Interaction of cathode spots of a vacuum-arc discharge with a metal surface during its deactivation

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Abstract. For the first time, the possibility of deactivation of a metal surface by the dry method by means of treatment with cathode spots of a vacuum-arc discharge is shown. A high deactivation coefficient is obtained by squeezing the liquid phase of the metal from the cathode spot with a high pressure created by the plasma flow at the base of the cathode jet. Some principles of controlling the movement of cathode spots of a vacuum arc on the surface are shown.

Over a long period of the history of the nuclear industry, a significant amount of radioactive waste has been received, and the problem of their disposal has always been acute. One type of waste is metal radioactive waste. Most enterprises use methods for removing radioactive contamination from the surface with various active reagents, such as acids and alkalis, including using ultrasound. All of them are labor-intensive, energy-intensive, require a large amount of expensive consumables and lead to the formation of a significant amount of liquid radioactive waste, the storage, processing and disposal of which requires huge costs.

Modern trends in the global development of technologies for deactivation of metal surfaces are characterized by the rejection from the "wet" methods and the search of effective "dry" methods of deactivation. The developed deactivation technology is based on the interaction of high-energy flows of plasma with the surface of solids, localized in the cathode spots of a vacuum-arc discharge, to remove radioactive contamination.

Studies show [1] that the crater in the cathode spot deepens mainly due to the melting of the metal under the spot and the extrusion of the molten film by the high pressure existing in the plasma at the base of the cathode jet. The thickness of the molten metal film in the cathode spot increases due to the melting of new cathode layers under the spot and decreases due to the extrusion of the molten metal. Calculations show that the plasma pressure at the base of the cathode jet can reach values at the level of $P \approx 300$ atmospheres. In order to create this pressure, the cathode must be heated to a temperature of $T \sim 5000$ K. The pressure exerted on the surface of the liquid metal in the cathode spot leads to its extrusion, and the metal flies out of the cathode spot in the form of micro drops.

In [1], mathematical expressions are presented for calculating the rate of deepening of the cathode spot crater $h(t)$ and the rate of change in the film thickness $\Delta$ of the molten metal in the crater:
\[ h(t) = \frac{Ra}{2\nu} \left\{ 1 + \ln \frac{1 + \sqrt{1 - \exp(-4vt/R)}}{1 - \sqrt{1 - \exp(-4vt/R)}} - \sqrt{1 - \exp(-4vt/R)} \right\} \] (1)

\[ \frac{d\Delta}{dt} = \frac{\chi}{\rho(CT_k + \lambda)} \left( T_k - T_{\text{mt}} \right) - \frac{dh}{\Delta} \approx \frac{a}{\Delta} \frac{dh}{dt}, \] (2)

where \( R \) is the radius of the spot, \( a \) – thermal diffusivity, \( v \) – speed of movement of molten metal leaving the crater, \( \rho \) – the material density, \( C \) – the heat capacity, \( \lambda \) – the heat of fusion, \( T_k \) – temperature on the surface of the cathode spot, \( T_{\text{mt}} \) – the melting temperature of the cathode, \( \chi \) – the thermal conductivity, \( h \) – the depth of the crater.

Liquid metal jets and droplets that fly out of the cathode spot play an essential role in self-sustaining of the combustion of a vacuum-arc discharge. In recent years, a mechanism for jets formation has been proposed that is associated with the development of azimuthal instabilities of the liquid boundary during its displacement from craters. It is believed [2] that hydrodynamic processes in the cathode spot lead to the formation of microinhomogeneities, the electric explosion of which provides conditions for the reproduction of new cathode spots.

Due to the evaporation of the metal and due to the fly out of molten metal in the form of microdrops, all contamination on the metal surface, including radioactive films, is removed. At the same time, the surface radioactive material does not melt with the product material. As a result, a clean metal surface is formed, and the deactivation coefficient reaches values of tens of thousands of units. Evaporating the surface films and other contaminants, numerous cathode spots create a favorable environment for maintaining of the discharge and, concentrating on surface contaminants and moving on them, carry out deactivation process, ensuring uniform processing of the surface. In this regard, for uniform surface treatment, including complex geometric shapes, there is no need to scan the heating source (cathode spots) over the surface. The process of uniform surface treatment is automatic. This circumstance has significant advantages over other surface treatment methods, for example, the laser method.

For the case of local surface deactivation, the movement of cathode spots along a given surface area can be carried out by using a system of additional screens, using a magnetic field, by switching current using various current leads (figure 1), and other methods.

Consider an example of deactivation of a section of a flat surface by connecting towards her several current leads of negative potential through current regulators (figure 1(a)).

![Figure 1. Deactivation of flat (a) and cylindrical surfaces (b).](image-url)
If to deactivated surface 2 is bring the current through current leads only to two points, for example "a" and "b", with the ability to change the currents through each of them, then the burning zone of the discharge is localized between the points of connection of current leads "a" and "b". With the same currents flowing through each current lead, the cathode spots do not have preferred localization areas and randomly move over the entire surface between the connection points of the current leads, forming a surface treatment area of the product between these points "a" and "b". If the through one of the current leads with help of current regulator, for example PT, to increase the current, then the zone of discharge is moved on the surface in the direction of point "a" of connection of current lead, move from the connection point "b" of the current lead with less current. By connecting a larger number of negative potential current leads to different points of the treated surface 2 and changing the currents flowing through the current leads, it is possible to influence the movement of the cathode region of the arc along the deactivation section. Regulated vacuum-arc discharge current sources can be used as current regulators.

Figure 1(b) shows the installation diagram for deactivation of the inner surface of the cylinder. The internal volume of the cylinder is hermetically closed with two stoppers 3 and 4. Inside the cylinder, along the treated surface there is an electrode 1, to which through the current lead the positive pole of power source of the arc U is connected. The negative pole of the arc power supply U is connected through current regulators PT1, PT2, PT3 to the deactivated surface 2. The positive electrode 1 rotates along the deactivated surface. Through one of the stoppers 3, air is pumped out to the set pressure. Between the surface to be treated and the positive electrode 1 a vacuum arc discharge is ignited and the surface of the product 2 is deactivated.

From the point of view of economic efficiency, the deactivation process is performed at a pressure of the residual air atmosphere from 1 Pa to 300 Pa. At a pressure above 300 Pa, oxidative processes of the surface begin to appear and significant oxide films are formed on it, which in some cases is unacceptable. In addition, when the pressure increases above 300 Pa, the speed of movement of cathode spots on the surface decreases, which affects on the duration and productivity of the deactivation process. At low speeds of movement of cathode spots of vacuum-arc discharge until they stop at high pressures, local surface melting may occur, which will lead to a violation of the deactivation process, i.e., the melting of the radioactive film into the material of the surface layer of the product.

Despite the fact that most of the radioactive material from the deactivated surface is deposited on the surface of the anode, a small part of it is deposited on the walls of the vacuum chamber and a small part with the gases pumped out of the chamber can be carried away to the pumping system. Therefore, during the deactivation process, it is advisable to cover the walls of the vacuum chamber with foil or other film material, and at the exit of the chamber, in front of the pumping system pipeline, install a filter for radioactive particles carried into the pumping system. As radioactive materials accumulate on the surface of the anode, on the surface of the film covering the chamber walls, and in the volume of the filter, they are disposed of as solid radioactive waste that does not occupy large volumes in storage areas.

To estimate the deactivation coefficient, we used stainless steel samples with a diameter of 24 mm and a thickness of 0.75 mm with a radioactive film of the isotope Cz on one side of the plate surface. Studies have shown that with a discharge processing time of 4 seconds, the average deactivation coefficient \( K_d \) was approximately 20000. Additional surface treatment for another 2 seconds resulted in complete removal of the radionuclide from the surface (\( K_d >100000 \)). When the surface of the samples was deactivated for 2 seconds, the average deactivation coefficient was at the level of 15000. Thus, the results obtained indicate about high deactivation rates and high deactivation coefficient.

References
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