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JET FORMATION IN PLASMA SPRAYERS

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Optospectroscopic studies of plasma jets in powder sprayers have been made. It has been shown that the jet of the "Plasma-Technik AG" sprayer is a periodically pulsating formation similar to that generated by the two-jet plasma torch. A scheme of a plasmasonic reactor for treatment and synthesis of gaseous and condensed materials is proposed.

Recently published monographs on plasma technologies are based on the results of investigations of the elementary processes in plasma generators made more than 30 years ago. The natural desire of the authors [1–3] to present the technological aspects as completely as possible leads to a "shading" of the plasma processes that are still not clearly understood, which damps the ardor of researchers to continue studies of the physics of plasma generators. The aim of the present paper is to consider the previously incompletely studied issues of the formation of jets of plasma sprayers of powder materials.

For plasma spraying of powders on the surfaces of elements of machines and mechanisms, a special type of plasma torches — plasma sprayers — are used. They are classified with linear-scheme generators [1] in which electrodes (rod, tubular, cylindrical, etc.) are arranged in one line directed along the gas stream. Under the action of the gas stream the closing (radial) part of the arc moves along the channel (Fig. 1a). In so doing, the increase in the arc length and in the voltage on it is restricted by the electrical breakdown between the arc and the electrode wall.

Local treatment of the surface requires the formation of a directed high-velocity, high-temperature particle flux. Therefore, plasma sprayers have a small diameter of the cylindrical channel of the anode d_n and use conditions where the free arc diameter d_a is approximately equal to d_n (Fig. 1a).

At the Institute of Molecular and Atomic Physics of the National Academy of Sciences of Belarus, investigations of the physical processes in plasma sprayers of domestic (M8-72, POZTO, GN-5, and PP-25) and foreign ("Metco," USA–Italy; "Plasma-Technik AG"; "Castolin-Eutectic," Switzerland) make have been carried out [4–10]. It has been shown that the operation of all sprayers relies on the shunting. The scheme of operation of the domestic sprayers corresponds to $d_a \le d_n$ and, therefore, is close to that presented in Fig. 1a. With the above parameters, reciprocating motion of the anode spot on the inner conical and cylindrical surfaces of the electrode occurs, which leads to its erosion. A particularly considerable destruction is observed at the transition point towards the gas stream when the limiting value of the arc voltage is reached. The intensive electrode ablation is due to the prolonged stay of the spot in the arc attachment zone. When the arc is strongly blown by the gas stream, the spot is blown out onto the cylindrical nozzle exit section. At this site the electrode breaks down intensively because of the interaction between the metal melt and the surrounding air oxygen. The chief disadvantage of the domestic sprayers is their short service life.

To the working conditions of the foreign sprayers there corresponds $d_a \ge d_n$, which is characterized by higher values of the electric power supplied and of the plasma-forming gas flow rate. Protection of the anode against destruction is achieved due to the intensive water cooling and the application of chemically neutral working plasma-forming gases. Analysis of the information on the character of the anode channel surface after prolonged operation of the plasma torch points to the fact that these devices operate in accordance with the scheme given in Fig. 1b. Destruction occurs mainly on the edge of the anode cylindrical channel close to the rod cathode. Under normal steady operating conditions of the sprayer, despite the large currents used (I = 300–700 A), no characteristic traces of arc attachment on the nozzle exit section is observed, i.e., the anode spot does not appear there. The internal cavity of the anode made of tungsten also makes for its small erosion.

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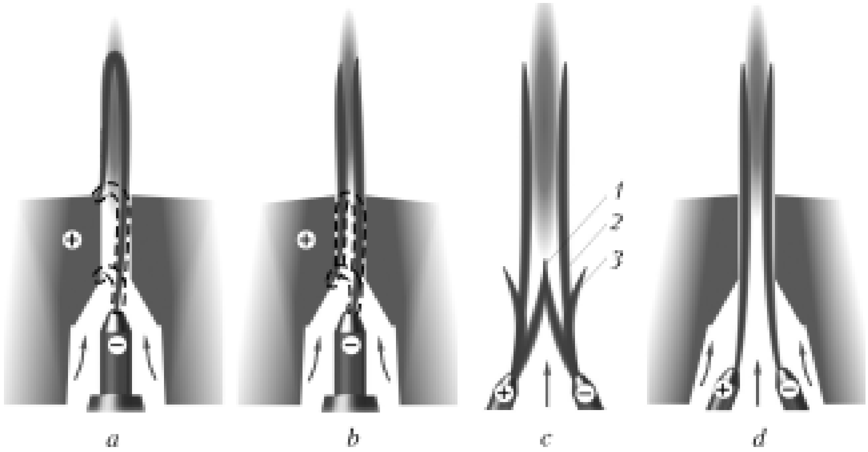

Fig. 1. Schemes of plasma sprayers: with possible appearance of the anode spot on the nozzle exit section (a); with an anode spot in the beginning of the cylindrical channel (b); two-jet plasma torch (c) at low (1), optimal (2), and high (3) gas flow rates; two-jet plasma torch — a sprayer with an acoustic nozzle.

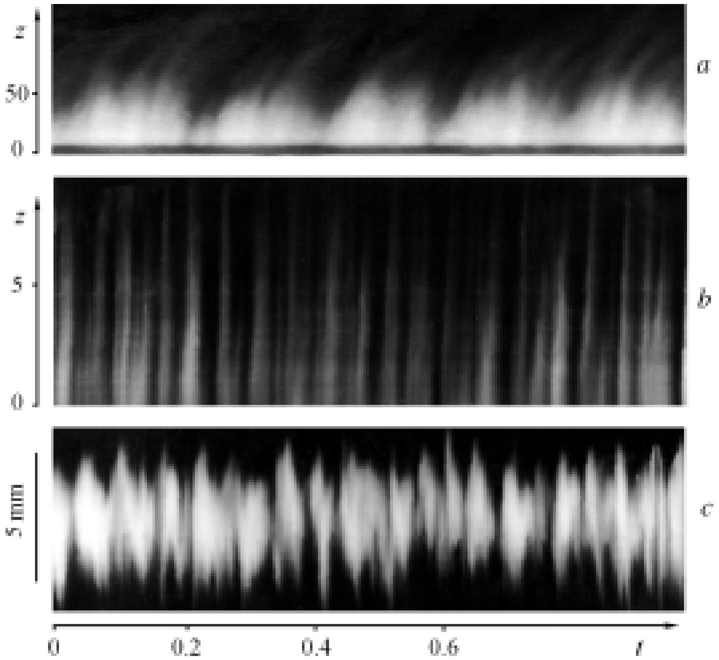

Fig. 2. Continuous scans of the radiation of the axial sections (a, b) and the cross-section (c) of the plasma sprayer jet at I = 400 A, U = 72 V, G_{Ar} = 50 liters/min.

Optospectroscopic studies of plasma sprayers were made in [4, 5]. Figure 2a shows a continuous scan of the radiation of the axial section of the plasma jet of the "Plasma-Technik AG" sprayer. The plasma torch has the following specifications: the cylindrical anode nozzle is of diameter d_{n} = 6 mm and length l_{n} = 12 m, direct current I = 200–700 A, the flow rate of the argon–hydrogen mixture G = 3–66 liters/min, and the pressure P = 1 atm. The sprayer jet is a nonstationary plasma formation with regular pulsation frequencies f = 0.1, 0.3, 4, and 28 kHz. The low-frequency oscillations, f = 0.1 and 0.3 kHz, are due to the processes in the electric power supply, and the mechanism of high-frequency oscillations f = 4 and 28 kHz is likely to be associated with the acoustic properties of the plasma torch [11]. A similar picture with the same characteristic frequencies is also observed in the continuous scan of the jet radiation with a time resolution of about an order of magnitude better but in a smaller spatial zone (Fig. 2b).

The sound oscillations in the linear plasma torch were first considered in [11]. Slightly varying the anode nozzle length, the authors elaborated methods for eliminating voltage fluctuations leading to a decrease in the mechanical strength of plasma torch units. It was shown that, according to the general laws of acoustics [12], in the cylindrical nozzle of the plasma torch resonance could occur in the presence of some driving force arising, for example, from the arc shunting. The sound frequencies of the cylindrical nozzle-resonator are determined by the relations

$$f_{\mathrm{c}} = c(T)/4l\ ,\ f_{\mathrm{o}} = c(T)/2l$$

for a closed and an open end of the resonator, respectively. Here $c(T)$ is the sound velocity depending on the resonator mean temperature and l is the resonator length. For the plasma torch investigated in [11], the excited oscillation frequency was equal to

$$f = 0.65c(T)/2l_{\mathrm{n}}\ .$$

Practically simultaneously with [11] we began to investigate the arc instability in the channel [6–8]. The plasma torch characteristics (d_{n} = 6 mm, l_{n} = 33 mm, I = 200–700 A) were similar to those given above for the "Plasma-Technik AG" plasma torch. Simultaneously with frame-by-frame photography we observed the plasma jet radiation with the aid of a photomultiplier (with the central zone at the nozzle exit section and a slit 0.5 mm wide and 5 mm long). We established that current pulsations, except for f = 300 Hz, were practically absent, and there was complete correlation between the fluctuations of voltage U, brightness B, and sound pressure P_{s}. At $I < 500$ A, the $U(t)$, $B(t)$, and $P_{\mathrm{s}}(t)$ oscillograms have a serrated shape, which is characteristic of the shunting processes in the channel that are random in nature. At $I > 600$ A, the $U(t)$ oscillograms are symmetric in shape, and at $I < 300$ A the plasma torch operation becomes unstable.

Measurements by means of two diametrically positioned microphones have shown that the sound pressure created by the plasma torch depends on the acceptance angle. The acoustic radiation is polarized similarly to the radiation of the dipole with the axis lying in the anode end plane. As the current is increased from 250 to 700 A, the sound oscillation frequency increases from 3.8 to 7 kHz.

The investigations made have shown that the oscillations in the cathode space are sharply enhanced in the resonator — the cylindrical channel of the anode — thus synchronizing the arc motion and the arc-wall electrical breakdown frequency. On the basis of this, we advanced the hypothesis that during the reciprocating motion of the high-temperature piston in the anode acoustic oscillations are generated. The sound intensity at a distance of 1 m from the plasma torch reaches 130 dB (150–160 dB for the region where the jet emerges from the generator nozzle) [8]. Comparison of the plasma torch with known sound sources (siren, Hartman whistle) shows that it has many advantages as to the specific acoustic power, gas flow rate, operating pressure, etc.

Our hypothesis that the arc plasma torch generates acoustic oscillations needs to be refined. As mentioned above, anode spots are formed mainly on the edge of the anode cylindrical channel close to the cathode and rotate due to the vortex supply of the gas stream and magnetic interaction ("Plasma-Technik AG" sprayer). The spot does not penetrate into the cylindrical channel because the near-anode region of the arc, especially at heavy currents, has large sizes due to the fact that to provide the required current transfer at high current densities, metal vapor jets are ejected from the anode surface [13]. On the other hand, if the spot penetrated into the channel and moved in it, such a motion would not be so regular. Highly ordered oscillation erosion processes corresponding to acoustic oscillations cannot be realized. Such ordered processes can only occur at erosion-free movement of plasma formations.

Characteristically, the plasma temperature at the nozzle exit is fairly high and reaches ~16,000 K [10], which can only be attained in the conducting column of the arc. In view of the foregoing, the current transfer in the cylindrical channel of the "Plasma-Technik AG" sprayer can be realized in two portions of the arc with reverse electric current. Because of the strong magnetic interaction, such portions of a high-current arc can exist in the narrow channel of the nozzle and form at its exit a loop structure. This plasma structure executes reciprocating and rotary motions in the cylindrical channel and causes the generation of acoustic oscillations in the plasma torch.

The total length of the loop arc of the plasma torch l_{a} is approximately equal to 30 mm. Let us estimate the electric energy supplied to the plasma torch for such a large arc length to exist. At I = 300–700 A the operating voltage on the plasma torch is $U \sim 70$ V. Less than 20 V will be expended in the near-electrode processes at the above

TABLE 1. Current Density, Plasma Temperature, and Velocity as a Function of Current and Nozzle Diameter

I, A	D_n, mm	j, A/mm^2	$T \cdot 10^{-3}$, K	$V \cdot 10^{-3}$, m/sec
200	2.5	40	19	1
300	3	42	19	1.3

currents, i.e., ~50 V remain to form the conducting zone of the arc inside the nozzle and at its exit. Assuming that the arc channel is axially symmetric, an electric field strength $E \sim 17$ V/cm is needed.

Let us estimate the parameters of the arc in the channel compressed by a powerful gas stream. To this end, we make use of the results obtained by us in studying the processes of plasma cutting [14]. Table 1 gives the parameters of the plasma stream flowing from the cylindrical nozzle depending on the discharge current intensity and the nozzle diameter in the case of using nitrogen as a plasma-forming gas with a flow rate G = 50 liters/min.

It is seen that the velocity of the stream flowing from the nozzle at plasma cutting agrees with the value attained in the "Plasma-Technik AG" plasma torch. The specific flow rates of the plasma-forming gas through the nozzles of the facilities under consideration are also approximately equal. These facts suggest that the results of the investigations of the plasma cutting can be used for estimating the processes in the object under consideration.

From Table 1 it follows that the current density of the compressed arc at I = 200–300 A is $j \sim 40$ A/mm^2 and the plasma temperature obtained from the spectroscopic measurements is 19,000 K. For such a temperature, according to [15], the nitrogen plasma conduction $\sigma \sim 100\ \Omega^{-1} \cdot \text{cm}^{-1}$. Then, according to Ohm's law ($j = \sigma E$), the electric field strength on the arc should be $E \sim 40$ V/cm. Consequently, in experiments a more complex plasma formation rather than an axially symmetric strongly compressed channel is realized.

For further consideration of this point, we registered a continuous scan of the radiation of the plasma-jet cross section (Fig. 2c). It has shown that the plasma formation emerging from the nozzle is pulsating, and the pulsation frequency $f \sim 30$ kHz thereby agrees with the frequency observed on the axial sweep of the jet (Fig. 2b). At a distance of 5 mm from the nozzle exit section the image of plasmoids is formed about its axis, but in general the observed pattern in not axially symmetric. At each instant of time the axis of the plasmoid image is arbitrarily shifted in the limit of the channel diameter. At some instants, two plasmoids at a time and sometimes a zigzaglike structure can be observed. The latter is characteristic of the reciprocating motion of luminous plasmoids. The above features of the longitudinal continuous scan are random in nature because of the simultaneous pulsations caused by the arc shunting, its rotation under the action of the vortex gas flow in the cathode space, the acoustic oscillations in the channel, the unstable position of the strongly compressed inhomogeneous arc plasma formation, etc.

Thus, the plasma piston executing reciprocating motions in the cylindrical channel is a strongly compressed arc transformed under the action of the shunting, the acoustic field, and the rotation. Such a plasma formation can exist in the presence of a diffusive discharge between closely spaced portions of the arc column with reverse electric current. Because of this complex space-time structure of the arc in the channel, the plasma torch cannot be a generator of strictly definite acoustic oscillations whose frequency is calculated by the above relations. The results of the experimental studies reported in [9] indicate that such a sound generator has many characteristic frequencies in a wide spectral range.

The diffusive volume discharge is likely to be also observed in the so-called two-jet plasma torch (TJPT) [16] generating an open portion of the arc consisting of an anode jet and a cathode jet (Fig. 1c), as does the "Plasma-Technik AG" sprayer. The operating conditions of the TJPT strongly depend on the flow rate of the gas supplied to each jet. The developers of the TJPT believe that at an optimum flow rate in the region where the jets coalesce a low-pressure zone is formed. It favors the appearance of the injection effect, which considerably expedites substance introduction into the high-temperature zone (Fig. 1c, variant 2). At low gas flow rates the electrodynamic interaction between the jets prevails (Fig. 1c, variant 1). At high gas flow rates the gas-dynamic component begins to prevail in the interaction mechanism (Fig. 1c, variant 2) and introduction of the substance into the central zone of the TJPT becomes difficult because return flows may appear.

On the basis of the investigations made and the consideration of the results of [1, 16] a new scheme of an arc plasma sprayer of powder materials can be proposed (see Fig. 1d). As in the two-jet plasma torch, in this scheme the electrodes are prepared separately and placed in a sealed chamber having a water-cooled conical channel changing to a cylindrical one and a hole for supplying the plasma-forming gas and processed products: gases or condensed materials. As in the "Plasma-Technik AG" plasma torch, the diameter of the cylindrical channel is comparable to the free arc diameter.

The basic operating conditions are similar to those used in the "Plasma-Technik AG" plasma torch but have an axial powder supply, which provides a more stable operation of the sprayer. The dynamic plasma pressure on the particle increases. This is primarily due to the higher temperature of the plasma into which powder is introduced. In conventional sprayers, $T \leq 6000$ K but in the proposed variant T can be much higher than 10,000 K. The proposed plasma torch has an advantage over the "Plasma-Technik AG" plasma torch in which one of the causes of plasma stream pulsations is the rotary movement of the arc attachment. At the same time, the serviceability of the proposed variant is beyond doubt, since the main heat-loaded assemblies of the plasma generator (the anode and cathode units as well as the nozzle) have been well tested in practice.

The advantages of such a plasma torch are indicated by the fact that it can be used for effective treatment of materials. Its nozzle is a reactor, which makes it possible to act on disperse condensed materials with a greater dynamic pressure than in the existing plasma systems, including the multi-jet ones. The high plasma temperature ($T > 10{,}000$ K) provides strong heating of materials by convective and radiation fluxes from the arc plasma. The action of a powerful spectrally selective radiation flux can stimulate selective chemical transformations. The small diameter of the reactor channel (6–8 mm) provides a strong local and short-term action on processed products.

The powerful acoustic waves generated in the channel intensify the plasma action on the source material, which is one of the ways of increasing the efficiency of high-temperature technologies [17]. Acoustic waves also protect the channel walls against the sticking of processed products to them. The high rate of the gas flow, $V \geq 1$ km/sec, favors rapid carry-over of synthesized materials from the reactor. The last fact makes it possible, in principle, to work with aggressive substances in the reactor.

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NOTATION

I, current strength, A; U, voltage, V; V, velocity, m/sec; P, pressure, Pa; T, temperature, K; d, diameter, mm; l, length, mm; G, gas-flow rate, liters/min; f, oscillation frequency, Hz; c, velocity of sound, m/sec; B, brightness; t, time, sec; E, electric field strength, V/cm; z, axial coordinate measured from the nozzle exit section, mm; j, current density, A/mm^2; σ, electrical conduction, $\Omega^{-1}\cdot$cm^{-1}. Subscripts: n, nozzle; a, arc; c, closed; o, open; s, sound.

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