and fusing crystal region directly adjacent to channel; W_D, W_I, energies expended in dissociation and ionization of NaCl molecules located in channel; W_t, energy expended in increasing particle temperature in channel; W_c, energy radiated from channel surface into crystal due to thermal conductivity of crystalline lattice; W, energy liberated in breakdown channel; k, Boltzmann's constant.

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INTENSIFIED PLASMA DEPOSITION WITH ACOUSTIC AND ELECTRICAL OSCILLATIONS APPLIED TO THE HETEROGENEOUS JET

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An experimental study has been made on the scope for improving the integral characteristics of plasma deposition when strong acoustic and electrical fluctuations are superimposed on a heterogeneous plasma jet.

Optimizing particle heating in a hot jet is important in depositing protective coatings. In the case of a homogeneous stationary plasma, the heat flux to the powder particles is [1]

$$Q_p/F \sim \alpha T_g l/v_p. \tag{1}$$

It follows from (1) that the heat-transfer rate will increase if the increase in one of the parameters α, T_g, and l/v_p appreciably exceeds the possible reduction in the others. The rate of heat transfer between particles and the plasma flow in coating deposition may be estimated from integral characteristics: the coefficient η for the plasma jet power use and the coefficient β for powder use, since there is a correlation between η and β, on the one hand, and the amount of the particles melted, on the other.

It has been found [1, 2] that high-frequency fluctuations in the electrical parameters of the arc increase η and β, while low-frequency ones reduce them.

The experiments were performed with a plasma deposition apparatus whose acoustic and electrical characteristics were studied in [3]. The acoustic oscillations were generated either by the plasmotron at its outlet or by means of gas-jet rod radiators [4] set up in various parts of the jet and around the substrate (Fig. 1a).

To increase the acoustic pressure amplitude and to focus the acoustic field, the plasmotron and the sources were set up within a concentrator or horn. When gas-jet radiators were used, the air flow was deflected from the direction of the beam of acoustic oscillations to prevent it from influencing the plasma jet. The acoustic characteristics were as follows: frequency 5-10 kHz, acoustic pressure level 150 dB, and acoustic power from 0.1 to 1 kW. The working conditions in the plasmotron were monitored from the average and fluctuation characteristics as recorded by probe instruments, oscillograms, and spectrograms. The Ni—Al powder was deposited on steel substrates of area 80 × 80 mm at 120-170 mm from the end of

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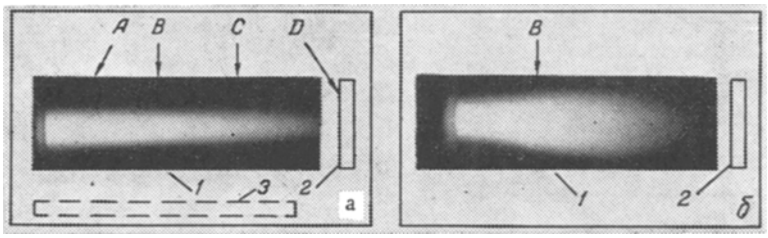

Fig. 1. Photographs of plasma jet: a) in the absence of the acoustic field; b) with an acoustic field acting. Zones: A) powder input; B) high-temperature core of jet; C) rapid heat transfer; D) interaction of particles with substrate; 1) plasma jet; 2) substrate; 3) acoustic reflector.

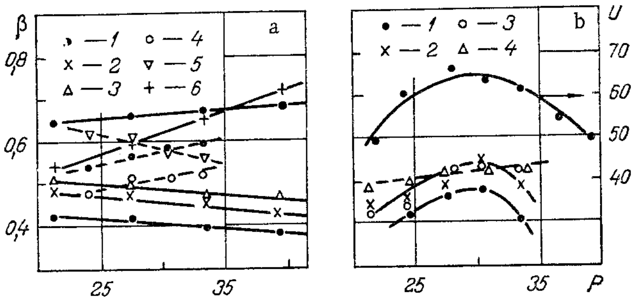

Fig. 2. Dependence of β and of voltage fluctuation amplitude U on input power P for various deposition conditions: a) with twisted gas flow: 1) control states; and with sound acting on the following zones: 2) A; 3) B; 4) C; 5) D; 6) with anode spot localized; b) without twist: 1) control states; 2-4) sound acting on zone C: 2) traveling sound wave; 3) standing wave (oscillation node at axis); 4) standing wave (antinode at axis).

the nozzle. The flow rates for the mixture of argon (40 liters/min) and hydrogen (10 liters/min) were kept constant, while the powder flow rate varied from 0.2 to 1.5 g/sec.

We found that η and β were very much dependent on the flow rate of the powder, the distance to the substrate, and the working conditions in the plasmotron in the working range. Therefore, in each experiment we performed a check deposition with the acoustic sources switched off. The powder-use coefficient was calculated from the measured powder flow rate and the increase in the mass of the specimen during deposition:

$$\beta = (m_2 - m_1)/(G_p \tau_p). \qquad (2)$$

When acoustic oscillations acted on zone A at low currents, β was less than without the acoustic field (Fig. 2a), since in that case there is partial dispersal of the powder by the acoustic field before entry to the plasma jet.

When the oscillations acted on zones B and C, β was higher than without the sound, while in zone D the result was lower than in the control experiment, because the acoustic field expands and turbulizes the hot jet (Fig. 1b), which provides more uniform and effective heating for most of the powder, while in the zone in front of the substrate there are rapid cooling and speed reduction, since the temperature of the particles is above the jet temperature in this region.

We also performed a special experiment in which the anode spot was localized by a ridge on the inner surface of the anode. In that case, the level of voltage fluctuations was reduced by a factor 6, which caused β to fall as the power increased (curve 6 in Fig. 2a), whereas in the control series of experiments we obtained an increase in β.

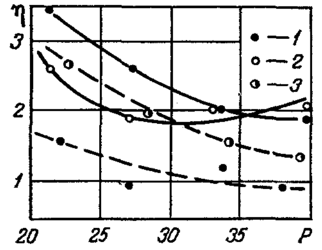

Fig. 3

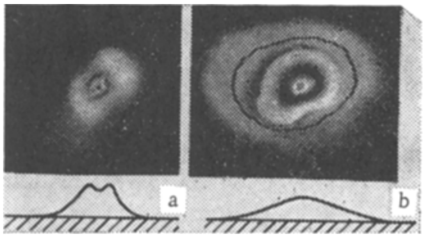

Fig. 4

Fig. 3. Variation in η with power P in a spiralling gas flow without acoustic oscillations (1) and with them (2 and 3) acting on the following: 2) zone A; 3) zone B.

Fig. 4. Distribution densities for deposited powder from a spiral flow at a current I = 500 A, powder flow rate G_p = 0.83 g/sec: a) control condition; b) with acoustic oscillations acting on zone B.

The action of acoustic vibrations on an untwisted plasma flow has some differences from that on a twisted one (Fig. 2b). The β(P) curve has a maximum at P = 30 kW, but the effects from the various zones are as before: β was above the control value when the oscillations acted on zones B and C.

A standing acoustic wave has more effect on the jet than a traveling one. To set up this wave, a reflector was placed opposite the emitter (Fig. 1a). When the flow interacted with the standing wave, the values of β were higher, while β(P) was more uniform, which was particularly notable if there was an antinode in the standing wave at the axis (curve 4 in Fig. 2b). This appears to be because the amplitude of the oscillatory velocity in a standing wave is higher than that in a traveling one. The differences in β for the twisted and untwisted flows are evidently due to the different radial distributions in the particle densities: in the untwisted flow, the particle density at the axis is higher, and therefore the effects of the acoustic beam on focusing at the axis are more pronounced.

It has been found [3] that the plasmotron in this apparatus had high-frequency voltage fluctuations at f = 3-7 kHz, whose amplitude was 60-70%, while the level of the current fluctuation was 1%.

Figure 2b shows that the effects on the powder use factor from the sound (curve 2) and in the absence of the sound (1) agree with the character of the voltage fluctuation amplitude, since the peaks in the dependence of β and U on power lie in the same range.

The power use coefficient was estimated from

$$\eta = c_p m_p^* (T_m - T_{p0})/(P_0 \tau_p). \tag{3}$$

The η(P) dependence is correlated with β(P): when the acoustic oscillations act on zone A, η(P) is less than for the control curve, whereas it is larger with zones B and C (Fig. 3). The falling branch in η(P) occurs because the increase in the amount of melted powder m_p^* is slower than the increase in P, and the differences decrease as the power increases, as is evident from the change in slope in the η(P) curves.

Under certain conditions, the acoustic oscillations alter the powder distribution on the substrate: the diameter of the deposition spot increases and the distribution becomes more uniform, which is due to turbulence in the plasma jet. Also, there is no recess at the center of the deposition spot due to dispersal of particles from the axis of the flow because of the gas spiraling, and one gets a uniform zone, which indicates elevated particle temperatures in this region (Fig. 4). The effect is even more pronounced when high-frequency acoustic oscillations at 150 dB are imposed on the jet, these being generated by the plasmotron with an acoustic horn at the exit. The local heating of the central part of the deposition spot was greater than that when rod radiators were used, but the dispersal of the powder during deposition was also more extensive. In that case, one does not obtain a single-valued β(P) in comparison with the control experiments. The accentuation of the local heating is evidently due to increase in the oscillation amplitude in the zone of action of the sound field on the heterogeneous flow.

The increase in $\beta(P)$ due to increase in the electrical input power is restricted not only by physical processes in an arc discharge [5] but also because the powder evaporates. The plasma temperature is well above the particle temperature in the heating zone. Therefore, the most promising way of improving the particle heating is to increase the heat-transfer coefficient by turbulizing the boundary layers around the particles and improving the uniformity of the heating over the cross section.

These results indicate that high-frequency voltage fluctuations and acoustic oscillations intensify the heat transfer between the particles and the plasma jet and can be used to optimize plasma deposition.

NOTATION

Q_p, heat flux to particles, J; P_0, power of plasma jet, kW; P, electric power of plasmotron, kW; T_g, gas temperature, °K; T_{p0}, initial particle temperature, °K; T_m, powder melting temperature, °K; v_p, particle velocity, m/sec; l, particle heating zone length, m; α, heat-transfer coefficient, $W/m^2 \cdot °K$; β, powder utilization coefficient; η, power utilization coefficient, %; m_1, sample mass before deposition, kg; m_2, sample mass after deposition, kg; m_p^*, coating mass, kg; G_p, powder flow rate, kg/sec; τ, deposition time, sec; c_p, specific heat of powder, J/kg·°K; U, amplitude of voltage fluctuations, %; F, total area of particles, m^2.

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