

Solving Eq. (6) with the appropriate boundary conditions ($n_e(x = \infty) = N_e$ and the Bohm's criterion at the plasma-sheath boundary) allows one to obtain $n_e(x)$ and $D_{pl}(x)$ functions. Calculations provide current density at the cathode, also. The external parameters of these calculations are the plasma pressure and temperature. One can say, therefore, that the solution is determined either by pressure and temperature or by pressure and current density, the statement we will use later.

For the escape factor, the following formula has been obtained [5]:

$$\frac{G}{G_0} = \frac{n_e(0)}{3S_C}\sqrt{\frac{M_c}{M_{pl}}}\left[\int_0^{X_b} n_e^2(x)dx\right]^{-1} \tag{7}$$

Coordinate of this point X_b, is the solution of the equation

$$V_{pl}(X_b) = D_c \frac{\nabla n_e}{n_e}\bigg|_{X_b} \tag{8}$$

Here M_{pl} is mass of the plasma gas atom, $n_e(0)$ its value at the plasma-sheath boundary, and S_c is the Coulomb collision cross-section. Assuming linear dependence of the plasma velocity on distance from the cathode, this condition can be rewritten in the following form:

$$\frac{dV_{pl}(0)}{dx} X_b = D_c \frac{\nabla n_e}{n_e}\bigg|_{X_b} \tag{9}$$

All the above parameters should be obtained by considering non-equilibrium plasma of the host gas at the cathode vicinity. While doing so, the presence of the evaporated atoms can be neglected. The corresponding procedure is described in [5] in detail.

Calculation Procedure

The sequence of calculations is as follows. Starting from some plasma temperature, we obtain $n_e(x)$, $D_c(x)$ and J_i, the density of the ion current of the main gas to the cathode. Formula (7) allows one to calculate the escape factor. As the next step, assuming that ions constitute 50 % of the total current density at the cathode, one can calculate the total current density and the electron emission current density.[1] With the known work function, the latter allowed us to calculate the cathode temperature from the Richardson-Dushman equation, the Schottky correction being taken into account. Now, as the cathode temperature is known, it is possible to calculate the evaporation rate (1), and, finally, the net erosion rate.

Results of Calculations and Comparison to Available Data

Two Methods of Comparison

It is customary in PAC Research and Development to measure erosion rate as the rate of deepening of the cathode cavity. There are several reasons for using this method of measuring erosion: (a) easiness to measure (can be done "in situ"), (b) the method ignores re-depositing of the erosion products on other than emitting parts of the cathode and, finally, c) it is the cavity depth that determines the double arcing criterion.

The described above procedure of calculations (at a given arc current and at a given pressure) puts into correspondence the current density and the erosion rate. The erosion rate measured as g (cm/s), the rate of the cavity deepening in time, could be transformed into G, the erosion rate in grams per second:

$$G = gI\rho/J \tag{10}$$

Here I is the current (A), J is the current density (A/cm^2) and ρ (g/cm^3) is density of the evaporating material. We see that in order to convert cavity deepening rate g into erosion

[1] Variation of the ion fraction of the total current density do not change the results much.

rate G, one has to know the current density J. As mentioned above, calculation of the erosion rate also demands the current density.

Comparison of the experimental data on erosion to calculated ones could be done in one of two methods: one that needs a priori knowledge of the current density at the cathode and another that doesn't need that knowledge.

1. In the first method, using available experimental data, one can try to estimate the current density and then perform calculations of the erosion rate based on these values of the current density. Advantage of this method is that it allows the direct comparison of the calculated and experimental values of the erosion.
2. The second method based on the fact that at a given experimental value of the cavity deepening rate g, the erosion rate G in gram per second is a falling function of the current density, see (10). On the contrary, the calculated erosion rate is a raising function of the arc current density. Intersection of these two graphs allows one to obtain data on current density and, therefore, on other characteristics of the arc, such as plasma temperature and cathode temperature. Advantage of this method is that it doesn't demand any a priori knowledge of the current density. However, this method doesn't allow one to compare calculated and measured erosion rates and one could judge the quality of the model on how reasonable are other characteristics of the arc.

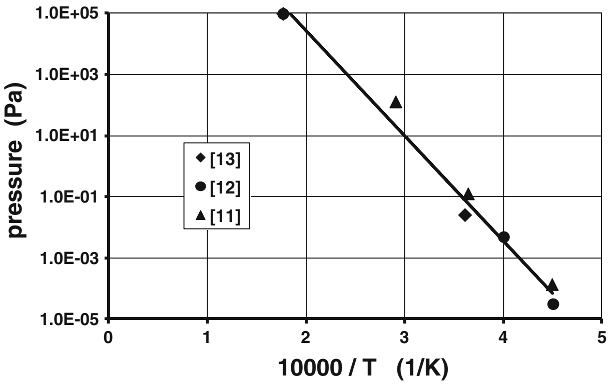
Before proceeding to results of our calculations let us discuss available data on the external parameters in the considered problem: plasma velocity gradient, cathode work function and hafnium oxide vapor pressure.

Choice of the External Parameters: Plasma Velocity Gradient, Work Function, Hafnium Oxide Vapor Pressure

1. To make calculations, we need to know dV_{pl}/dx, the plasma velocity gradient at the cathode surface. The pictures of the plasma velocity presented in different works, allowed us to estimate this parameter, however, the accuracy of these estimations is low. According to [7] it is in the range from 1×10^5 to 2×10^5/s; according to [8]—about 2×10^5/s, and according to [9] about 3×10^5/s. We used the 2×10^5/s value, however, the result depends on this parameter in a rather weak way.[2]
2. The second parameter we need to make calculation is the HfO_2 work function. We took it equal to 3.76 eV [10]. The Schottky effect being taken into account, the effective work function has been reduced to 3.2–3.4 eV depending on the J_{ion} current density at the cathode.
3. For temperature dependence of the rate of HfO_2 vapor pressure, we used data from [11–13] They are shown in Fig. 1. The $p(T_c)$ dependence was approximated as $p(Pa) = 1.9 \times 10^{11} \exp(-79{,}000/T)$, where temperature is in Kelvins and pressure is in Pascals.

[2] In our previous paper [5], we explained the observed erosion rate dependence on the swirling of the plasma gas by moving of the point of no return away from the cathode. There is another, also important factor: high swirling squeezes the arc attachment. This increases the current density and cathode temperature, thus, increasing the erosion rate.

Fig. 1 HfO_2 vapor pressure dependence on temperature according to different literature sources



Results of Calculations with Method 1

Current Density at the Cathode

One can more or less reliably estimate the current density at the cathode since the area of the current attachment is limited. Based on the visual inspection of the cathode after switching the arc off, the diameter of the current attachment is approximately from 50 to 75 % of the emitter diameter. This means that in the experiments [6] the current density was from 1.2×10^4 to 2.5×10^4 A/cm^2, although the accuracy of this estimation is low.

Some conclusions on current density could be drawn from our old experiments. Figure 2 shows results of the tests to find the optimum hafnium insert diameter. (Details of the experimental arrangement can be found elsewhere [6]). The picture presents erosion rate for 260 and 400A arcs in oxygen as function of insert diameter. Plasma pressure was around 3 atmospheres in both cases. The erosion rate is related to the erosion rate at the optimum insert diameter. These dependences have their minima at 1.5 and 1.7 mm, respectively. It can be seen that the erosion increases rapidly if the insert diameter is too low. One can suggest different explanations of this fact.[3] In any case, it is plausible to suggest that the current density at the cathode is about (if not larger than) $4I/\pi d_{opt}^2$. This gives us the following estimates: J(260A) $\sim 1.5 \times 10^4$ A/cm^2 and J(400A) $\sim 1.7 \times 10^4$ A/cm^2. Close number, 1.2×10^4 A/cm^2, was claimed in patent [14] as the optimum current density.

Visual observation of the arc through a window in the nozzle of the 200A arc showed that the current density $\sim 1.6 \times 10^4$ A/cm^2 [2]. Measuring the erosion crater by profiometer in [15] showed that after a few cutting cycles, the diameter of the recessed part of the crater was about 0.14 cm. For the arc current equal to 250A, this means that the current density $J = 1.6 \times 10^4$ A/cm^2.

According to the model [16], the current density at the cathode attachment is approximately proportional to the pressure. Summarizing the above information on the current

[3] For example, if the arc attachment covers the most part of the insert surface, and the temperature of the emitter-holder boundary exceeds a certain limit (e.g. holder melting point), the thermal contact between the emitter and the holder deteriorates, cooling condition deteriorates as well, and this leads to a rapid insert erosion. Another explanation: loss of the thermal contact during switching arc on and off.

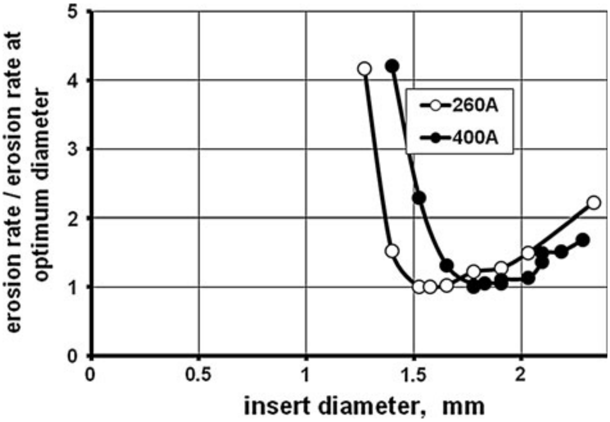


Fig. 2 Non-dimensional erosion rate at different insert diameters for two arc currents. Erosion rate is related to the erosion rate at the optimum Hf diameter. The graph allows one to estimate the optimum insert diameter and the corresponding current density. (the author's experimental data)

density, we assumed that it could be estimated as J/p = 0.45 A/cm^2/atm. This approximation has been used during our calculations with the method 1.

The results of the calculations are shown in the Table 1, where they are compared to results of erosion rate measurements [6]. From this table, one can see that measured and calculated erosion rates are close: maximum difference of four times is for 400A 4.8 atm case, when J/p = const condition could be not so good approximation [16]. In the rest of the considered cases, the difference in measured and calculated erosion rates is less than two times.

Byproduct of our calculations is the electron temperature close to the cathode. It would be very desirable to compare the calculated values to available information on this parameter. Unfortunately, at this time, it is not possible. The reason is as follows.

Plasma Temperature Close to the Cathode

Unlike temperature outside the nozzle, there is no experimental data on the temperature at the cathode proximity. The only information, therefore, can possibly be obtained from simulations. Unfortunately, it is temperature at the cathode proximity that is the least accurately calculated since it depends on the accepted boundary conditions at the cathode.

Close to the cathode, one should distinguish between heavy species temperature (T_h) and electron temperature (T_e). The present calculations provide the electron temperature because it determines ionization processes and, therefore, the ion current to the cathode. Unfortunately, the existing models are unable to provide the necessary information. The value of the plasma temperature close to the cathode is determined by the corresponding boundary conditions. In all the existing works modeling the plasma parameters in PAC systems, the plasma temperature at the cathode vicinity is set equal to the temperature of the cathode itself, i.e. in the range of 3,000–3,500 K. Although it is a good approximation for the heavy particles temperature, the electron temperature could not be so low: plasma electrical conductivity at this temperature is absolutely negligible. It is not clear how electrical current can flow close to the cathode at these electron temperatures.

Further from the cathode, the plasma temperature rises rapidly as a result of a very high Joule heating. At maximum, it could reach very high values: from 15,000 K up to

Table 1 Arc current, plasma chamber pressure and experimental erosion rate g(in mm/min) are taken from [6]. Arc current density is calculated according [16]. Calculations allowed us to find calculated erosion rate G_{calc}, current density, plasma temperature, effective work function, and escape factor. For details of the calculation procedure (method 1) see the text

Arc current A	Pressure atm	g mm/min	Gexp g/s	Gcalc g/s	Current density 10^4 A/cm^2	Plasma temp. 1,000 K	Cathode temp. K	Effective work function eV	Escape factor
200	2	1.2E−03	4.39E−07	4.45E−07	0.90	20.6	3,250	3.36	1.13E−03
200	3.3	2.2E−03	4.78E−07	8.28E−07	1.50	21.3	3,340	3.30	1.13E−03
200	3.9	4.7E−03	8.44E−07	1.07E−06	1.80	21.6	3,370	3.28	1.17E−03
400	3.3	2.80E−03	1.20E−06	7.10E−07	1.50	15.2	3,340	3.30	9.30E−04
400	4.8	1.25E−02	3.59E−06	1.38E−06	2.16	22.0	3,410	3.26	2.10E−03

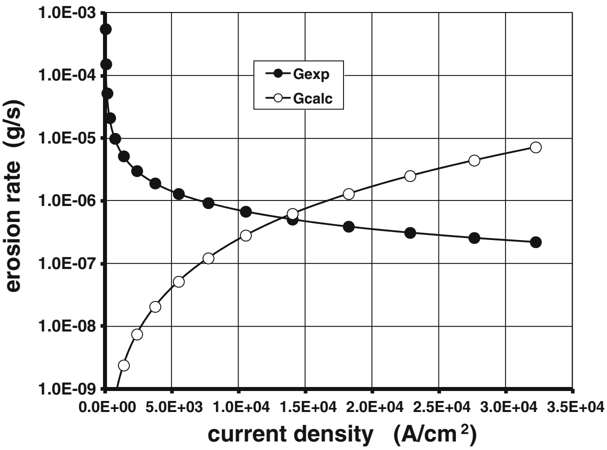


Fig. 3 Obtaining current density from comparison experimental and calculated erosion rates. G_{exp} is calculated according to (10) using the author's experimental data on the rate of the cathode cavity deepening. (Method 2)

30,000 K at different models. Although these numbers are in line with our estimations, however, by plasma temperature we mean T_e at the plasma-cathode boundary, not at its maximum. Therefore, without underestimating the importance of the calculations at the rest of the arc, we see that the existing models are unable to predict the electron temperature value at the very proximity of the cathode.

Cathode Temperature Inside the Arc Attachment

The only experimental information on the cathode temperature at the arc attachment was obtained in [2]. For 200A, the experimental value is 3,600 K. Our estimations give lower values; depending on the plasma pressure it changes from 3,260 K (2 atm) to 3,370 (3.9 atm). Extrapolation our calculations to pressure of 5 atm and to cathode work function of 3.9 eV (parameters used in [2]) gives for the cathode temperature 3,550 K.

Table 2 Arc current, plasma chamber pressure and experimental erosion rate g(in mm/min) are taken from [6]. Equating experimental erosion rate to the calculated one allowed us to find current density, plasma temperature, effective work function, and escape factor. For details of the calculation procedure (method 2) see the text

Arc current	Pressure	g	G	Current density	Plasma temp.	Cathode temp.	Effective work function	Escape factor	J/p
A	atm	mm/min	g/s	10^4 A/cm^2	1,000 K	K	eV		10^4 A/cm^2/atm
200	2	1.2E−03	5.00E−07	0.96	20.7	3,260	3.35	1.2E−03	0.48
200	3.3	2.2E−03	5.90E−07	1.36	20.9	3,280	3.32	9.4E−04	0.41
200	3.9	4.7E−03	1.03E−06	1.79	21.5	3,370	3.28	1.1E−03	0.46
400	3.3	2.80E−03	9.37E−07	1.74	21.8	3,360	3.27	1.3E−03	0.53
400	4.8	1.25E−02	2.76E−06	2.94	23.1	3,450	3.22	1.9E−03	0.61

Results of Calculations with Method 2

Example of the calculations to evaluate the current density is demonstrated in Fig. 3, where the calculated and the measured erosion rates in grams per second as functions of the arc current density are shown. According to this picture, these two graphs intersect at $J \sim 1.4 \times 10^4$ A/cm^2. Table 2 displays the obtained in this way results for experimental conditions used in the work [6]. One can see that the parameters calculated using method 1 and method 2 are close, including the cathode temperatures, plasma temperatures, escape factors. Interesting to note, that the calculated by this method the current density to pressure ratio remains approximately independent of pressure and current.

Conclusion

Method of calculation of the erosion rate developed in [5] is applied to evaluate the evaporation rate of the cathode in a plasma arc cutting torch. Electrode material is hafnium, plasma gas is oxygen. Arc current is 200 and 400A, plasma pressure is from 2 to 5 atm.

Results of calculations are compared to experimental data obtained in our work [6].

In spite of some lack of perfect knowledge of several important parameters (hafnium oxide vapor pressure at high temperatures, its work function), the measured and calculated erosion rates reasonably agree. The escape rate of the evaporated particles (the net erosion rate to evaporation rate ratio) was close to 0.001 in all the considered cases: only one tenth of percent of the evaporated particles participate in the net erosion.

The suggested approach also provides estimations of some important characteristics of the arc. Byproduct of the present approach is for the first time evaluated T_e, the electron temperature close to the cathode. The calculated value of T_e is close to 20,000 K.

By equating the calculated and measured erosion rates, one obtains equation for the current density at the cathode surface. Obtained this way current density is approximately directly proportional to the plasma pressure and independent on the arc current: the conclusion that follows from the model of the cathode processes [16].

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