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The influence of magnetic field on the rate of cathode erosion at vacuum arc spraying

I V Karpov[1,2], A V Ushakov[1,2], A A Lepeshev[1,2], L Yu Fedorov[1,2], E A Dorozhkina[3], O N Karpova[3], A A Shaikhadinov[1,2], V G Demin[1,2], E P Bachurina[1,2], D V Lichargin[1], A K Abkaryan[2], G M Zeer[2], S M Zharkov[2,4]
[1]Federal Research Center "Krasnoyarsk Scientific Center" of the Russian Academy of Sciences, Krasnoyarsk, 660036, Russia
[2]Siberian Federal University, Krasnoyarsk, 660041, Russia
[3]Reshetnev Siberian State University of Science and Technology, Krasnoyarsk, 660037, Russia
[4]Kirensky Institute of Physics, Federal Research Center KSC SB RAS, Russia

E-mail: sfu-unesco@mail.ru

Annotation. The influence of the magnetic field in the cathode space on the synthesis of metal oxide nanopowders by vacuum-arc spraying was studied. It was found that, depending on the geometry of the magnetic field and the pressure of gaseous medium in plasma-chemical reactor, particular conditions which enhance the efficiency of CuO synthesis, appear.

One of the basic investigation tasks in the development of nanoparticles synthesis method [1-23] is to study the dependence of the average size and morphology of nanoparticles on process parameters. It is necessary to determine and optimize the physical variables that influence on the nucleation and growth of particles in the vapor phase in order to understand the synthesis process.

Within the presented work, we carried out the experimental study of nanoparticles synthesis processes in order to identify the influence of the magnetic field in the cathode space on the efficiency of the vacuum-arc spraying method.

Although vacuum arc of cathodic shape with cold cathode is one of the most efficient sources of metal ions in respect of power consumption, however, there are opportunities to further enhance the degree of ionization of the plasma flow through the ionization of vapor components. The principal way of increasing the degree of ionization of the plasma flow is to use a special configuration of electric and magnetic fields in the volume of the plasma generator.

In the end generators of metals plasma various types of solenoids are used to create an external magnetic field. Solenoids create a field B in the system, which possesses a cylindrical symmetry [24]. This field is intended to stabilize the cathode spot (CS) on the end face of the cathode. However, it can be used for additional ionization and acceleration of plasma flow in the case of a correct choice of its size and configuration. Vector $\vec{B}$ in this case can be resolved into two components: B_r - radial and B_z - axial. An external electric field E between the cathode and the special cylindrical anode or metal walls of the generator (playing the role of the anode) also possesses a cylindrical symmetry. In general, the field lines of the fields E and B intersect so tha7t the angle between $\vec{E}$ a $\vec{B}$ is a function of coordinates z and r. Thus, we have a situation of movement of the plasma flow in crossed inhomogeneous electric and magnetic fields.

In general, the analysis of the plasma flow in the end low-current accelerator can be carried out within the MHD approximation.

To obtain the accelerated metal plasma for coating, the system parameters are selected from the following relations:

$$R_e << L << R_i;\ \omega_i\tau_i << 1,\ \omega_e\tau_e > 1;\ N = 1\text{-}100\ \text{kW}$$

where N is a power of electric arc; L is a characteristic length of the acceleration zone.

In this case, the plasma acceleration occurs mainly by magnetic forces, plasma electrons are strongly magnetized and ions slightly change their trajectory while moving through the acceleration zone L. The direction of discharge current around the cathode coincides with the direction of the force lines of the magnetic field, which greatly facilitates the emission of electrons into the plasma. Near the anode, the electrons must move across the force lines $\vec{B}$, which decreases their outflow and creates conditions for further ionization of the vapor component.

Charge separation during the particles move into the azimuth direction causes an azimuth current. The physical origin of this current is determined by the presence of the azimuth components of the Hall voltage in the corresponding equations of the MHD approximation. Thus, the value of azimuth current exceeds the value of radial and axial currents.

An accelerating force, acting on the plasma in the axial direction, is defined by equations (1-3):

$$F = \int_{S_2} \rho V_z^2 dS = F_1 - F_2\,, \tag{1}$$

$$F = \int_V j_\varphi B_z dSdz - \frac{1}{2}\int_V j_\varphi B_z r dS\,, \tag{2}$$

$$F_2 = P_1 S_1 + \int_0^L P dS\,, \tag{3}$$

where S_1 and S_2 are inlet and outlet cross-sections of the plasma jet acceleration zone; V is a volume of acceleration zone; P_1 is a pressure at the inlet of the acceleration zone.

The force F_1 is specified by interaction of the discharge current with the external magnetic field B and has an opposite force applied to the solenoid and the cathode. The force F_2 is of gas-dynamic origin and has an opposite force applied to the inner walls of the accelerator.

Thus, at the area of a diverging magnetic field, the Hall plasma acceleration zone appeared. The Hall accelerating force (1) can be represented as:

$$F = \alpha\beta_e I_d B_e \tag{4}$$

where *a is* a geometric factor. A rate of plasma outflow V under the action of this force is defined by the relation:

$$V \cong F / \dot{m} - \beta_e B_r\,, \tag{5}$$

where $\dot{m}$ is a mass flow rate of plasma.

Interaction of Hall current with a magnetic field component leads to the focusing of plasma jet along the axis of the system under the influence of a force $F_r = j_\varphi B_z$. Wherein, a component of ion current *j*, along the *Z* axis is changed slightly due to $\beta >> 1$. However, under certain circumstances, due to the interaction of electrons with neutral atoms and ions, the integral spin of the plasma flow can be observed.

In the end Hall accelerator there is the effect of autoseparation of microdrop phase on the periphery of the plasma jet, which is apparently due to a negative charge appearing on the electrically insulated microdroplets in plasma.

The influence of longitudinal magnetic field on the character and rate of cathode erosion was studied by means of the installation described in [6, 20]. Copper of M0 grade was used as a cathode for spraying. In order to begin plasma chemical reactions, the chamber was preliminary evacuated to a pressure of $1.33 \cdot 10^{-3}$ Pa and then it was filled by gas mixture composed of 10% O_2 + 90% Ar. The synthesis was carried out at a pressure of gas mixture of 60 Pa. The value of the magnetic field generated by the solenoid at the cathode surface was varied from 40 to 80 Oe. A pulse arc with a frequency of 1 kHz, a pulse duration of 250 μs and an amplitude of the current in a pulse of 2.3 kA were supported by the power supply system.

Fig. 1 shows the experimental dependence of the magnetic field on the rate of cathode erosion and the voltage in the discharge gap. Increasing an intensity of the magnetic field causes decreasing an erosion rate by 1.8 times, while increasing a voltage in the discharge gap. The magnetic field influences on the character of the cathode spot motion, moving it from the center to the edges of the working face of the cathode. [25] Wherein uniform erosion of the entire working surface of the cathode is provided, while in the case without a magnetic field cathode erodes mainly in the central part, which is explained by the localization of the spot in the given area of the cathode under the influence of its own magnetic field of the arc. Extension of the area of cathode spot migration, under the influence of the solenoid field, increases the time during which the spot traverses the entire eroding surface of the cathode. The specific thermal load on the cathode surface decreases, which leads to some decrease in the rate of the cathode erosion by reducing the amount of generated droplets.

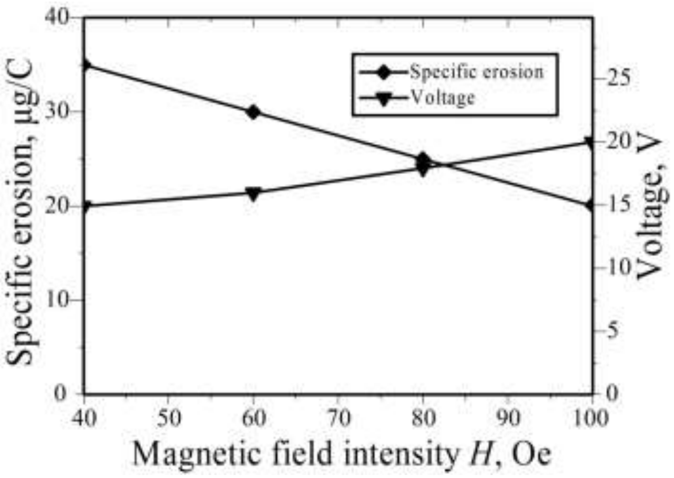

Figure 1. Dependence of the cathode specific erosion and the voltage in the discharge gap on the intensity of the longitudinal magnetic field

Under the condition of oxygen content in the volume, the expansion of spot migration area leads to increasing the time interval, during which at the sites of the cathode surface, which are not occupied by spot, copper oxide inclusions are formed, and hence the content of CuO on the cathode surface increases. When the cathode spot is situated on the copper oxide inclusions, the voltage drop at the discharge reduces. As a result, under the condition of sufficient density of CuO inclusions on the cathode surface, arcing occurs mainly on this material. Wherein, the magnetic field at the cathode does not influence the rate of the cathode erosion. The nature influence of the magnetic field in the volume on the rate of cathode erosion during the formation of copper oxide inclusions at its surface can be understood by assuming that active gas molecules enter into the reaction of CuO synthesis; and a basic elementary process, resulting in oxygen activation in these experimental conditions, is recharging copper ions on the gas molecules. This assumption is valid because of the presence in the vacuum arc plasma of a large number of multiply charged ions, exchange cross sections of which at low energies can be substantially higher than the gas-kinetic ones. Oxygen ions, appearing as a result of recharge process, have energies close to thermal and change their direction of motion under the presence of even weak electric fields in plasma. The paper [26] shows that in the presence of an external magnetic field, satisfying the condition: $\rho_i<\Lambda<<\rho_e$ (where ρ_i, ρ_e are ion and electron Larmor radius, respectively, Λ is a characteristic size of the system), electric field appears in vacuum arc plasma, and magnetic lines play role of equipotential lines of electric field [27].

Thus, while using the geometry of magnetic field, in the cathode space of plasma the electric field component appears, it directs toward the cathode working surface and accelerates oxygen ions into the given direction. At constant gas pressure in the system this effect causes increase of activated particles flow onto the working surface of the cathode, which causes an increase of efficiency of CuO synthesis, the formation of which determines decrease of the cathode erosion in the present case.

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