EFFECT OF THE MAGNETIZING CURRENT ON THE STRUCTURE OF COATINGS OBTAINED BY THE VACUUM ELECTRIC-ARC METHOD

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The article examines the effect of the current intensity in a magnetic coil surrounding the cathode on the content of drop phase in coatings and its distribution according to size.

A considerable shortcoming of vacuum coatings obtained by electric-arc evaporation of an integrally cold electrode is the fact that they contain microdrop phase of the cathode material causing microdefects in the condensed film and impairing the operational characteristics of coatings. The formation of the drop phase is due to cathodic processes of the vacuum arc, and it is determined by the thermophysical characteristics of the cathode material (specific heat, thermal diffusivity, melting point and specific heat of melting, boiling point, saturated vapor pressure), the state of its working surface (existence of microunevennesses, cracks, oxide films) and of its bulk (existence of gas inclusions) as well as by the technological parameters of the coating process (current of the arc, partial gas pressure in the chamber of the installation, intensity of the magnetizing current). It is therefore a very topical problem to optimize the choice of the technological parameters of the spray coating regime with the object of reducing the content of drop phase in the coatings.

In the present work we investigated the effect of the intensity of the magnetizing current in the magnetic coil surrounding the cathode and ensuring its uniform burnup on the content of drop phase in the coatings and its size distribution. Titanium nitride coatings were applied with the following parameters: $I = 75$ A, $U_{bi} = 180$ V, $p = 3$ Pa, $\tau = 5$ min, $I_\mu = 0$, 0.1, 0.2, 0.3 A. In each series we used three specimens which were placed at different distances (minimal, maximal, and intermediate in the middle) from the cathode axis. The structure of the surface of the specimens was studied under a metallographic microscope Polyvar. The geometric dimensions of the drop phase were evaluated according to area on a semiautomatic image analyzer MOR-AMO-3 (Reichert, Austria). On the substrate we took into account drops with diameter $d \geqq 1.6$ μm only. The mean number of drops counted per specimen was ~ 1000. Then we calculated the concentration of drops for each specimen (number of drops per 1 mm^2 surface) and determined its mean value in each series. This method makes it possible to eliminate the effect of nonidentical conditions of transporting the drops to different points of the substrate with different intensities of the magnetizing current, and this means that the obtained results express the regularities of formation of the drop phase which are of the greatest interest.

The corresponding results of metallographic investigations are presented in Table 1. Photographs of the surface of the specimens illustrating the change of structure of the coatings when the intensity of the magnetizing current is increased are shown in Fig. 1.

An analysis of the obtained results permits the following conclusions:

1) when the intensity of the magnetizing current increases (within the mentioned limits), the content of drop phase in the coatings decreases considerably (Fig. 2): from 3.5% with zero current to 0.9% with $I_\mu = 0.3$ A;

2) small drops have greater probability of forming, and this regularity manifests itself particularly strongly with $d < 7$ μm: thus, with $I_\mu = 0$, the drops, whose surface area on the substrate is $2 \leqq S \leqq 10$ μm^2, represent 83.2% of the total number, and the proportion of drops with $10 \leqq S \leqq 18$ μm^2 is equal to 8.9% only;

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TABLE 1. Size Distribution of Drop Phase in TiN Coatings Obtained with Different Intensities of the Magnetizing Current

Class No.	S of drop, μm^2	d of drop, μm	No. of drops per 1 mm^2 with different I_μ, A			
			0	0,1	0,2	0,3
1	2	1,6	3166	1505	972	852
2	10	3,6	340	213	151	144
3	18	4,8	105	60	48	41
4	26	5,8	56	29	26	18
5	34	6,6	36	17	16	9
6	42	7,4	24	11	10	5
7	50	8,0	17	7	6	3
8	58	8,6	13	4	4	2
9	66	9,2	11	2	3	1
10	74	9,7	9	2	2	1
11	82	10,2	7	2	2	1
12	90	10,7	5	2	1	1
13	98	11,2	4	1	1	1
14	106	11,6	3	1	1	1
15	114	12,0	2	1	1	1
16	122	12,4	2	1	1	—
17	130	12,8	1	1	1	—
18	138	13,2	1	1	1	—
19	146	13,6	1	1	1	—
20	154	14,0	1	1	1	—
21	162	14,4	1	1	1	—
	170	14,7				

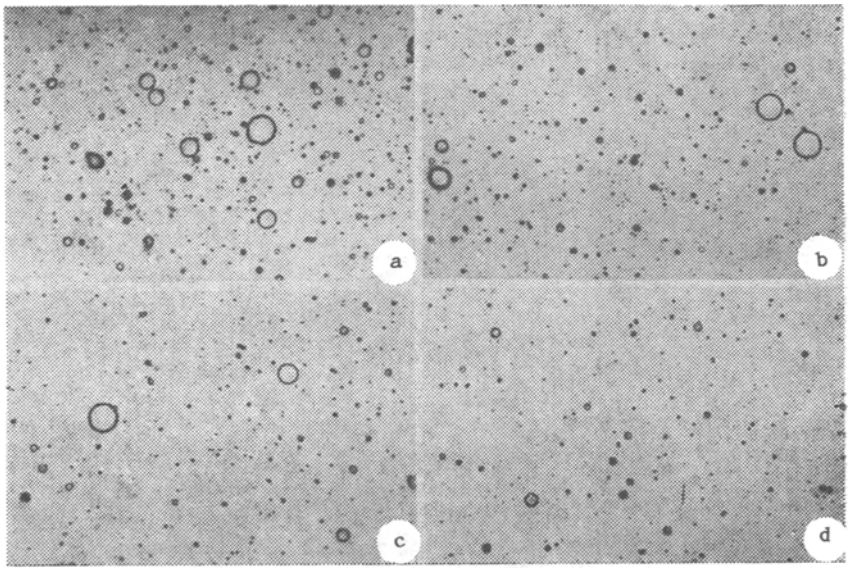

Fig. 1. Photographs of the surface of specimens (× 500) with TiN coatings applied with different intensities of the magnetizing current I_μ: a) I_μ = 0; b) 0.1; c) 0.2; d) 0.3 A.

3) when I_μ increases, the maximal size of the forming drops decreases: with I_μ = 0.3 A drops with d > 12 μm were not registered whereas with zero magnetizing current drops with diameter up to 15 μm were encountered.

The discovered regularities of drop formation are explained by the effect of the induction of the magnetic field on the speed with which the cathode spots move; each of these spots has to be regarded as a heat source with a certain power within the framework of the model of cellular structure.

According to this model [1], that which is visually perceived as one spot is a set of k active emission cell sections, each of which has the diameter d_0, lets the current I_0 pass, and is situated on a circle with fixed characteristic distance L from the nearest neighbors. The maximal number of cells contained in a cathode spot is limited by the possibility of the development of thermal instability due to Joulean heating. The diameter of the cathode spot

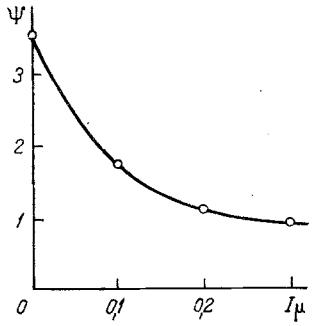

Fig. 2. Dependence of the content of drop phase Ψ in coatings of TiN on the intensity of the magnetizing current I_μ (I = 75 A, p = 3 Pa). Ψ, %; I_μ, A.

formed by a cluster of k cells is equal to the diameter of the circle circumscribed around the cells composing this cluster of cells, and it is determined by the formula

$$d_k = \frac{L}{\sin\left(\frac{\pi}{k}\right)} + d_0 \,(k > 1).$$

We will regard the cathode spot as a heat source with power $\dot{q}$ which can be approximately evaluated by the formula [2]:

$$\dot{q} = U_c I_i a_i + (U_i - \varphi) I_i a_{in} + 0.6\,[UI - U_c I_i a_i - (U_i - \varphi) I_i a_{in} - U_a I].$$

Part of the power released in the cathode spot is removed by heat conduction, and part is expended on removal of cathode material in the form of brittle, drop, ionized, and vapor phases. Here the formation of drops is effected from baths of molten metal whose diameter is of the same order of magnitude as d_k. The weight of a forming drop is determined from the following relation (on the assumption that the cathode is situated above the substrate):

$$mg + (p_1 - p_2)\frac{\pi d_k^2}{4} = \pi d_k \sigma.$$

The pressure p_1 acts on the surface of the cathode spot from the side of the liquid metal, and it is associated chiefly with the existence of gas inclusions in the cathode. The pressure p_2 from the side of the catholyte plasma is due to ionic pressure, the pressure of the neutrals, the effect of the reaction force associated with the evaporation of metal and electron emission on the cathode surface, and also to the interaction between the spatial ion charge and the negative charge on the cathode surface induced by it [3].

The time during which the heat source acts on the area with diameter d_k is the time within which the cathode spot passes the given distance:

$$t = \frac{d_k}{v}, \tag{1}$$

and the amount of heat liberated on the given area is determined as:

$$Q = \dot{q}t = \dot{q}\frac{d_k}{v}. \tag{2}$$

Therefore increased speed of motion of the cathode spot entails a reduced amount of heat released in the region in which the drops are formed, and consequently, the probability of this process becomes smaller.

The existence of some boundary maximal dimension of the forming drops follows directly from the model of the cellular structure of the cathode spot, and it is associated with the possibility of developing thermal instability. For titanium cathodes the maximal size of drops encountered on the substrate is ∿ 15 μm. With increasing speed of motion of the cathode spots the maximal size of the baths of molten metal becomes smaller because there is less heat supplied for the formation of these baths.

Let us analyze the effect of the intensity of the magnetizing current I_μ on the speed at which the cathode spots move. The induction of the magnetic field excited at the surface of the cathode by the solenoid surrounding it can be evaluated by the formula (we neglect the edge effect):

$$B = \mu_0 \mu N I_\mu.$$

The magnetic field straightens the path of the cathode spots. With increasing induction of the magnetic field B up to some boundary value B* the true speed of the spot does not change but the speed of the directed motion increases and approaches in magnitude the true speed. When the induction has reached the value B*, a further increase of the induction of the magnetic field does not entail an increased speed of directed motion of the cathode spot. It should be noted that what is involved in formulas (1), (2) is in particular the speed of the directed motion of the cathode spots.

If some parameter ξ is a function of the speed of the directed motion of the cathode spot v and consequently also the induction of the magnetic field $\xi = f(B)$, then $\lim_{B \to B^*} df/dB\,(B) = 0$, and with $B > B^*$ $df/dB\,(B) = 0$. Such a situation also applies to the parameter Ψ determining the content of drop phase in the coating (Fig. 2).

The notions that were presented here shed light on the regularities of the effect of the magnetizing current on the content of drop phase in coatings and on its size distribution. To obtain quantitative evaluations it is necessary to know the dependence of the speed of directed motion of the cathode spots on the magnetic field intensity $v = v(B)$. We do not have such information.

To reduce the content of drop phase in coatings we can use methods based on the utilization of the regularities of its formation as well as various methods of affecting the flux of evaporated substance (shadowing of the substrates, application of curvilinear plasma-optical systems, various procedures of separating the plasma flux), and also their combination. Of particular interest is the first group of methods, and we shall briefly dwell on its characteristics.

1. Since the formation of the drop phase is due to a considerable extent to intense gas liberation in the cathode spot at elevated temperatures, the first method of reducing the spatter effect is thorough preliminary degassing of the cathodes.

2. The second method consists in ensuring effective heat removal from the cathode so that erosion of the material is effected preferentially rapidly by the moving cathode spots of the first type associated with the autoelectronic mechanism of emission predominating at that time on the cathode.

3. The third, the most cardinal method, is connected with the elimination of the localization of heating. Inhibition of heat removal from the working surface of the cathode has the effect that a high temperature is established on the surface of the cathode; this is necessary for maintaining the intensive processes, both of evaporation of substance and of electron emission. As a result the vacuum arc may change into another form: an arc with distributed discharge on a hot consumable electrode [4, 5]. Then plasma with purely ionic phase composition is produced while there is no microdrop phase.

NOTATION

I, current of the arc; I_μ, magnetizing current; I_i, ionic current to the cathode; U, voltage drop on the arc; U_c, cathodic voltage drop; U_a, anodic voltage drop; U_{bi}, bias voltage on the substrate; U_i, ionization potential; ϕ, electron work function; p, reaction-gas pressure in the chamber; τ, time of applying the coating; v, speed of directed motion of cathode spots; σ, surface tension of the molten metal; S, surface area of a drop on the substrate; d, diameter of a drop on the substrate; a_i, coefficient of ion accommodation; a_{in}, accommodation coefficient of an ion that has become a neutral atom; μ_0, magnetic constant; μ, magnetic permeability of the medium; N, number of turns per unit length of the solenoid.

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