SOME TECHNIQUES FOR REDUCING FILLER POWDER LOSSES IN MICROPLASMA CLADDING

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At reconditioning of the edges of gas turbine engine blades by microplasma powder cladding losses of cladding materials are inevitable. In order to increase the process effectiveness in this work the method of assessment of deposited bead mass at successive increase of weld pool dimensions on a wide and a narrow substrate was used to study the regularities of radial distribution of two-phase flows of microplasma-filler powder. It is established that experimental data of radial distribution of such flows on the anode surface are in satisfactory agreement with the normal distribution law. The method of calorimetry on a two-section water-cooled anode was used to evaluate the coefficient of concentration of specific heat flow of microplasma arc for cladding. It is shown that in the region of modes of microplasma cladding filler powder can be fed into the product plane with the concentration up to four times greater than the specific heat flow of the arc, and the ratio of effective diameters of powder feeding and heating spot is equal to 0.57–0.92. Influence of some design parameters of microplasmatron and process parameters of cladding on gas-powder flow concentration is described. Relationships between bead width, microplasmatron focusing nozzle diameter and characteristics of concentration of powder feeding into the weld pool required to limit filler powder losses within 1.44–2.56 % at deposition of metal of less than 3 mm thickness on blade edges are established. 11 Ref., 2 Tables, 7 Figures.

Keywords: *microplasma powder cladding, blade edges, microplasmatron, coefficient of powder utilization, concentration of two-phase flow, microplasma-filler wire*

Investigations performed at the E.O. Paton Electric Welding Institute and practical verification of the process of microplasma powder cladding (welding) showed a reliable achievement of technological strength in fusion welding and subsequent heat treatment, as well as high performance of welded joints of high-temperature nickel alloys with γ′-phase content of more than 45 % [1–4]. Microplasma powder cladding at repair of edges of gas turbine engine blades is characterized by: range of effective thermal power of the arc of 100–650 W and heat input of 250–3000 J/mm; capability of application of filler material identical in its chemical composition to blade material, for instance, ZhS32-VI, IN738LC, ZhS6U; reliable protection of repair zone and good formation of deposited metal. The process does not require item preheating and in most of the cases preliminary homogenizing of blade material before cladding.

At reconditioning of edges of gas turbine engine blades losses of cladding materials are inevitable, which, in their turn, are assessed as difference of masses of consumed filler material and deposited metal. Comparative analysis [5] showed that at microplasma powder cladding of the edges of blades by a bead 3.5 mm thick an increased level of filler material losses is observed compared to argon arc cladding. More than 3/4 of them are remains unsuitable for further application. An acceptable level of losses (≈ 10.5 %) in microplasma powder cladding on a narrow substrate (blade edge) with more than 3 mm deposit thickness was achieved due to re-use of powder remains at the coefficient of powder utilization (CPU) of 0.625 after collection of its remains, sieving and drying. During batch microplasma powder cladding of blade edges less than 3 mm wide [3, 4], it was established that the fraction of remains unsuitable for use can increase up to 30 % of the initial amount of filler material. Further utilization of such filler remains at cladding of high-temperature nickel alloys with γ′-phase content of 45 % is not rational in view of considerable deterioration of the quality of bead formation. Analysis of surface morphology of powder samples after using it three times at cladding showed that approximately 50 % of oxidized particles are present in the field of view of optical microscope (×50). Gradual accumulation of such particles in the dispersed filler material, probably, is the main cause for deterioration of welding-technological properties of filler material.

Thus, in the case of deposition of metal of not less than 3 mm thickness on blade edges, filler powder losses, despite it re-use, become much

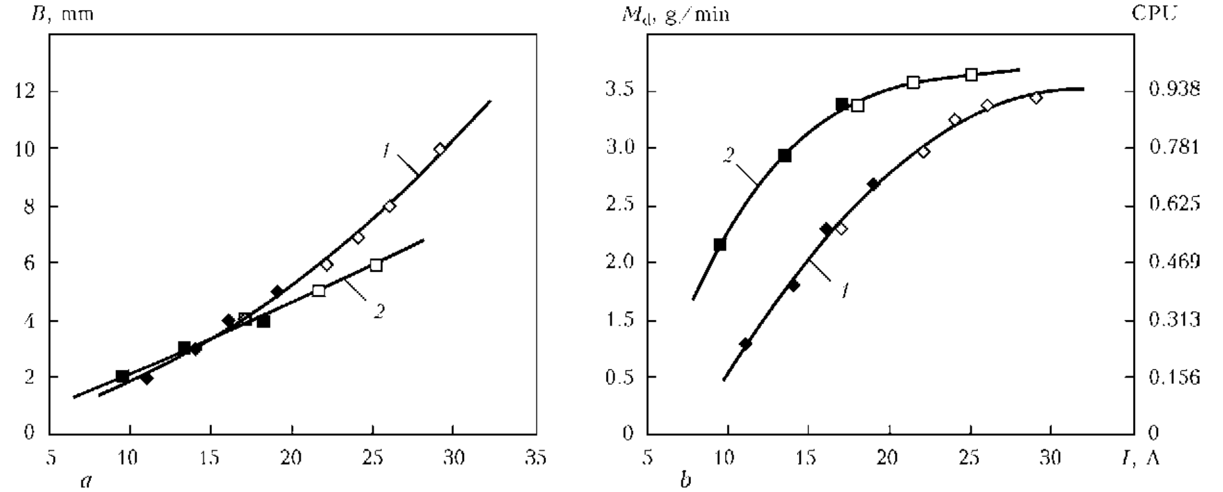

Figure 1. Dependence of bead width B (a), deposited metal specific mass M_d and CPU (b) on welding current I at v_d = = 2.75 m/h (flow rate of carrier gas (argon) 2.5; shielding gas (mixture of 90 % Ar + 10 % H_2) 7 l/min; base metal — austenitic stainless steel); *1* — microplasmatron with d_{pl} = 2.5 mm, d_f = 4.5 mm; 2 — d_{pl} = 1.8 mm; d_f = 2.5 mm; dark symbols — deposition on a narrow substrate; light ones — deposition on a wide substrate

greater. In view of the high cost of filler materials, such tasks require additional optimization of the process of microplasma powder cladding.

The main cause for filler losses is movement of its disperse particles on the periphery of plasma arc column, and furtheron — elastic recoil from the clad item surface beyond the weld pool zone [6]. In order to optimize the paths of filler material motion in the plasma arc, it is recommended to apply filler powders with particle diameter below 150–200 μm, adding them to the arc with the velocity of not less than 2 m/s at up to 40–45° angle to plasmatron axis. In view of considerable width of the weld pool (18–35 mm), filler powder losses in optimum modes of plasma-powder cladding do not exceed 5–8 % [6].

For deposition of less than 3 mm thick metal layer on blade edges, it is rational to lower powder losses by increasing microplasma arc concentration with fed disperse filler, i.e. increasing its relative quantity hitting the weld pool. The objective of this work is to consider the technological features of focusing of two-phase flows of microplasma-filler powder, which ensure concentrated delivery of filler material through the high-temperature region of the microplasma arc into the weld pool on a narrow substrate less than 3 mm wide.

Microplasmatron PPS-004 with side distributed feed of filler powder and focusing nozzle channel diameters of 2.5 and 4.5 mm was selected as the object of study. With these nozzles its stable operation is provided at up to 30–50 A welding current. It is known that plsmatrons with 4.0–4.5 mm diameter of focusing nozzle channel provide the most concentrated feeding of filler powder into the plasma arc at plasma-powder cladding [6, 7].

Concentration of filler powder feeding through the microplasma arc to the anode plane was assessed by determination of the mass of powder, hitting the weld pool at successive increase of its dimensions. Weld pool width was changed with increase of welding current at constant speed of microplasma arc displacement (Figure 1) within 2–5 mm for a narrow substrate (Table 1) and 4–10 mm for a wide substrate (2 mm thick plate). At cladding of a narrow substrate the bead was formed with more than 90° angle of contact to its surface, i.e. with side reinforcement from two sides. During a simple experiment at successive increase of weld pool width by 5 times, dependencies of variation of deposited bead specific weight M_d and CPU were derived, which characterize radial distribution of filler powder in the anode plane (see Figure 1). The above procedure allows elimination of the influence of elastic recoil of particles, inevitable at filler powder collection into multisection catchers.

Filler powder of austenitic stainless steel with 63–160 μm particle size was used in the experi-

Table 1. Deposited metal specific mass M_d and bead width B at deposition on a narrow substrate of width δ, depending on diameter d_f of plasmatron focusing nozzle channel

d_f, mm	δ, mm	I, A	B, mm	M_d, g/min
4.5	1.0	11.0	2.0	0.80
	1.6	14.0	3.0	1.30
	2.0	16.0	4.0	1.80
	2.5	19.0	5.0	2.18
2.5	1.0	9.5	2.0	1.66
	1.6	13.5	3.0	2.42
	2.5	18.0	4.0	2.88

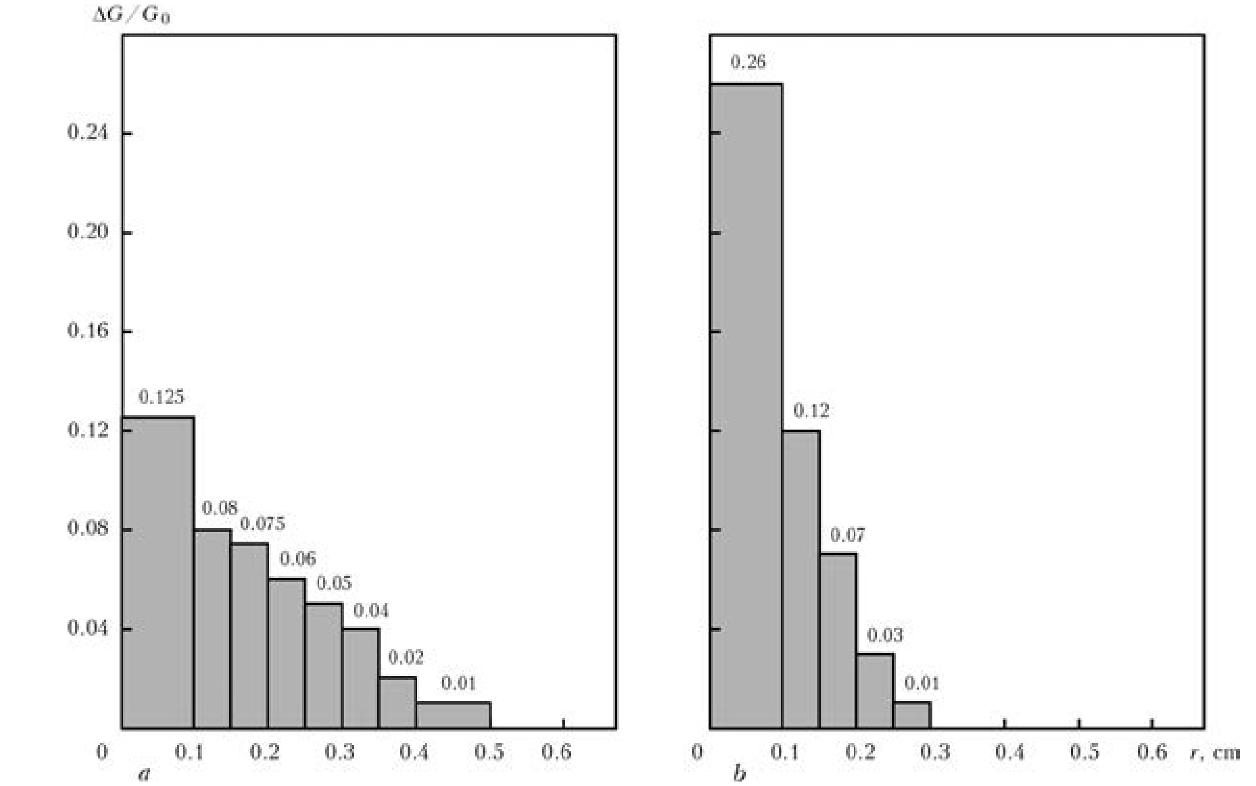

Figure 2. Histrogram of fed powder distribution in the direction normal to deposited bead axis, depending on parameters of PPS-004 microplasmatron: a — d_{pl} = 2.5 mm, d_f = 4.5 mm; b — d_{pl} = 1.8 mm; d_f = 2.5 mm

ments. Its tentative granulometric composition was as follows: −63 μm — 7 %; +63−80 μm — 10 %; +80−100 μm — 32 %; +100−125 μm — 39 %; +125−160 μm — 12 %. Efficiency of filler powder feed G_0 was equal to 3.20 g/min; powder was fed with 1 s interval. Such a specific amount of filler in all the experiments provided a stable formation of beads and was selected proceeding from practical application of blade edge building-up. M_d was experimentally determined by weighing the sample-plate with 0.02 g accuracy before and after cladding of 1 min duration. CPU was determined as the ratio of M_d to powder feed efficiency G_0.

Relative distribution of the amount of deposited metal $\Delta G/G_0$ in the direction normal to deposited bead axis (Figure 2), was calculated by experimental data in Figure 1 as:

$$(\Delta G/G_0)_i = (M_{B_{n+1}} - M_{B_n})/(2G_0), \qquad (1)$$

where $M_{B_{n+1}}$, M_{B_n} is the mass of deposited metal at successive increase of the weld pool width; n is the experiment number; i is the ordinal number of distribution. Obtained results, presented in Figure 2 in the form of histograms, characterize the distribution of filler powder in microplasma arc on the anode level during the process, and show the preference of application of microplasmatrons with d_f < 4.5 mm at deposition on a narrow substrate in terms of effectiveness of filler powder application.

In order to describe the specific heat flow of the arc a normally-circular heat source is widely used in the theory of welding processes, in which the intensity of its specific heat flow diminishes from the center to the edges of the heating spot by the so-called normal law (Gaussian distribution). The main parameters of such a representation were defined by N.N. Rykalin [8] and are interrelated by known relationships:

$$q_2(r) = q_{2m}e^{-kr^2}, \qquad (2)$$

$$q_{2m} = \frac{k}{\pi}q_{ef}, \qquad (3)$$

$$r_0 = \frac{1}{\sqrt{k}}, \qquad (4)$$

$$d_{ef} = 3.46/\sqrt{k}, \qquad (5)$$

where $q_2(r)$ is the radial distribution of power of welding arc heat flow in the item; q_{ef} is the effective thermal power of the arc; q_{2m} is the power of heat flow in heat source center or thermal energy density in the equivalent heating spot; r is the distance from the heat source center; k is the coefficient of specific heat flow concentration; r_0 is the equivalent radius of the heating spot, i.e. radius of a circle with uniform distribution of the heat flow from the source equivalent in its power to normal-circular distribution of heat flow; d_{ef} is the effective diameter of the heating spot, i.e. diameter of the spot, through which 95 % of specific heat flow for the welding heat source passes into the item.

In our case establishing the relationships between the concentration of specific heat flow of microplasma arc and concentration of filler powder feeding into the weld pool is of interest.

Closeness of experimental histrograms (see Figure 2) to exponential dependence and of the weld pool shape in typical modes of microplasma powder cladding to a circle leads to an assumption of filler material distribution in the microplasma arc on the level of anode surface (weld pool) following the normal law. This was checked by the procedure of [9] based on superposition of the data of experimental histograms (Figure 2) onto an imaginary two-section powder catcher, successively moving with the histogram step along y axis (Figure 3). Distance from 0 to r_i (current step of histogram values) corresponded to $-y$ coordinate, and the sum of histogram ordinate values $\Delta G/G_0$ from r_i to ∞ characterized the relative intensity of powder flow in the right segment of powder feeding spot circumference.

Presentation of experimental data of histograms in the form of dependence $G(r) = G_{2m} \exp(-k_{p.c}r^2)$ is in good agreement with the normal law of distribution (Figure 3, b), where $k_{p.c}$ is the coefficient characterizing the concentration of filler powder feeding into the weld pool similar to the coefficient of concentration of arc specific thermal flow; G_{2m} is the relative density of application of filler powder on the level of anode surface. A number of parameters of filler powder feeding concentration calculated by experimental data, are given in Table 2.

It is established that decrease of channel diameter of focusing microplasmatron from 4.5 to 2.5 mm ensures a change of the area of effective spot of power feeding from 128.6 to 30.2 mm^2, i.e. actually by 4 times. Analysis of experimental (see Figure 2) and calculated (see Table 2) data shows that CPU values in the range from 0.84 to 0.88 correspond to equivalent radius of powder feeding spot.

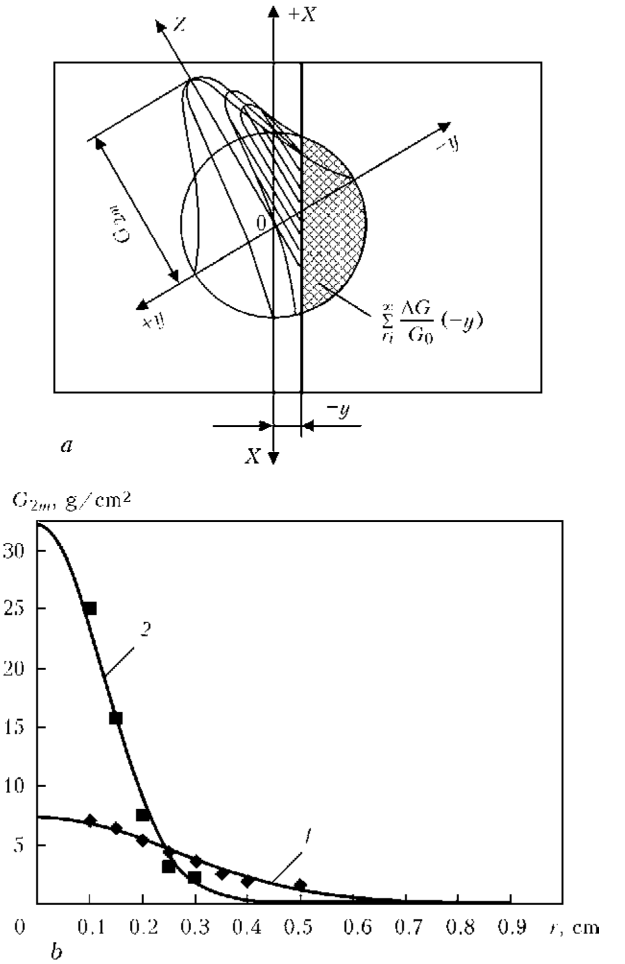

Figure 3. Schematic of two-phase microplasma-filler powder flow over two-section powder catcher (a) and calculated distribution of fed powder by a normal law in anode plane (b): 1 — d_{pl} = 2.5 mm, d_f = 4.5 mm; 2 — d_{pl} = 1.8 mm, d_f = 2.5 mm; symbols — experimental data, solid curve — simulation

Thus, in order to ensure a high effectiveness of filler powder utilization at certain design parameters of microplasmatron, determined mainly by value d_f, weld pool width should be larger than the equivalent diameter of powder feeding spot ($B \geq 2r_0$). In the general form for deposition on a narrow substrate the above dependence, allowing for (4), can be written as:

$$B = \delta + 2y_d \geq 2r_0 = \frac{2}{\sqrt{k_{f.c}}}, \quad (6)$$

where y_d is the design side allowance at bead formation.

Table 2. Characteristics of radial distribution of two-phase microplasma–filler powder flow in anode plane (5 mm distance from focusing nozzle edge)

Designation	d_f, mm	d_{ef}, cm	$k_{p.c}$, cm^{-2}	r_0, cm	CPU at $B = 2r_0$	B, cm	P_{res} at $B = 2r_0$
Experimental	4.5	1.28	7.24	0.37	0.88	0.74	0.0144
Experimental	2.5	0.62	31.60	0.18	0.84	0.36	0.0256
Calculated	1.6	0.35	100.00	0.10	0.85	0.20	0.0225

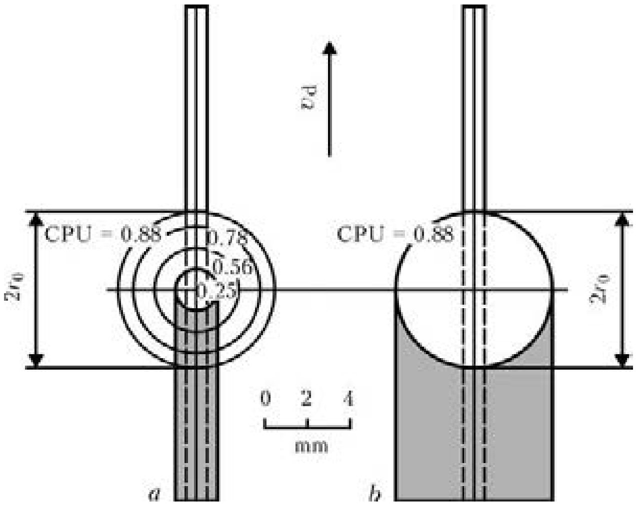

Figure 4. Features of cladding of a narrow substrate 1 mm wide at application of microplasmatron with d_f = 4.5 mm with insufficient concentration of two-phase microplasma-filler powder flow: *a*, *b* — see the text

At insufficient concentration of powder feeding into the weld pool during deposition on a narrow substrate of a bead 1–3 mm wide two limit cases can be distinguished, lowering the effectiveness of the process of microplasma powder cladding:

- increased powder losses at cladding at lower current (Figure 4, *a*);
- increased side allowances of the deposited bead at cladding at higher current (Figure 4, *b*).

In case $B \geq 2r_0$ anticipated powder losses P_{res} after two cycles of its utilization, calculated by the dependence given below

$$P_{res} = (1 - CPU) - (1 - CPU)CPU = \\ = CPU^2 - 2CPU + 1, \quad (7)$$

will be not more than 1.44–2.56 %.

Detected regularities further allowed prediction of parameters of concentration of powder feeding onto the anode plane (see Table 2), required for microplasma powder cladding with low powder losses at 2 mm width of the weld pool.

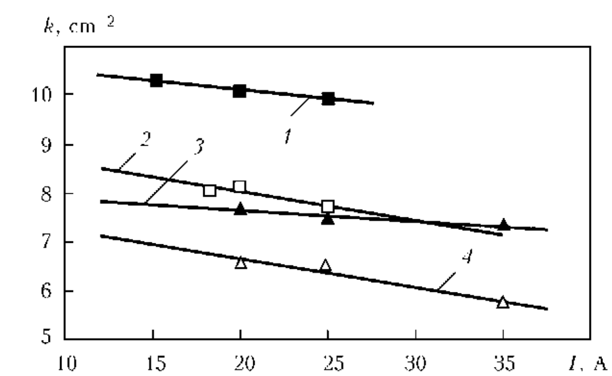

Figure 5. Dependence of coefficient of concentration of specific heat flow *k* into microplasma arc anode on welding current: *1* — d_{pl} = 1.8 mm; d_f = 2.5 mm, shielding gas — 90 % Ar + 10 % H_2; *2* — d_{pl} = 1.8 mm; d_f = 2.5 mm, shielding gas — Ar; *3* — d_{pl} = 2.5 mm; d_f = 4.5 mm, shielding gas — 90 % Ar + 10 % H_2; *4* — d_{pl} = 2.5 mm; d_f = 4.5 mm, shielding gas — Ar

Coefficient of concentration of specific heat flow, *k*, of microplasma arc without powder feeding, corresponding to conditions of experiments in Figures 2, 3, was determined by the procedure of [9] by calorimetry in a two-section flow calorimeter.

For the given microplasma arc in the range of currents of 10–40 A, *k* experimental values are equal to 5.5–10.5 cm^{-2} (Figure 5). Appearance of microplasma arc for cladding with different kinds of shielding gas and degree of its constriction by plasmatron nozzles is given in Figure 6. For plasma arcs in plasma-powder cladding in the range of currents of 50 to 300 A, respective *k* values are equal to 1.8–2.0 — 4.8–6.5 cm^{-2} [6, 7]. For a microplasma arc for welding [10], running in argon, by the data of [11], coefficient of concentration of specific heat flow in the range of currents of 4–25 A is equal to 40–150 cm^{-2}.

Comparison of experimental data for radial distribution of filler powder in its feeding spot and of specific heat flow on anode surface (see Table 2 and Figure 5) shows that at microplasma powder cladding the ratio of the respective concentration coefficients is in the range of 0.96 to 4.00. In its turn, the ratio of effective diameters

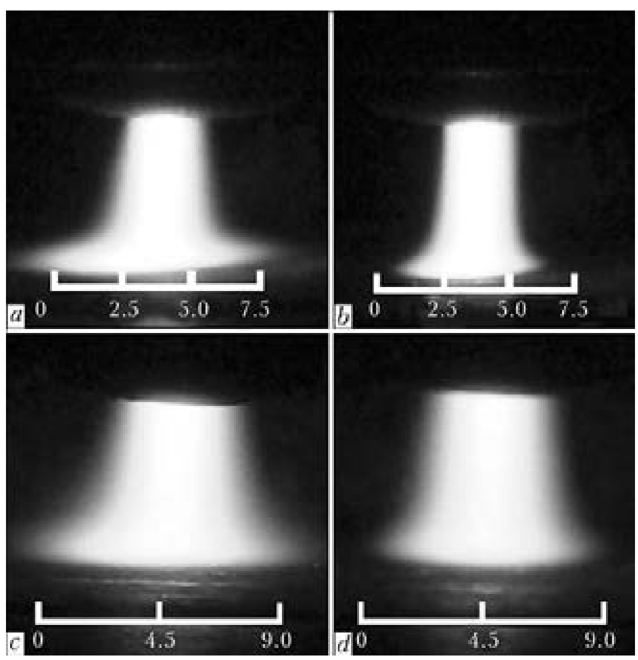

Figure 6. Appearance of a microplasma arc with effective thermal power of 341 W at different degrees of arc constriction by microplasmatron nozzles: *a* — d_{pl} = 1.8 mm, d_f = = 2.5 mm, shielding gas — Ar; *b* — d_{pl} = 1.8 mm; d_f = = 2.5 mm, shielding gas — 90 % Ar + 10 % H_2; *c* — d_{pl} = = 2.5 mm, d_f = 4.5 mm, shielding gas — Ar; *d* — d_{pl} = = 2.5 mm; d_f = 4.5 mm, shielding gas — 90 % Ar + 10 % H_2. Distance to anode is 5 mm

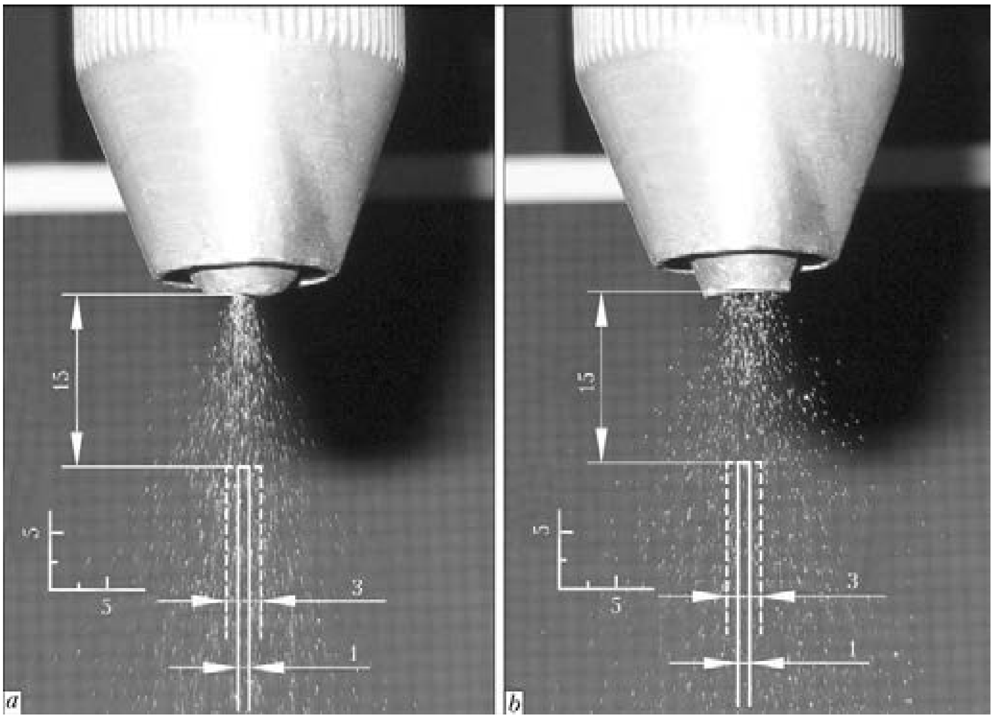

Figure 7. Appearance of powder flow at exit from microplasmatron focusing nozzle, depending on its channel diameter: a — d_f = 2.5 mm; b — d_f = 4.5 mm

of powder feeding and heating spot is equal to 0.57 to 0.92.

Analysis of experimental and published data shows that characteristics of specific heat flow of microplasma arc for cladding are close to respective characteristics of plasma arc for plasma-powder cladding. However, the task of optimization of concentration of powder feeding for deposition of metal less than 1.5 mm thick on blade edges (see Table 2), requires application of microplasmatrons with nozzle design parameters similar to those of plasmatrons for microplasma welding [10]. Derived dependencies of radial distribution of heat flow of microplasma arc and filler powder can be used for further optimization of design parameters of microplasmatrons with a high concentration of disperse filler feeding (ensuring the necessary stability of arcing and cladding, and reliability of weld pool shielding).

In microplasma powder cladding of blade edges with deposition of metal 1–3 mm thick, filler losses can be reduced not only by reducing d_f in microplasmatron, but also by optimizing the concentration of microplasma-powder flow through rational selection of the distance from focusing nozzle to item. A feature of microplasma powder cladding is the fact that at powder feeding at less than 5 g/min, its flowing either in the arc column, or in the mode of power feed checking, is poorly registered by the human eye.

Powder flow photographing against a contrast background was used for visual assessment of the concentration of powder flow in the mode of powder feed checking (Figure 7). Analysis of photographs showed that such a flow preserves its concentration assigned by the diameter of focusing nozzle channel, at 5 to 7 mm distance from its edge, and then becomes considerably wider. In this case dependence (6) for the above distance can be complemented by:

$$B = \delta + 2y_d \geq 2r_0 = \frac{2}{\sqrt{k_{p.c}}} \approx d_f. \quad (8)$$

With flow expansion at more than 7 mm distance from the focusing nozzle edge, quantity of powder, which can hit the weld pool on a narrow substrate 1–3 mm wide, becomes essentially smaller.

Conclusion

The paper deals with technological features of focusing of two-phase flows of microplasma-filler powder, delivering filler material to the weld pool through high-temperature region of the arc for the case of microplasma cladding of blade edges less than 3 mm wide. Technological recommendations have been substantiated on selection of focusing nozzle channel diameter and distance from microplasmatron to the item, depending on the width of narrow substrate being clad.

A good agreement was established between the normal law of distribution for a radial distribution of a two-phase flow of microplasma-filler powder in the spot of its feeding in the anode plane.

For the conditions of microplasma powder cladding, a relationship between the coefficients of concentration of specific heat flows of filler powder and arc heat (0.96–4.00) was established, as well as the ratio of effective diameters of powder feeding spot and heating spot (0.57–0.92).

Relationships of bead width, diameter of microplasmatron focusing nozzle and characteristics of concentration of powder feeding into the weld pool were established, which are required for limitation of filler powder losses within 1.44–2.56 % in cladding of blade edges. It is shown that for cladding on a narrow substrate less than 3 mm wide it is necessary to provide the coefficient of concentration of specific flow of powder in its feeding spot in the range of 31.6–100 cm^{-2}. Derived regularities can be used for further optimization of design parameters of microplasmatrons with a high concentration of disperse filler feed.

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