Ion-plasma coatings performance properties improvement obtained by arc deposition

V I Bogdanovich and M G Giorbelidze
Samara National Research University, 34, Moskovskoe Highway, Samara, 443086, Russian Federation

E-mail: bogdanovich@ssau.ru; m.giorbelidze@ssau.ru

Abstract. Influence of micro-droplet phase content in erosion products of cathodes made of various materials on coating properties produced by vacuum ion-plasma electro-arc method has been revealed. Amount of micro-droplet phase and its fractional content in a plasma jet have been researched. Coefficient standard distribution of micro-droplet phase content depending on cathode material and production conditions, distance from the cathode to the deposition surface, arc current and the temperature of the cathode surface have been obtained. General manufacturing methods and design concepts to reduce micro-droplet phase have been formulated.

1. Introduction
Development of coating deposition technologies supposes solving a number of tasks. They are the following: to choose deposited materials, to reach a certain property level, to model and to optimize the process, to designate deposition modes, etc. [1, 2]. All these aspects determine quality and product cost. One of these tasks is to control micro-droplet phase content (MDPh) contained in cathode erosion products. To solve this task, the researchers have applied the method of micro-droplet phase share determination in a vacuum chamber operating area and some manufacturing and design methods [1-2].

In case of obtaining nitrides, carbides and oxides, emergence of MDPh results in performance properties reduction of coatings (especially tribotechnical). However, in obtaining coatings of pure metals negative influence of MDPh is not practically observed, and in case of obtaining coatings made of multicomponent alloys (for instance, nickel-chrome-aluminium-yttrium), MDPh influences positively providing phase composition similarity of cathode and coating materials. The objective of this work is to generalize accumulated experience on MDPh reduction and development of general manufacturing principles of its control.

2. Experimental research of content of a micro-droplet phase
Experimental research of quantity and fractional content of MDPh was carried out by short-term putting of glass plates in a plasma jet. MDPh composition was researched using metallographic microscope, and quantitative assessment of a relative area occupied by MDPh was carried out using metallographic installation with an image analyzer in compliance with the relation:
where $S_{\text{cph}}$ – area occupied by micro-droplets, $S_0$ – total area of analyzed surface.

It should be noted, that absolute value of MDPh quantity could be determined by weighing only. However, it is impossible to separate MDPh from steam (atomic) phase. Measurement of the droplet phase coefficient $k_{\text{cph}}$ allows to obtain only relative change of this magnitude in comparison with the certain reference value conditionally accepted as a unit. Analysis of these changes allows to choose events and modes reducing MDPh quantity, but obtained results do not allow to claim that exactly the same share of MDPh is in the coating.

During micro-droplet phase content measurements, it was considered that in initial period of the arcing, MDPh quantity was maximum because of uncontrolled compounds at the cathode surface. Under the following arcing, quantity of MDPh reduces at first, then it monotonically increases and in a certain time period $t_0$ it reaches stationary value in accordance with changes of mean integral temperature of the cathode surface. As a result, input of glass plates in a plasma jet is to be implemented after cathode running-in during the period $t \geq t_0 = \delta/a^2$, where $\delta$ - cathode thickness, $a$ – temperature conductivity of cathode material. Hold up time of plates in a plasma jet was determined experimentally so that the background deposition of the coating would allow to carry out optical analysis for transparency of plates with MDPh.

Figures 1 and 2 show standard distributions of MDPh coefficient $k_{\text{cph}}$ depending on cathode material and its manufacture conditions, distance from the cathode to the deposited surface, arc current, and the cathode surface temperature.

**Figure 1.** MDPh coefficient depending on the distance to the cathode for the materials: 1 - BT-6 (Ti-6Al-4V, Grade 5), 2 - BT-1-0 (Grade 2), 3 - BT-1-00 (ERTi-1), 4 - BT-1-00 (ERTi-1) vacuum annealing. Arc current 100 A.
Figure 2. MDPh coefficient depending on arc current for various cathode thickness:

1 - $\delta=4.2$ cm; 2 - $\delta=3$ cm; 3 - $\delta=2.5$ cm; 4 - $\delta=2$ cm.

Research has shown that phase composition of cathode material and its manufacture method greatly influence on quantity and MDPh composition. For example, alloy BT-6 gives four times as much MDPh in comparison with pure titanium BT-1-00 (ERTi-1) subjected to vacuum annealing (Figure, points 1 and 4). Besides, fraction MDPh composition from alloy BT-6 is substantially coarser. It is seen from Figure 1 that because of influence of gravitational separation MDPh quantity along the axis of a plasma jet in proportion to moving off from the cathode diminishes quickly enough due to going away of the coarsest fractions. Comparison of points 3 and 4 in Figure 1 allows evaluating influence of high-temperature annealing on MDPh content.

Scientific articles have more than once claimed that mean integral temperature of the cathode surface influences on MDPh quantity. To verify this statement, cathodes made of BT-1-00 with diameter $D = 8.0 \cdot 10^{-2}$ m and thicknesses $\delta$: 4.2 $\cdot 10^{-8}$ m; 3.0 $\cdot 10^{-8}$ m; 2.5 $\cdot 10^{-8}$ m; 2.0 $\cdot 10^{-8}$ m were manufactured for the same metal plasma generator. Measurement results $k_{ph}$ depending on arc current for the given cathode thicknesses are shown in Figure 2. Research has shown that monotone increase of $k_{ph}$ for each thickness is observed. Moreover, if the arc current $I_{d,k}$ exceeds certain value, MDPh quantity increases greatly. It depends on delivered heat flow to the cathode and its cooling conditions.

Equation for mean integral temperature of the cathode surface is the following:

$$T_k = T_0 + \frac{0.3I_d U_d \delta}{\pi R_k^2 \lambda},$$

(1)

where $U_d$ - voltage at the arc, $\delta$ - cathode thickness, $R_k$ – cathode radius; $\lambda$ - thermal conductivity of the material.

Having distinguished arc current values in Figure 2 at which we observe fast growth of MDPh for different thicknesses $\delta$ (point 1 - $I_d = 95$ A; point 2 - $I_d = 135$ A; point 3 - $I_d = 155$ A) and having substituted these values into (1), considering that $\lambda \approx 17$ W/m·K, $U_d = 22$ V, $T_0 = 323$ K, we get the following values of cathode temperatures $T_k$: 631 K, 636 K, 622 K, 585 K.

Similarity of all four values of temperature allows to state that characteristic increase of MDPh quantity in Figure 2 has the same thermal nature. When the mean integral temperature of the cathode surface reaches some characteristic value (in given case $T_{ch} = 630$ K) MDPh quantity grows fast. Some
reduction of $T_{\text{em}}$ for high currents (point 4 Figure 2) is apparently connected with the fact that at high currents, cathode spots are concentrated at the cathode center, and its surface temperature at the central part is to be determine according to the relations different from (1).

The same characteristic values have been found for other cathode materials too. That is why formula (1) is the following:

$$\frac{R^2_k}{\delta} \geq \frac{0.3I_cU_d}{\pi\lambda(T_{\text{em}}-T_0)},$$

(2)

where it is considered that $T_k \leq T_{\text{em}}$.

Equation (2) allows choosing dimensions of a cathode to achieve needed productivity or at the given cathode dimensions to find the value of a maximum arc current at which MDPh does not grow fast. For example, for the installation NNV-6.6-I1 with recommended dimensions of a titanium cathode ($R_k = 4 \times 10^{-2}$ m, $\delta = 4.2 \times 10^{-2}$ m) maximum arc current is not to exceed 95 A.

3. Results and discussion

The important aspect of MDPh quantity reduction is correct choice of initial cathode shape taking into account geometry of magnetic field lines. After long operation of a cathode, its surface takes the shape orthogonal to magnetic field lines (2). Later on, this stationary shape of the cathode surface is retained. At the same time, cathode surface shape depends not only on the direction of magnetic field lines, but also on the cathode material – diamagnetic, paramagnetic or ferromagnetic. Research has revealed that reaching this stationary shape is characterized with increased ejection of micro-droplet phase. As a result, when using new cathodes or at considerable changing of deposition mode (arc current or magnetic field induction) it is recommended to run in the cathode by means of deposition to the special shield to get stationary shape surface.

Emergence of such stationary cathode surface shape is getting clear at the basis of the following argumentation. Let at some initial moment, vector $\vec{B}$ is crossing the cathode surface at some angle that is it has perpendicular component $B$ and parallel component $B||$ to the surface. Arc current with density $\vec{j}$ and its direction is perpendicular to the surface. Therefore, cathode spot rotation is appearing under the action of the force proportional to $[\vec{j} \cdot \vec{B}]$ and as a result, azimuthal current $\vec{j}_\phi$ is arising. Interaction of $\vec{j}_\phi$ and $\vec{B} \perp$ gives the force proportional to $[\vec{j}_\phi \cdot \vec{B} \perp]$, this force is directed to the cathode center (under redirection of $\vec{B} \perp$ directed from the cathode center). As a result, cathode spots are in the cathode center for a longer time providing removal of large amount of material at this place. In the course of such selective cathode making, value $B|| \rightarrow 0$ and cathode spots rotation with preferred staying in the center is turning into chaotic motion in this area with uniform surface development (self-regulation).

Under increasing of magnetic field value perpendicular to the cathode surface, rotation rate of the cathode spot over the surface is also increasing. However, starting with certain values $\vec{B}$ cathode spot is squeezed in the central part of the cathode. It is deduced from experiments that at a certain value of magnetic field induction, cathode spot localization in the central part of the cathode results in the temperature of the cathode surface at this area exceeds critical value and MDPh content in a plasma jet increases sharply. Value of magnetic field induction at which MDPh output increases, depends on some factors including a specific design of a vacuum arc generator and a solenoid developing outer magnetic field.

4. Conclusions

Executed researches allow to formulate general manufacturing and design principles of MDPh reduction:

1) to choose cathode material purposefully and to prepare it specially before deposition;
2) it is initially necessary to give cathodes the shape that would remain under its erosion;
3) to optimize deposition modes to minimize MDPh quantity;
4) when developing new plasma generators, it is necessary to optimize electrodes geometry, electric and magnetic field lines configuration.

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