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COEFFICIENT OF ION EROSION OF THE VACUUM ARC OF METALS AND ALLOYS

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Consideration has been given to the basic processes in the cathode spot of the vacuum arc of metals and alloys. Based on the analysis of a simplified equation of heat balance of the vacuum-arc cathode spot, formulas for evaluating the values of the coefficient of ion erosion of metals and alloys have been obtained. The calculated and experimentally measured values of the coefficients of ion erosion of certain metals have been compared and their satisfactory agreement has been shown.

In the past two decades, the vacuum electric-arc method (method of condensation with ion bombardment) of deposition of coatings [1] has become widespread owing to its properties and advantages; this method belongs to the group of ion-plasma methods of deposition. Among its features we note the following ones: a coating is deposited by the flow of positive metal ions, which makes it possible to easily control the energy of the ions and accordingly the structure and composition of the coating; by allowing reaction gases (O_2, N_2, and C_2H_2) to bleed into the vacuum chamber in the process of deposition of a coating, one can produce coatings with unique properties from compounds (oxides, nitrides, and carbides); using multicomponent cathodes, one can produce multicomponent composite coatings with different functional properties. All of this is due to the fact that in this method the main tool of deposition of coatings is the vacuum-arc plasma excited (initiated) in vacuum between the metallic cathode and anode. The role of the latter is usually played by vacuum-chamber walls. The cathode spot of the vacuum arc chaotically moving over the cathode surface is the source of the positive ions of the cathode metal whose flow shapes the coating.

One of the most important characteristics of the deposition of coatings is the deposition rate. For the vacuum electric-arc method it is determined by the coefficient of ion erosion μ of metals under the action of the cathode spot of the vacuum arc. The quantity μ is the mass of the cathode metal lost irretrievably by the cathode from a unit cathode spot in the form of the atoms and positive ions of the vacuum-arc plasma when a 1 C electric charge passes through it. The coefficient μ takes no account of the mass that is lost by the cathode in the form of microdroplets.

To obtain formulas using which one could evaluate μ of metals and alloys it is necessary to consider the processes in the cathode spot of the vacuum arc. The classical picture [2–8] of the basic physical processes occurring in the cathode spot where a certain electric-potential difference U is created between the cathode and the anode and a vacuum arc exists includes evaporation of the metal atoms from the cathode surface and thermal-field emission of the electrons from the same surface. Next, we have separation of the atoms (expansion of metallic vapor) and acceleration of the electrons in the electric field U in the region adjacent to the cathode surface where the cathode drop of the potential U_c of the vacuum arc occurs. For the vacuum arc it is characteristic that $U \sim U_c$. In acceleration in the electric field U_c, at a distance from the emission surface, the electrons begin to efficiently ionize the atoms evaporated and a plasma cloud with a degree of ionization of 0.5–0.95 is formed [2, 4]. Most of the positive ions formed [9] return to the cathode surface in the cathode spot under the action of the field U_c, heating the cathode surface up to temperatures close to the boiling temperature of metal and creating pressures of tens of atmospheres, which causes the microdroplets to appear. The smaller part of the ions propagate into the volume of the vacuum chamber, acquiring energies of the order of 20–120 eV [3, 6, 11] due to gasdynamic acceleration [10], which is much higher than the quantity U_c. From what has been said above it follows that the ion-erosion coefficient μ is determined by that part of the ions which propagate into the volume of the vacuum chamber.

Ion-Erosion Coefficient. To find the formulas using which one could evaluate the quantity μ we turn our attention to the simplified equation of heat balance of the cathode spot:

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$$I_{\mathrm{i}}\,(U_{\mathrm{c}}+\varepsilon_{\mathrm{i}})\,dt + r dM_{\mathrm{i}} = r dM_{\mathrm{a}}\,. \tag{1}$$

Here the heat loss by heating, melting, and radiation from the cathode spot has been neglected in view of its smallness as compared to the value of the heat of evaporation rdM_{a}. We also took no account of the cooling of the cathode in the cathode spot because of the electron emission, since here we have an electronic work function smaller by a order of magnitude and the electronic specific heat of metals is 100 times or more lower than the specific heat of the crystal lattice of the metals [12]. Consequently, this component of the equation of heat balance of the cathode spot is smaller than the heat going to evaporate the metals, and we can disregard it.

The determination of the ion-erosion coefficient μ yields that

$$dM_{\mathrm{a}} = dM_{\mathrm{i}}^{*} + dM_{\mathrm{i}}\,, \tag{2}$$

$$dM_{\mathrm{i}}^{*} = \mu I_{\mathrm{arc}}\,dt\,, \tag{3}$$

$$I_{\mathrm{arc}} = I_{\mathrm{i}} + I_{\mathrm{e}} + I_{\mathrm{i}}^{*}\,. \tag{4}$$

Then from (1)–(4) we obtain

$$\mu = \frac{U_{\mathrm{c}}+\varepsilon_{\mathrm{i}}}{r\left(1+\frac{I_{\mathrm{e}}}{I_{\mathrm{i}}}+\frac{I_{\mathrm{i}}^{*}}{I_{\mathrm{i}}}\right)}\,. \tag{5}$$

According to the evaluations of different researchers [5, 8], the value of $I_{\mathrm{i}}^{*}/I_{\mathrm{i}}$ in formula (5) is no higher than 0.1–0.15; therefore, we can disregard it without a great error. Consequently, the most undetermined quantities in (5) are I_{e}, I_{i}, and U_{c}. Whereas the material on the cathode potential drop is rather voluminous [2, 6–8, 13], the quantities I_{e} and I_{i} are rather difficult to evaluate [9]. The results of analyzing experimental data [2–4, 6, 8] enable us to state that about 60–80% of the number of atoms evaporated from the cathode surface in the cathode spot return to the same surface under the action of the field U_{c}. Therefore, we can use $n_{\mathrm{e}}v_{\mathrm{e}}/n_{\mathrm{a}}v_{\mathrm{a}}$ instead of the ratio $I_{\mathrm{e}}/I_{\mathrm{i}}$ to evaluate the maximum values of μ. Thus:

$$\mu = \frac{U_{\mathrm{c}}+\varepsilon_{\mathrm{i}}}{r\left(1+\frac{n_{\mathrm{e}}v_{\mathrm{e}}}{n_{\mathrm{a}}v_{\mathrm{a}}}\right)}\,. \tag{6}$$

If such calculations are performed for an alloy consisting of s components, we obtain

$$\mu_{\mathrm{al}} = \frac{\sum\limits_{s}(U_{\mathrm{c}s}+\varepsilon_{\mathrm{i}s})\,\frac{n_{\mathrm{a}s}v_{\mathrm{a}s}}{n_{\mathrm{e}}v_{\mathrm{e}}}}{\left(1+\frac{\sum\limits_{s} n_{\mathrm{a}s}v_{\mathrm{a}s}}{n_{\mathrm{e}}v_{\mathrm{e}}}\right)\frac{\sum\limits_{s} g_s r_s P_s m_s^{0.5}}{\sum\limits_{s} g_s P_s m_s^{0.5}}}\,. \tag{7}$$

Analysis Results. The ratio $n_{\mathrm{e}}v_{\mathrm{e}}/n_{\mathrm{a}}v_{\mathrm{a}}$ can be evaluated if we use the formulas of Dushman and Richardson with allowance for the Schottky effect [14] for thermal-field emission and of Hertz and Knudsen [15] for atomic evaporation. To perform this evaluation it is necessary to know the temperature of the cathode surface and the electric field strength in the cathode spot. In our opinion, with allowance for what has been said above, it is appropriate to take for evaluation of the maximum value of μ that the temperature of the cathode surface in the cathode spot is equal to the boiling temperature of the metal for pure metals and to the boiling temperature of the alloy component in which it is the lowest for alloys. The strength of the electric field in the cathode spot E can be evaluated using the relation

$$E \approx U_c \sigma_{max} n_a \, . \tag{8}$$

The maximum values of the impact-ionization cross section σ_{max} in (8) are rather easy to compute using the tested semiempirical formulas [16, 17].

The results of calculating the ratio $n_e v_e / n_a v_a$ with allowance for the assumptions given above show that it is equal to (5–7) for Al, to (2–4) for (4), to (15–20) for Ti, and to (100–150) for Mo; for alloys it is as follows: (2–5) for (Ni–50Fe), (2–4) for (Cu–30Al), and (1–2) for (Cu–40Zn). Alloys in which the boiling temperatures of the components differ by more than 400–500^{o}C are characterized by a ratio of $\Sigma n_e v_e / n_{as} v_{as} \sim 1$. This leads to the fact that the content of the ions charged doubly or more is very low in the vacuum-arc plasma of such alloys [18].

Now we can evaluate the quantity μ. Thus, $\mu \approx (2–3) \cdot 10^{-7}$ kg/C for Al, $(6–8) \cdot 10^{-7}$ kg/C for Cu, $(7–9) \cdot 10^{-8}$ kg/C for Ti, and $(1–2) \cdot 10^{-8}$ kg/C for Mo. As is seen, we have obtained quite plausible values which are comparable to experimental data [2, 4, 7, 8, 19].

We investigated experimentally the coefficient of ion erosion μ_{al} of the alloy Cu – 30wt.% Al. We measured the mass lost by the cathode over a certain period of time (~1 h) as a function of the vacuum-arc current. It turned out that the coefficient μ_{al} is no higher than $2.5 \cdot 10^{-7}$ kg/C for this alloy, whereas it is 1.5–3 times higher in pure Cu and Al. The value of μ_{al} obtained involves the removal of the cathode mass by microdroplets. Evaluation of the coefficient of ion erosion μ_{al} of this alloy with the use of (7) shows that the calculated values of μ_{al} lie in the interval $(1–2) \cdot 10^{-7}$ kg/C.

Thus, we can infer that formulas (6) and (7) make it possible to correctly evaluate the coefficient of ion erosion of the vacuum arc of metals and alloys and in doing so to determine the value of the rate of deposition of a coating by the vacuum electric-arc method with an accuracy sufficient for practice.

NOTATION

μ, ion-erosion coefficient, kg/C; U_c, cathode potential drop, V; ε_i, ionization potential, V; r, specific heat of evaporation, J/kg; I_i, current of the ions returning to the cathode surface, A; dM_a, mass of the metal atoms evaporating from the cathode surface in the cathode spot over the period dt, kg; dM_i, mass of the cathode-metal ions returning to the cathode surface over the period dt, kg; I_{arc}, total current of the vacuum arc, A; I_e, part of the total arc current transferred by the emitted electrons, A; I_i^*, current of the ions propagating into the volume of the vacuum chamber, A; $n_e v_e$ and $n_a v_a$, numbers of electrons and atoms emitted and evaporated, respectively, from a unit area of the surface in the cathode spot in a unit time, $1/(m^2 \cdot sec)$; g_s, content of the sth component in the alloy; P_s, partial pressure of the vapor of the sth component of the alloy, Pa; m_s, atomic mass of the sth component of the alloy; E, electric field strength in the cathode spot, V/m; σ_{max}, maximum value of the electron impact ionization cross section of the atom, m^2; n_a and n_e, densities of the evaporated atoms and the emitted electrons, respectively, in the cathode spot, m^{-3}; v_a and v_e, velocities of the evaporated atoms and the emitted electrons, respectively, in the cathode spot, m/sec. Subscripts: c, cathode; i, ion; arc, arc; e, electron; a, atom; s, 1, 2, ...; max, maximum; al, alloy.

REFERENCES

1. Zh. A. Mrochek, B. A. Éizner, and G. V. Markov, *Principles of the Technology of Formation of Multicomponent Vacuum Electric-Arc Coatings* [in Russian], Minsk (1991).
2. J. Lafferty (ed.), *Vacuum Arcs* [Russian translation], Moscow (1982).
3. G. A. Lyubimov and V. I. Rakhovskii, *Usp. Fiz. Nauk*, **125**, No. 4, 665–706 (1978).
4. V. I. Rakhovskii, *Physical Principles of Commutation of Electric Current in Vacuum* [in Russian], Moscow (1970).
5. I. I. Beilis, M. P. Zektser, and G. A. Lyubimov, *Zh. Tekh. Fiz.*, **58**, No. 10, 1861–1870 (1988).

6. R. L. Boxman, D. M. Sanders, and P. J. Martin (eds.), *Handbook of Vacuum Arc Science and Technology*, Noyes Publ., Park Ridger, New Jersey (1995).
7. I. G. Kessaev, *Cathode Processes of an Electric Arc* [in Russian], Moscow (1968).
8. G. A. Mesyats, *Ectons in Vacuum Discharge: Breakdown*, *Spark*, *and Arc* [in Russian], Moscow (2000).
9. V. A. Nemchinskii, *Zh. Tekh. Fiz.*, **52**, No. 9, 1748–1755 (1982).
10. V. A. Nemchinskii, *Zh. Tekh. Fiz.*, **55**, No. 1, 60–66 (1985).
11. B. Ya. Moizhes and V. A. Nemchinskii, *Zh. Tekh. Fiz.*, **52**, No. 4, 684–689 (1982).
12. C. Kittel, *Introduction to Solid State Physics* [Russian translation], Moscow (1978).
13. G. V. Markov, *Inzh.-Fiz. Zh.*, **75**, No. 1, 171–173 (2002).
14. E. M. Savitskii, I. V. Burov, and S. V. Pirogova, *Electrical and Emission Properties of Alloys* [in Russian], Moscow (1978).
15. M. N. Ivanovskii, V. P. Sorokin, and V. I. Subbotin, *Evaporation and Condensation of Metals* [in Russian], Moscow (1972).
16. A. A. Vainshtein, I. I. Sobel’man, and E. A. Yukov, *Cross Sections of Electronic Excitation of Atoms and Ions* [in Russian], Moscow (1973).
17. A. A. Vainshtein and V. P. Shevel’ko, *Structure and Characteristics of Ions in a Hot Plasma* [in Russian], Moscow (1986).
18. B. A. Éizner, G. V. Markov, and A. A. Minevich, et al., *Élektron. Obrab. Mater.*, No. 1, 3–15 (1995).
19. A. A. Plyutto, V. N. Ryzhkov, and A. T. Kalin, *Zh. Tekh. Fiz.*, **47**, No. 8, 494–501 (1964).