Thermal regime of the cathode in a vacuum-arc discharge during coating deposition

V G Kuznetsov, D K Kostrin and V P Valuev

Institute of Problems of Mechanical Engineering, Russian Academy of Sciences, 199178, Saint Petersburg, Russia

E-mail: kvigipme@gmail.com

Abstract. The questions of stabilizing the cathode temperature in a vacuum-arc discharge are discussed. A model and a method for calculating the temperature of the working surface of the cathode end, eroded under the action of cathode spots, are presented. Stabilization of the cathode temperature is carried out by changing the arc discharge current during the operation of the evaporator in accordance with the obtained regularity or design solutions.

The balance of power generated on the electrodes of the vacuum-arc evaporators is essential both for the calculation of evaporators and for the coating deposition processes implemented with their help. The integral temperature of the cathode surface affects the composition of the erosion products coming from the cathode spots and the properties of the coatings. Power $P_k$, released at the cathode of the vacuum arc [1], if the binding of the discharge to the electrode surface is carried out in the form of cathode spots, is defined as

$$P_k = h_k IU,$$

where $I$ – vacuum-arc discharge current; $U$ – arc voltage drop; $h_k$ – cathode power factor, defined as the ratio of the power released at the cathode to the total discharge power.

The power released on the working surface of the cathode is spent on the evaporation of material $P_{ev}$, radiation $P_r$ and, as a result of thermal conductivity, is transferred to the cooling system $P_c$. The power used to vaporize the cathode material can be expressed through the erosion rate as follows:

$$P_{ev} = \dot{m} W_{ev}/M,$$

where $\dot{m}$ – erosion rate of the cathode material (kg/s); $M$ – mass of the atom; $W_{ev}$ – specific heat of evaporation. In this expression, the specific heat of melting is not taken into account, since it is significantly less than the specific heat of evaporation.

It is assumed that in the first approximation, the erosion rate of the cathode material depends on the current linearly:

$$\dot{m} = \mu I,$$

where $\mu$ – electric transfer coefficient depending on the cathode material. With this in mind, expression (2) will take the form:

$$P_{ev} = \mu W_{ev}/M.$$  

Using formula (3) it is possible to calculate the power consumed for evaporation of the cathode material for various materials. The calculation shows that, for example, for copper at a discharge...
current of 100 A on the evaporation of the material will be spent power $P_{ev} \approx 56$ W. The total discharge power in this case can be estimated using data on the arc voltage drop, which is approximately 21 V. Thus, the ratio $P_{ev}/IU$ for the selected mode as an example is equal to 0.027.

For molybdenum at discharge current of 200 A $P_{ev} \approx 55$ W, and $P_{ev}/IU \approx 0.01$. It can be seen that the power consumption for the evaporation of the material in the arc with the cathode spot is relatively small.

The second component of power $P_r$ consumed for radiation can be significant only when working with refractory materials. In accordance with the Stefan-Boltzmann law $P_r = \sigma e S_k T_k^4$, where $\sigma = 5.67 \times 10^{-8}$ W/m²K⁴ – Stefan-Boltzmann constant; $e_r$ – integral radiation coefficient; $S_k$ – area of the working surface of the cathode; $T_k$ – mean square value of the temperature of the cathode material.

The natural limit for $T_k$, unless other restrictions apply, is the melting point. Power taken away by radiation during the extreme thermal regime of the cathode made of molybdenum is up to 100 W/cm².

If the radiating surface of the cathode is equal to several tens of square centimeters, it is obvious that when working with refractory metals, the radiation power cannot be neglected. Thus, the values of power $P_{k}$, $P_{ev}$ and $P_r$ were clarified. Now, having determined $P_{c} = P_{k} - P_{ev} - P_{r}$, it is possible to formulate the requirements for the cooling system and find the dimensions of the cathode of the vacuum-arc evaporator. In the most common designs of evaporators the cathode in the first approximation has the shape of a cylinder. The working surface is one end of the cylinder, and the other one is washed by the coolant.

It should be borne in mind that as the cathode works due to erosion of the material, its length decreases. Due to the improvement of the heat sink, the surface temperature of the cathode $T_k$ decreases and, accordingly, the power withdrawn by radiation falls. Therefore, at the end of the life of the electrode, almost all the power $P_{k}$, released at the cathode (without deducting the power $P_r$), should be diverted to the cooling system.

Favorable from the point of view of reducing the microdroplet fraction of the cathode erosion products conditions of its operation with a decrease in temperature as the thickness decreases can adversely affect the properties of the coatings [2]. Changing the number and size of microdroplets in the layers as the coating thickness increases can lead to different phase composition of the coating through its thickness and to internal stresses that worsen the adhesion of the coating. Therefore, in some cases it is advisable to maintain the cathode temperature at a predetermined level during the coating deposition process.

One way to maintain the temperature of the cathode at a predetermined level is a change in the current of the arc discharge in the evaporation process of the cathode. Making the assumption that all the power supplied to the cathode from the discharge is diverted to the cooling system, it is possible to obtain

$$T_k - T_c = \frac{P_k L_k}{\lambda S_k}, \quad (4)$$

where $S_k$ – surface area of the working end of the cylindrical cathode; $L_k$ – length of the cathode; $\lambda$ – coefficient of thermal conductivity of the cathode material; $T_c$ – temperature of the cooled end of the cathode.

The ratio (4) allows connecting the cathode geometry with the power of the installation and the applied material. Typically, the diameter of the cathode and therefore $S_k$ are determined by design considerations. Then, by setting the $T_k$ value based on a suitable temperature criterion, or at least not allowing the cathode to melt, formula (4) can be used to determine the length of the cathode $L_k$.

It can be seen from (4) that if we want to keep $T_k$ constant (at the same time $T_k - T_c$ will also be approximately constant), it is necessary that the product $P_k L_k$ be constant.

If we assume that the initial length of the cathode was $L_{k0}$, and during time $t$ it decreased by $\delta L_k$, then we can write:

$$L_k(t) = L_{k0} - \frac{1}{\rho S_k} \int_0^t \mu dt;$$
\[ h_k IU \left( I_{k_0} \int_0^t \mu I \, dt \right) = \lambda S_k (T_k - T_c) \quad (5) \]

where \( \rho \) – density of the cathode material.

Solving equation (5), we obtain the time dependence of the arc discharge current, which allows regulating the current in time to maintain the temperature of the working surface of the cathode at a given level:

\[ I = I_0 \left( 1 - 2 \frac{\mu I_0 L_1}{\rho S L_0} \right)^{1/2} \quad \text{(6)} \]

where \( I_0 \) – initial value of the arc discharge current at \( t = 0 \).

Similarly, we can obtain the expression for the erosion of the cathode in time:

\[ L_k = L_{k_0} \left( 1 - 2 \frac{\mu I_0 L_1}{\rho S L_0} \right)^{1/2} \quad \text{(7)} \]

Another method (mechanical) to maintain the temperature of the cathode at a predetermined level can be proposed. Figure 1 shows the scheme of the cathode of a cylindrical vacuum-arc evaporator.

![Figure 1. Scheme of the cathode of a cylindrical vacuum-arc evaporator.](image)

The working surface of the cathode, from which the material under the action of a vacuum arc is eroded, is the end with the size \( D_k \). The opposite end is connected to the cooling system and washed with water. In the immediate vicinity of this end is made a pierce in the form of a groove with a diameter \( D_1 \) and a width \( L_1 \). The length of the working part of the cathode is indicated as \( L_k \). In the corresponding sections along the length of the cathode the integral temperatures \( T_k \), \( T_1 \) and \( T_c \) are indicated, taking place during the cathode operation. The integral temperature of the working surface of the cathode is determined by the power supplied from the discharge and the power withdrawn to the cooling system. The power taken to the cooling system can be adjusted by the depth of the groove located near the cooled surface.

For the current time value \( t \) and at \( L_1 \leq z \leq L_k \) we can write:

\[ T(Z,t) = \frac{T_k - T_1(t)}{L_k} (Z - L_1) \]

During the time \( t \), the cathode length due to the erosion of the material at a constant current of the arc discharge \( I \) will decrease:

\[ L_k = L_{k_0} - \frac{\mu I t}{\rho S_k} \]

At a constant value of the power \( P_k \), released at the cathode, a decrease in its length should cause a decrease in the temperature head at the site \( L_k \).
\[ P_k = \lambda S_k \frac{T_k - T_i(0)}{L_{x0}} = \lambda S_k \frac{T_k - \delta T_k - T_i(0)}{L_k}. \]

In this expression, the numerator of the right side of the equation contains \( T_k - \delta T_k - T_i(0) \), because if \( D_1 \) is not changed, then (at \( P_k = \text{const} \)): \( P_k = \lambda S_i(T_1 - T_c) / L_1 = \text{const} \), and therefore, \( T_1 = \text{const} \) (we assume that \( T_c \) is fixed by the coolant), where:

\[ \delta T_k = [T_k - T_i(0)] \left( 1 - \frac{L_k}{L_{x0}} \right). \]

For the stabilization of \( T_k \) at a given level \( S_1 \) must be reduced so that the increase in \( T_1 \) compensate \( \delta T_k = T_1 - T_i(0) \)

\[ P_k = \lambda S_i (t) \frac{T_i(t) - T_c}{L_1}; \quad T_i(t) = \frac{P L_1}{\lambda S_i(t)} + T_c. \]

Without demonstrating further intermediate calculations, we obtain an expression for calculating the diameter of the groove at the cathode, which helps to maintain the temperature of its working surface at a given level during the material erosion:

\[ D_1 = \frac{D_k}{\left( 1 + \frac{L_{x0}}{L_{x1}} \right)^{1/2}}, \quad (8) \]

where \( 1/t_0 = \mu / p S_i L_{x0} \).

In practice, the proposed method cannot be implemented in the process of evaporation of the cathode material. However during short technological processes the diameter of the groove can be changed after the end of each cathode cycle.

References
[1] Kuznetsov V G and Lisenkov A A 2009 Metal processing 6 14–9
[2] Vetrov N Z, Kuznetsov V G, Lisenkov A A, Radzig N M and Sharonov V P 1999 Vacuum technique and technology 3 27–30