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Modeling of thermal processes in the modification of the surface by means of the cathode spot of vacuum arc on equipment with non-cooled rotating anode

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Abstract. Theoretically and experimentally the thermal processes in the case of modification the inner surface of the cylindrical cavity by means of the cathode spots of vacuum arc discharge are investigated. As the anode was used uncooled graphite electrode in the form of a half cut in diameter of a cylindrical rod. At the modeling of thermal processes was taken into account the process of heating the surface of the cylinder by radiation from the hot surface of the anode. In this case the cylindrical surface has been uneven wall thickness around the perimeter.

A fundamentally new field of use of the vacuum-arc discharge [1, 2], developing in recent years, demanded to study the behavior of cathode spots of a vacuum arc on the moving surfaces and, in some cases, covered with films of other material. In such circumstances the researches of cathode spots is not practically implemented. The behavior of cathode spots has been primarily addressed on fixed and clean from surface contamination of the electrodes.

An important parameter in determining the efficiency of the process of vacuum-arc treatment of metal surfaces is the temperature of the product. It should not lead to a change in material properties of the product. The uneven heating of the product must also be insufficient to change its geometrical shape by the generated mechanical stresses.

In some cases, on the contrary, the impact of cathode spots of a vacuum arc can cause change in the surface properties of the metal, for example, can be used for surface hardening [3] or for the recovery of plastically deformed areas of the surface [4]. Vacuum-arc technology can be efficiently applied for machining internal surfaces of cylindrical articles, simultaneously performing the role of the cathode and the vacuum chamber. As such products can be tubes, couplers, axle boxes of railway wagon [5] and many others.

Figure 1 shows the installation for vacuum-arc cleaning of the inner surface of the axle box of a railway wagon.

We consider the solution to the heat problem during the glowing of a vacuum-arc discharge in the electrode system (figure 2): cathode – is a cylinder of height $H$ with an irregular perimeter by wall thickness (similar to a box); the anode – electrode in the shape of a half cylindrical rod, cutting along the diameter, of length $L$ and radius $R_a$, rotating along the inner surface of the cathode.
Figure 1. Installation of vacuum-arc cleaning of the inner surface of axle boxes of wagon (a); a rotating anode (b); surface boxes before cleaning (c); surface boxes after cleaning (d).

Figure 2. Scheme of the computational domain: A – cathode; B – anode.

The inner surface of the cathode was set as a cylindrical surface of radius $R_1$. The outer surface was set as a cylindrical surface with radius $R_2$, which depends on the angle $\phi$:

$$R_2 = \begin{cases} \frac{R_4 - R_3}{\pi} \phi + R_3, & \phi \in [0, \pi] \\ \frac{R_1 - R_4}{\pi} \phi + 2R_4 - R_3, & \phi \in [\pi, 2\pi] \end{cases}$$

where $R_3$ is the radius of the outer surface of the cylinder at the thinnest point of the wall of the cylinder; $R_4$ is the radius of the outer surface of the cylinder at the thickest point of the wall of the cylinder.

The process of heat transfer in the cylinder describes a three-dimensional unsteady heat conduction equation in cylindrical coordinates in the form:
\[ \rho c_p \frac{\partial T}{\partial t} = \lambda \left( \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{\partial^2 T}{\partial z^2} + \frac{1}{r^2} \frac{\partial^2 T}{\partial \varphi^2} \right), \quad (1) \]

where \( \rho \) is the density of the cylinder material; \( c_p \) is the heat capacity of the cylinder material; \( \lambda \) is the coefficient of thermal conductivity; \( T \) is the temperature. On the outer and end surfaces of the cylinder was set the boundary conditions of free convective heat transfer with the surrounding environment in the form of:

\[ \lambda \frac{\partial T}{\partial r} \bigg|_{r = R_2(\varphi)} = \alpha_1(T_\infty - T); \quad (2) \]

\[ \lambda \frac{\partial T}{\partial z} \bigg|_{z = 0, H} = \alpha_2(T_\infty - T); \quad (3) \]

where \( \alpha_1, \alpha_2 \) are the coefficients of heat exchange with the environment.

Inside the cylinder convective heat transfer can be neglected. Here we simulated the radiative heat transfer, which is determined by the temperature of the inner surface of the cylinder, the temperature of the rotating electrode and their instant mutual arrangement.

In each moment of time the surface of the cathode \( S_c \) and rotating anode \( S_a \) was divided into 2 parts. Surface \( S_c \) divided into \( S_{c1} \) – cathode surface under the anode and \( S_{c2} = S_c - S_{c1} \). Surface \( S_a \) divided into \( S_{a1} \) – flat part of the surface of the anode and \( S_{a2} = S_a - S_{a1} \).

Then, the total radiant heat flux between surfaces \( S_{c1} \) and \( S_{a1} \) can be written as:

\[ Q_1 = \sigma e \left( S_{a1}(T_a + 273)^4 - S_{c1}(T_c + 273)^4 \right), \quad (4) \]

where \( T_{c1} \) – average surface temperature \( S_{c1} \); \( T_a \) – temperature of anode; \( \sigma \) – is the Stefan-Boltzmann constant; \( e \) – is the integral radiation coefficient.

Similarly, the full radiant heat flux between surfaces \( S_{c2} \) and \( S_{a2} \) can be written as:

\[ Q_2 = \sigma e \left( S_{a2}(T_a + 273)^4 - S_{c2}(T_c + 273)^4 \right), \quad (5) \]

where \( T_{c2} \) – average surface temperature \( S_{c2} \).

On a time-variable part of the inner surface asked the flow of heat from the heat source. Considering this condition, and given (4) and (5) the boundary condition on the inner surface boxes was set as:

\[ \lambda \frac{\partial T}{\partial r} \bigg|_{S_{c1}} = \frac{Q_1}{S_{c1}} + \frac{U I h_c}{S_{c1}}; \quad (6) \]

\[ \lambda \frac{\partial T}{\partial r} \bigg|_{S_{c2}} = \frac{Q_2}{S_{c2}}, \quad (7) \]

where \( U \) is the arc voltage; \( I \) – current; \( h_c \) – the ratio of cathode capacity.

The temperature change of the rotating electrode is described by the equation:

\[ \rho_a V_\varphi c_{\varphi} \frac{\partial T}{\partial t} = U I h_a - Q_1 - Q_2, \quad (8) \]

where \( \rho_a \) is the density of the material of the rotating electrode; \( V_\varphi \) is the volume of the rotating electrode; \( c_{\varphi} \) – heat capacity of the material of the rotating electrode; \( h_a \) is the ratio of the anode capacity.

The solution of equations was performed numerically. The computational domain was divided differencing three-dimensional uniform grid in the directions of \( r, \varphi \) and \( z \). To solve this problem (equations (1)–(7)) used the numerical method of variable directions [4]. Before the solution of the problem on the computer in the table (figure 3) are made to the source data.
Figure 3. Table with the source data for calculation and temperature field on the surface of cylindrical product.

When the program is run in real time the temperature field on all surfaces of a cylindrical product in the form of contour lines with different colors is displayed. On color can be judged the temperature. For any number of points with given coordinates is selected on the surface of the cylinder (inside and outside), temperature data is written in a separate file. For one of the points the temperature value is displayed in the table (figure 3). There you can observe the temperature change of the rotating anode. Figure 4 presents the calculated and experimental dependences of change of temperature on time in one of the selected points on the outer surface of the cylinder.

Figure 4. The calculated and experimental dependences of change of temperature on time at the point on the outer surface of the cylinder.
Experimental study of the temperature of the external surface of the cylinder during heating and cooling was carried out using an infrared optical pyrometer “PYTHON 102”. As can be seen from figure 4 experimental and calculated data differ by no more than 10%.

References
[1] Kuznetsov V G 2005 Films and coatings 57–62
[2] Kuznetsov V G 2009 Vacuum technique and technology 2 81–4
[3] Kuznetsov V G and Ashihmin A A 2012 Wagons and wagon farm 2 36–8
[4] Samarskiy A A 1971 Introduction to the theory of difference schemes 552