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INFLUENCE OF ACCOMPANYING COMPRESSING AIR FLOW ON THE COATING STRUCTURE AND PROPERTIES IN PLASMA-ARC SPRAYING BY CONSUMABLE CURRENT-CONDUCTING WIRE

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ABSTRACT

The paper is devoted to studying the technological features of plasma-arc spraying by consumable current-conducting wire-anode. The relevance of applying such a process is related to the possibility of spraying directly by atomization of wires without the need to make powder materials from them. Experimental verification of the results of mathematical prediction of the influence of annular protective flow of compressed air, accompanying the particle-loaded plasma jet, on the results of plasma-arc spraying by compact wire anodes was performed. The key role of increasing this flow rate above 20 m^3/h for improvement of the spay-deposited coating formation and quality was established. In spraying of coatings from compact wires porosity decreased with increase of the values of flow rates of accompanying air flow G_2, and achievement of this parameter values within 0.5–2.5 %. Conducted experiments allow producing porefree coatings in spraying with wires from M2 copper, Kh20N80 nichrome, NP1 nickel, AMg63 aluminium-magnesium alloy. Studying these experimental results showed that at increase of the rate of accompanying protective air flow G_2 from 0 to 40 m^3/h, the loss of alloying elements (C, Mn) during spraying by steels wires of 65G and 70 grades decreases by 30–40 % on average. Increase of the parameter of rate G_2 of the air flow accompanying the particle-loaded plasma jet influences improvement of the coating bond strength and wear resistance. So, at G_2 = 20–40 m^3/h the bond strength at tearing off of coatings from steel 70 along the normal reaches 60–70 MPa, and that of coatings from M2 copper is 40–55 MPa. Wear resistance of coatings under the conditions of boundary friction and resistance at cavitation wear increases at G_2 increase from 0 to 40 m^3/h, which is manifested in reduction of such wear from 1.35 to 0.32 mg/min.

KEYWORDS: plasma-arc spraying, compact wires-anodes, accompanying flow, material utilization factor, coating bond strength, wear resistance

INTRODUCTION

At present, there exists a certain number of promising industrial technologies of functional coating deposition [1]. In particular, such technologies are used, which allow spraying compact metal and flux-cored wires by plasma-arc process. At application of such a process arc melting of the wire takes place with formation of liquid metal drops in argon atmosphere [2]. For consumable-wire plasma-arc spraying the plasma arc which runs between the tungsten cathode and the wire, is blown by an intensive accompanying air flow. The argon flow around the arc is fed through a plasma nozzle with small flow rate. Air is fed into the gap between the plasma and protective nozzles at considerable rate [3]. The features of such a process consist in that wire material melting and atomization take place in a shielding argon atmosphere, and melt fragmentation and disperse particle acceleration occur in the plasma jet, compressed by a accompanying air flow, coming out of an annular gap between the plasmatron nozzles. It allows ensuring minimum evaporation losses of wire material and optimum fractional composition of the sprayed dispersed phase, spraying material particles reaching a subsonic speed at the moment of collision with the base, high volume concentration of the sprayed particles and minimum opening angle of the particle-loaded plasma flow [4]. However, there arises the risk of molten wire material saturation with oxygen and nitrogen from the air at its introduction into the zone of the electric arc impact, which may cause disturbance and air penetration into the high-temperature arc. The molten metal drops are also influenced by the conditions of protection of the particle-loaded plasma jet at the working distance between the plasmatron and the sprayed surface [5]. As a result, the chemical composition of the deposited coating may differ considerably from that of the wire fed into the arc. In order to eliminate this phenomenon, it is necessary to create reliable protection of not only the wire fusion zone, but of the entire particle-loaded plasma jet. Solving this problem, as well as improvement of service characteristics of the coatings, applied by the described method, and strength of their bond with the base is an urgent task.

The objective of the work is studying the influence of shielding gas flow accompanying the particle-loaded plasma jet on the process of plasma-arc spraying by a consumable wire-anode and on the service properties of the coatings which are deposited using this process.

THEORETICAL ANALYSIS OF THE ACCOMPANYING FLOW INFLUENCE ON THE PLASMA FLOW CHARACTERISTICS

The following tasks were solved to achieve the defined objective: analysis of the computational modeling of the process and influence of the rate of the accompanying gas flow on its characteristics, experimental studies of the influence of the accompanying flow of shielding gas on the material utilization factor, as well as such service properties of the coating as porosity, bond strength, and wear resistance.

According to the technological scheme of the process of plasma-arc spraying by wire-anode, the refractory cathode forms an annular electrode nozzle of radius R_n with the channel wall (Figure 1), through which the plasma gas is fed at rate G_1 and the total arc current I flows. Plane $z = 0$ was taken as the start of the computational domain, assuming that it is located at a certain distance from the cathode working edge. It allowed at the first stage excluding the near-cathode processes from consideration and regarding the arc plasma flow in this plane as axisymmetric and unidimensional along OZ axis, and, thus correctly assigning the initial boundary conditions. It is assumed that shielding gas with flow rate G_2 is fed through annular channel R_1–R_2 as an axisymmetric flow at angle α to the system axis of symmetry. Anode wire is located at distance Z_2 from the start of computational domain. It is assumed that the anode current decreases smoothly in the region of anode binding and then (at $z > Z_2$) currentless inertial movement of gas takes place.

At theoretical analysis of the processes of gas heating and movement at plasma-arc atomization of the wire-anode the computational domain can be conditionally divided into three regions (Figure 1): *1* — arc plasma flow region inside the plasmatron nozzle ($0 \le z < Z_1$); *2* — region of external flow of arc plasma and its interaction with the shielding gas flow ($Z_1 \le z \le Z_2$); *3* — region of inertial movement without the current plasma ($z > Z_2$).

The following assumptions were taken for mathematical description of the processes occurring at formation and flowing out of the plasma jet from the plasmatron nozzle:

● the considered plasma system has cylindrical symmetry, and the occurring processes are considered stationary;

● shielding gas is fed as an axisymmetric flow through the annular channel;

● shielding gas flow in the channel is considered laminar and is described by model dependencies;

● plasma is in the state of local thermodynamic equilibrium, plasma self-radiation is volumetric;

● joule heat release is the main mechanism of plasma heating (the work of the pressure forces and viscous dissipation can be neglected), and energy transfer in the arc column takes place due to heat conductivity and convection (natural convection is ignored);

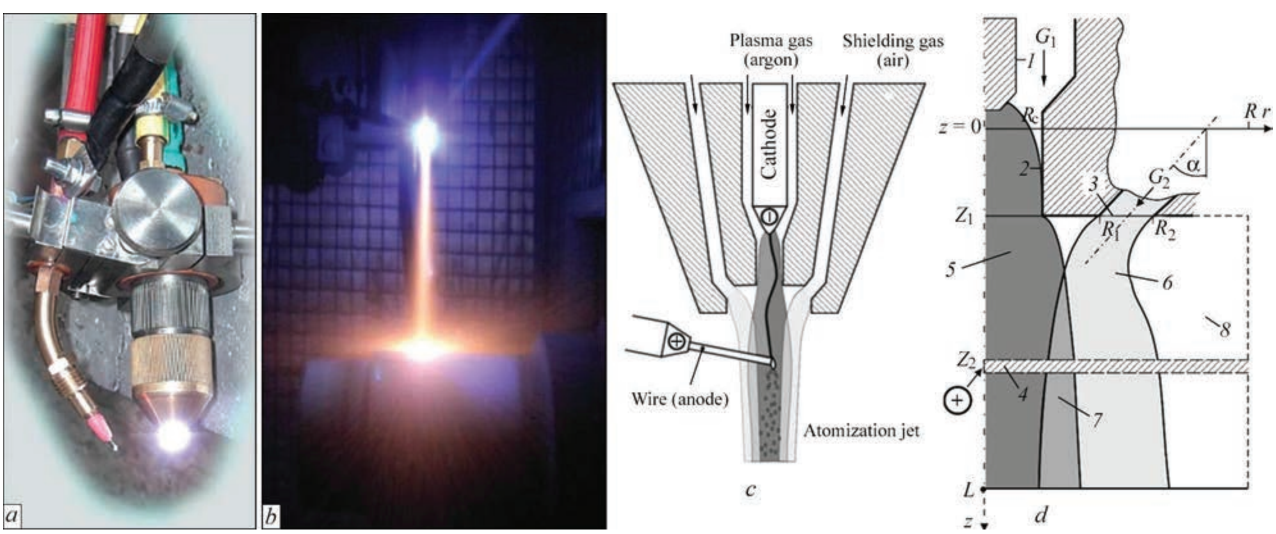

Figure 1. Plasmatron appearance (*a*), visualization (*b*) and technological scheme of the process and scheme of computational mathematical model of heating and movement of gas at plasma-arc spraying of coatings by current-conducting wire-anode: *1* — cathode; *2* — nozzle; *3* — blowing gas feeding channel; *4* — wire-anode’ *5* — arc plasma; *6* — blowing gas (accompanying gas flow); *7* — mixing zone; *8* — external gas atmosphere

- plasma flow is viscous, subsonic, flow mode is turbulent;
- external magnetic fields are absent.

At construction of the physico-mathematical model it was assumed that refractory cathode forms an annular electrode nozzle of radius R_n with the channel wall (Figure 1), through which the plasma gas is fed at flow rate $G_1 = 2\pi \int_0^{R_c} \rho u r\, dr$, and the total arc current $I = 2\pi E \int_0^{R_\sigma(z)} \sigma r\, dr$ flows. Plane $z = 0$ located at a certain distance from the cathode working edge, was taken as the start of the computational domain. It allows regarding the arc plasma flow in this plane as axisymmetric and unidimensional along axis OZ. Shielding gas is fed at rate G_2 through annular channel R_1–R_2 as an axisymmetric flow at angle α to the system axis of symmetry. Anode wire is located at distance Z_2 from the start of the computational domain. It is assumed that in the region of anode binding the arc current smoothly decreases and furtheron (at $z > Z_2$) currentless inertial movement of gas takes place.

The system of magnetohydrodynamic (MHD) equations in the approximation of turbulent boundary layer for time-average values of plasma temperature and velocity is as follows [3, 4]:

$$\frac{\partial}{\partial z}(\rho u) + \frac{1}{r}\frac{\partial}{\partial r}(r\rho\bar{v}) = 0; \quad (1)$$

$$\rho\left(u\frac{\partial u}{\partial z} + \bar{v}\frac{\partial u}{\partial r}\right) = \frac{1}{r}\frac{\partial}{\partial r}\left(r\bar{\eta}\frac{\partial u}{\partial r}\right) - \frac{\partial}{\partial z}\left(p + \mu_0\frac{H^2}{2}\right); \quad (2)$$

$$\rho C_p\left(u\frac{\partial T}{\partial z} + v\frac{\partial T}{\partial r}\right) = \frac{1}{r}\frac{\partial}{\partial r}\left(r\bar{\chi}\frac{\partial T}{\partial r}\right) + \frac{j^2}{\sigma} - \psi, \quad (3)$$

where T is the average plasma temperature; $\bar{v} = (\rho v + \rho' v')/\rho$, v is the mean radial velocity, r is the mean plasma density, r' and v' are the fluctuations of the density and radial velocity; u is the mean axial velocity of plasma; p is the pressure, which within the plasma-forming channel is defined as $p = p_{ext} - \int_z^{Z_1} \frac{dp_c}{dz} dz + \mu_0 E \int_r^{R_c} \sigma H\, dr$, and in the open area of the arc discharge ($z > Z_1$) $p = p_{ext} + \mu_0 E \int_r^{R_c} \sigma H\, dr$; $C_p(T, p)$ is the specific heat capacity at constant pressure; s is the plasma electric conductivity; j is the vector of electric current density; $\psi(T, p)$ is the bulk density of self-radiation power; $\bar{\eta}$ and $\bar{\chi}$ are the total coefficients of dynamic viscosity and heat conductivity of plasma, which are the sums of molecular and turbulent viscosity and heat conductivity, respectively; μ_0 is the universal magnetic constant; $H = \frac{1}{r} E \int_0^r \sigma r\, dr$ is the azimuthal component of the arc current magnetic field.

The system of MHD equations together with the accompanying relationships, k-e model of turbulence and boundary conditions completely defines the thermal and gas-dynamic characteristics of turbulent plasma flow, both in the arc and inertia areas of the flow. These equations make up the base of a unified mathematical model, suitable for calculation of spatial distributions of temperature and velocity of the subsonic plasma flows, which in our case are generated by the plasmatron with a partially open arc in the presence of an accompanying gas flow around the arc.

The developed physico-mathematical model and software for its computer realization were used to conduct numerical analysis of the characteristics of the subsonic turbulent flow of argon plasma, which is generated by the plasmatron with a consumable wire-anode at different modes of its operation (Figures 2, 3). This analysis showed that flow rate G_2 of the gas flow accompanying the particle-loaded plasma one, has a rather substantial impact on velocity u and temperature T of the latter. With increase of value G_2, values u and T grow in direct proportion. It is rational to use the accompanying gas flow with rates $G_2 = 20$ m^3/h and higher.

Numerical studies in work [3, 4] showed that blowing of the plasma jet by an accompanying flow of cold gas prevents its expansion and essentially increases its extent. So, at a distance of approximately 50 mm from the plasmatron nozzle edge, the width of the plasma flow core, not blown by shielding gas, approximately two times exceeds the respective value for a jet, surrounded by the flow [3]. Argon concentration in the high-temperature core of the plasma jet, surrounded by the accompanying shielding gas, remains high at considerable distances (close to 0.5 at 150 mm distance from the nozzle edge) [4]. As a result, the protected plasma jet preserves its momentum and energy much longer, and practically does not mix with the accompanying gas.

Thus, numerical calculations given in works [3, 4], show that the technological measure of applying an accompanying flow, which compresses the plasma jet, essentially influences the characteristics of particle-loaded plasma jet. A comprehensive assessment of the rationality of application of this technique during plasma-arc spraying with wire-anodes requires a more complete study of its influence both on distribution of plasma temperature and velocity, and on the structure

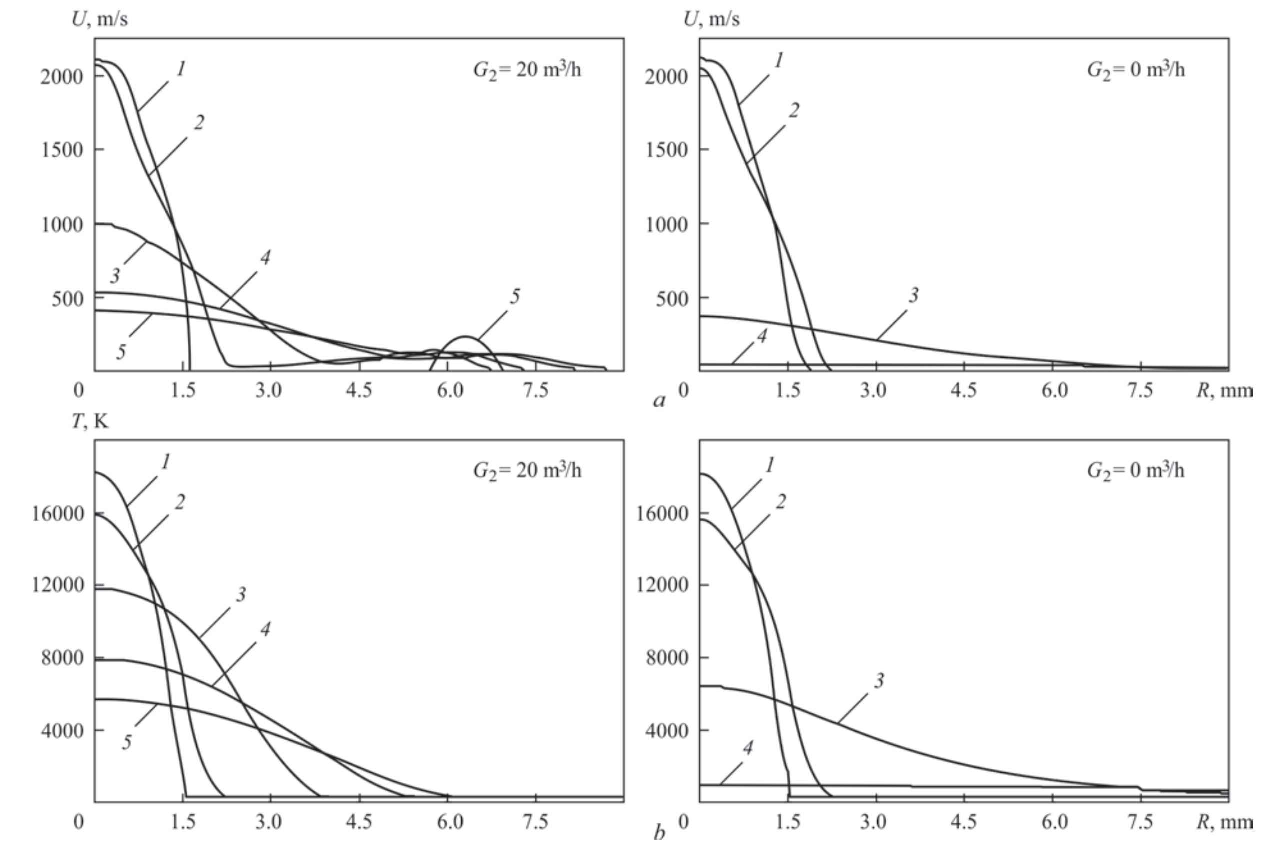

Figure 2. Radial distributions of plasma velocity (*a*) and temperature (*b*) at I = 200 A and G_1 = 1 m^3/h in the following regions [3, 4]: *1* — nozzle edge (z = 3 mm); *2* — wire-anode region (z = 9.3 mm); *3* — z = 150 mm; *4* — z = 250 mm

and properties of the spray-deposited coatings from different types of wire materials.

EXPERIMENTAL PROCEDURE

Technological experiments on determination of the influence of the accompanying flow on service properties of the produced coatings were performed, proceeding from the above calculation-based recommendations. A laboratory facility based on Plazer 30PL-W unit (upgraded batch-produced UN-126 unit) was developed for this purpose [6]. This unit was further fitted with equipment to study the micrometallurgical processes, which included thermal vision and original video optic systems for recording the spraying process [7–10]. Carbon steel of grade 20 (GOST 16523–97) was used as the base. Plates from this steel were sprayed with compact wires of 1.2–1.6 mm diameter from steel 70 (GOST 103–2006), 65G (GOST 103–2006), 18Kh15N3M (GOST 103–2006), Kh20N80 nichrome (GOST 12766.1–90), M2 copper (GOST 859–2001) and AMg63 aluminium alloy (GOST 4784–97). Wire from commercial NP1 nickel (GOST 492–2006) was spray-deposited on high-strength VCh 35 cast iron with globular graphite (GOST 7293–85).

The value of breaking stress in "coating-base" composition at normal tear, determined by the "conical pin" procedure, was used to assess the strength of coating bond $\sigma_{b.s}$ with the base [11]. Tribotechni-

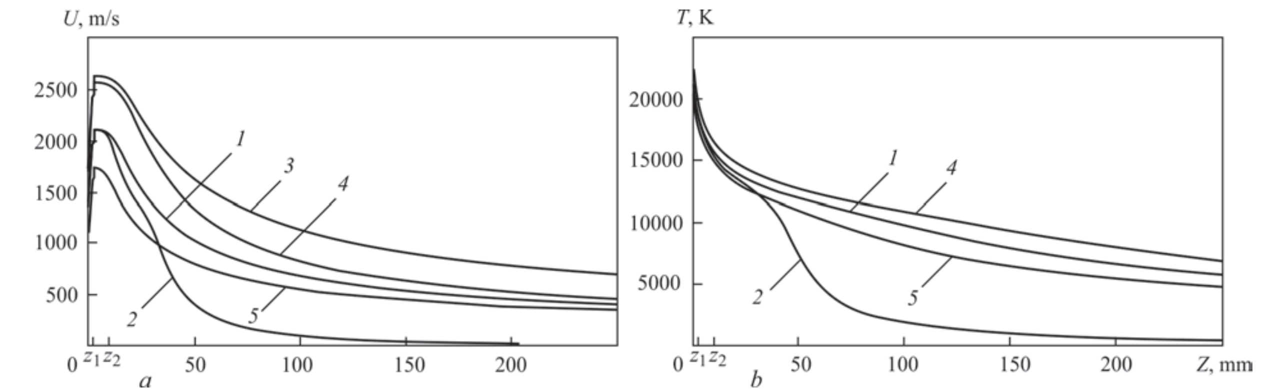

Figure 3. Longitudinal changes of plasma velocity (*a*) and temperature (*b*) on the jet axis at different modes of plasmatron operation [3, 4]: *1* — I = 200 A, G_1 = 1 m^3/h, G_2 = 20 m^3/h; *2* — I = 200 *A*, G_1 = 1 m^3/h, G_2 = 0 m^3/h; *3* — I = 200 *A*, G_1 = 1.5 m^3/h, G_2 = 20 m^3/h; *4* — I = 260 *A*, G_1 = 1 m^3/h, G_2 = 20 m^3/h; *5* — I = 160 *A*, G_1 = 1 m^3/h, G_2 = 20 m^3/h

cal testing of coatings was conducted using friction testing machine 2070 CMT-1 under the conditions with limited lubrication and without it by the schemes of "coated disc–block (SCh-20 cast iron, steel 40Kh, copper-asbestos alloy, steel 45)", "cylinder (SChNMD cast iron) — ring (coating)", "plane (steel 20 — after carbonization, bronze, SCh-20) — coating"; "disc–plane" (Amsler procedure), as well as reciprocating motion with 61 mm amplitude, V = 0.023 m/s, P = 11 MPa [12]. Metallographic investigations of the coatings were conducted in optical microscopes MIM-7, MIM-8, Neophot-23 at up to ×1000 magnification. The composition of the etchants and modes of etching of the polished samples were selected according to the recommendations [13].

The cavitation wear resistance was determined by the method of magnetostrictive vibration. Test samples were prepared in keeping with the requirements of ASTM G32-10 standard. Testing was conducted at the frequency of 20 ± 0.1 kHz, amplitude of 55 ± 3 μm and 500 kW power of ultrasonic generator. Water was used as the test solution.

ANALYSIS OF EXPERIMENTAL RESULTS

Compressed air was used as accompanying shielding gas with flow rate G_2 from 0 to 40 m^3/h. First, the impact of rate G_2 on the parameters of the technological mode of spraying was determined, in particular, on the material utilization factor (MUF). For this purpose, value G_2 was varied, leaving other parameters constant: flow rate of plasma gas (argon) G_1 = = 1.5 m^3/h; arc current I = 200 A; spraying distance of 160 mm; wire-anode from steel 70 (1.6 mm diameter). MUF value was determined by the following formula: MUF = $(m_c/m_w)\cdot 100$ %, where m_c is the weight of the coating spray-deposited per a unit of time; m_w is the weight of the wire-anode, spray-deposited per a specified unit of time. It was found that with increase of value G_2 from 0 to 20 m^3/h, MUF is also gradually increased from 52 to 72%. At $G_2 \geq 20$ m^3/h MUF stops growing and a remains stable value of the order of 72 %.

Proceeding from the results of further experiments, it was found that at increase of flow rate values G_2 from 0 to 40 m^3/h, the degree of loss of alloying elements (C, Mn) during spraying with steel 70 wire, decreases by 30–40 % on average, compared with the initial chemical composition of this wire. When spraying with wire from 18Kh15N3M stainless steel, the content of such alloying elements as Ni, Mo, W in the coating remains practically unchanged, compared to their content in the sprayed wire. It was found that at values G_2 = 20–40 m^3/h, oxygen content in the melting zone at the wire-anode tip after an abrupt breaking of the arc is close to these values in spray-deposited coatings for such wire grades with elements with a higher affinity to oxygen, as Kh20N80 and AMg63, and in the case of spraying with copper wire M2 this value in the coating is smaller by 1.5–2.0 times on average.

Spray-deposited coatings, produced by plasma-arc atomization of copper wire-anode of M2 grade, have a dense layered structure, characteristic for plasma coatings (Figure 4). Porosity value mainly is within 0.5–2.5 %. A tendency to lowering of this value with increase of flow rates of the accompanying air flow was established. At values G_2 = 20–40 m^3/h, porefree coating were produced, alongside optimization of such parameters as current, plasma gas flow rate and pressure and spraying distance, at spraying with wires from copper M2 (Figure 4), stainless steel (Figure 5), nichrome, nickel (Figure 6) and AMg63 aluminium-magnesium alloy.

Thickness of the lamellas in the coating is equal to 8–30 μm on average, the lamella interfaces are defectfree (Figure 5). This is an indirect indication of formation of a metallurgical bond between them and realization of a totality of microwelding processes between the earlier solidified layers in the coating and spray-deposited molten particles. Formation of such a bond is possible only under the conditions of increase of the velocity of particle-loaded plasma jet at its acceleration by the accompanying flow. Another indication of the effectiveness of the influence of accom-

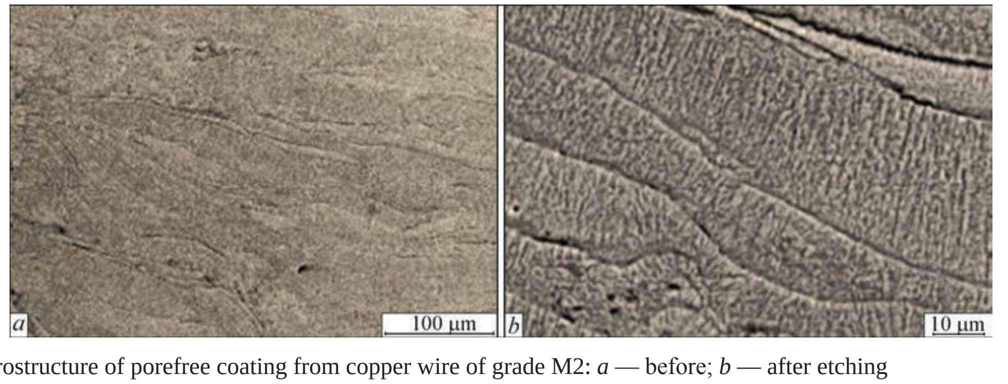

Figure 4. Microstructure of porefree coating from copper wire of grade M2: *a* — before; *b* — after etching

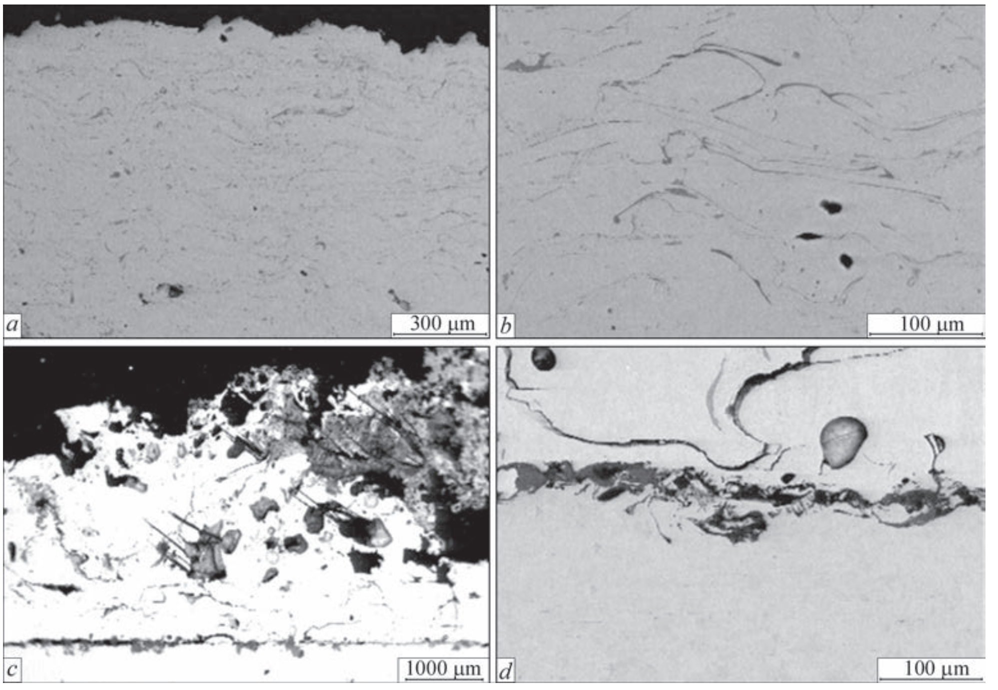

Figure 5. Layer microstructure of coatings, produced by plasma-arc atomization by moving wire-anode from 18Kh15N3M stainless steel, at the following rates of accompanying air flow, compressing the plasma: G_2 = 40 m^3/h (*a*, *b*) and G_2 = 5 m^3/h (*c*, *d*)

panying flow on the process of plasma-arc spraying is minimizing pore formation in the produced layers, which can be clearly traced at comparison of the results of spraying with different rates G_2 of the accompanying air flow (Figure 6).

At determination by the pin procedure of bond strength of coatings spray-deposited by the studied plasma-arc process, it was found that the value of this characteristic is influenced by rate G_2 of the accompanying air flow, coming out of the annular gap between the plasmatron nozzles. Figure 7 shows an example of the influence of rate G_2 of accompanying air flow on bond strength $\sigma_{b.s}$ of coatings produced by plasma-arc spraying with wires (1.6 mm diameter) from steel 70 and M2 copper (tearing along the normal, base is steel 20).

The bond strength of spray-deposited coatings is also influenced by current *I* of the plasma arc. At plasma-arc spraying of wire from steel 70, with increase of current the bond strength $\sigma_{b.s}$ of coatings (tearing along a normal, base is steel 20) first rose, and then somewhat decreased by the end. Spraying was conducted with the following mode parameters: plasma gas (argon) flow rate G_1 = 1.5 m^3/h; rate of accompanying air flow, G_2 = 40 m^3/h; spraying distance of 160 mm. Comparison of the influence of G_1 and G_2 parameters on bond strength showed that the latter of them is more significant.

It is found that the technological parameter of rate G_2 of accompanying annular air flow, coming out of the annular gap between the plasmatron nozzles, influences the increase of coating wear resistance under the conditions of boundary friction and cavitation wear. So, for instance, an increase of coating wear resistance under the conditions of boundary friction and cavitation wear was

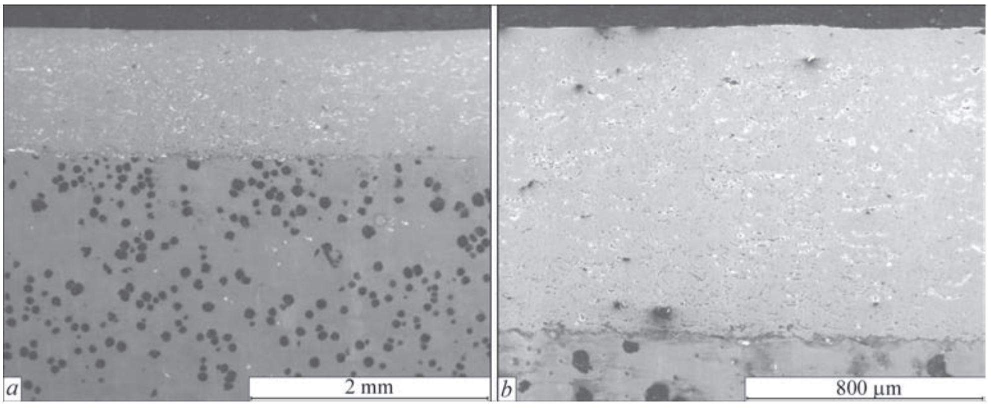

Figure 6. Porefree coating produced by plasma-arc spraying of NP1 nickel wire (base is high-strength cast iron with VCh 35 globular graphite)

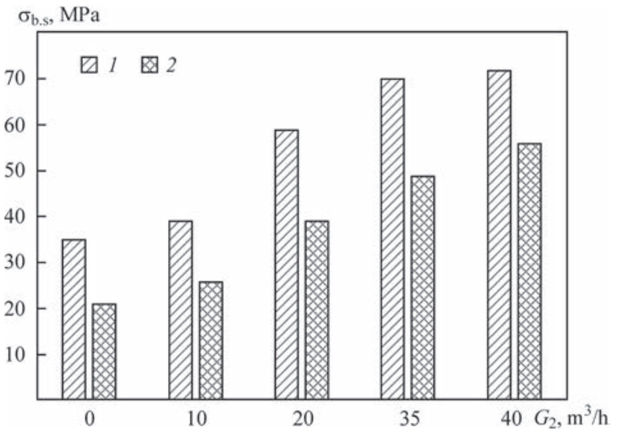

Figure 7. Influence of accompanying air flow rate G_2 on coating bond strength $\sigma_{b.s}$ (steel 20): *1* — steel 70; *2* — copper M2

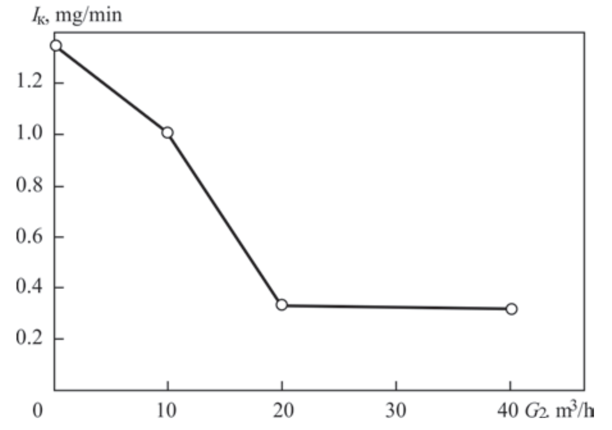

Figure 8. Change of cavitation wear intensity I_c, depending on accompanying flow rate G_2

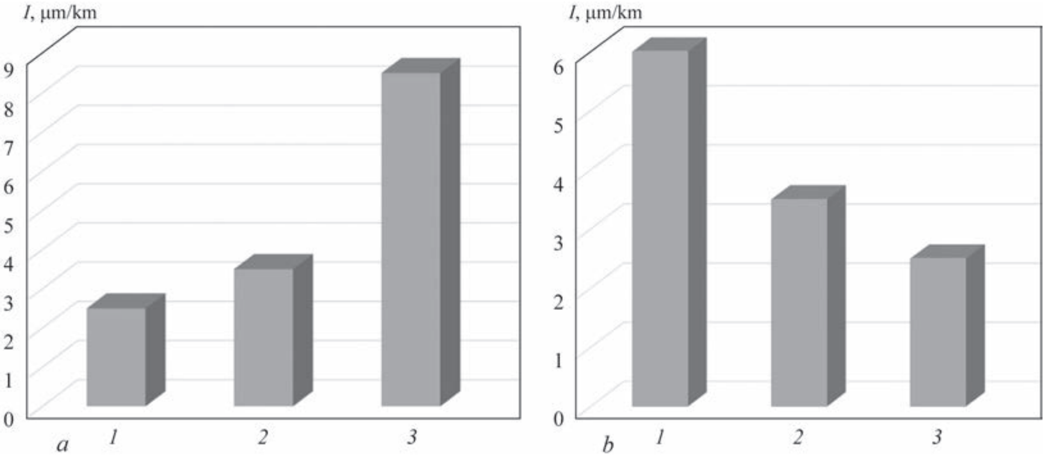

Figure 9. Wear intensity *I* of plasma coatings produced by atomization of wires-anodes (rider is steel 40X; load *P* = 10 MPa; velocity *V* = 1 m/s; lubrication is oil *HC*20, 30 drops/min; friction machine 2070 CMT-1): *a* — from steels 65G (1) and 70 (2) at G_2 = 20 m^3/h, compared to steel 20 after carburization (3); *b* — from steel 70 at accompanying flow rates: G_2 = 5 m^3/h (1); 20 (2); 40 (3)

revealed at G_2 increase from 0 to 35–40 m^3/h (Figure 8). This is attributable to increase of adhesion strength between the coating layers at G_2 increase.

Conducting tribotechnical testing of coatings deposited by plasma-arc atomization of compact metal wires-anodes, showed the positive influence of increase of accompanying flow rate G_2. Under the conditions of friction with limited lubrication by the schemes of coated disc – block, steel 40X)", it was found that coatings from steels 65G and 70 deposited at G_2 = 20 m^3/h have 60–70 % higher resistance than that of steel 20 after carbonization (Figure 9, *a*). At decrease of accompanying flow rate (G_2 = 5 m^3/h) the coating wear resistance decreases, and at increase of the rate (G_2 = 40 m^3/h), it increases (Figure 9, *b*).

CONCLUSIONS

1. Experimental verification of the results of mathematical prediction of the influence of annular shielding flow of compressed air, accompanying the particle-loaded plasma jet, on the results of plasma-arc spraying by compact wires-anodes showed the key role of increasing this flow rate above 20 m^3/h for improvement of formation and quality of the sprayed coatings.

2. A tendency was established to lowering of porosity of sprayed-deposited coatings with increase of the values of accompanying air flow rate G_2 and reaching this parameter values within 0.5–2.5 %, and at G_2 = 35–40 m^3/h porefree coatings were obtained at spraying by wires from M2 copper, Kh20N80 nichrome, NP1 nickel, and AMg63 aluminium-magnesium alloy.

3. It was confirmed that at increase of accompanying shielding air flow rate G_2 from 0 to 20–40 m^3/h, the loss of alloying elements (C, Mn) during spraying by steel wires of grades 65G and 70 decreases by 30–40 % on average. Here, oxygen content in the melting zone at the tip of the wire-anode after an abrupt breaking of the arc for such wire materials as Kh20N80 and AMg63 with elements with a higher affinity to oxygen, is close to these values in spray-deposited coatings, and for the case of spraying by copper wire M2 this value in the coating is smaller by 1.5–2 times on average.

4. The influence of increase of the parameter of rate G_2 of air flow accompanying the particle-loaded plasma jet, on improvement of bond strength and wear resistance of coatings was established. It is shown that at G_2 = 20–40 m^2/h the bond strength at coating tearing from steel 70 along a normal reaches 60–70 MPa, and that of M2 copper coating is 40–35 MPa. An increase of wear resistance of coatings was found under the conditions of boundary friction and cavitation wear at G_2 increase from 0 to 35–40 m^2/h.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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