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INVESTIGATION OF PLASMATRON ELECTRIC AND ENERGY CHARACTERISTICS IN MICROPLASMA SPRAYING WITH WIRE MATERIALS

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To determine the range of operating voltages of the plasmatron MP-04 of installation MPN-004 for microplasma spraying, a family of volt-ampere characteristics was plotted, each of which was measured at the constant composition and consumption of the working gas, length of the arc open section and the design dimensions of the plasmatron. The heat flux was determined by the continuous-flow calorimetry method. It allowed under the conditions of microplasma wire spraying to determine the thermal efficiency of the plasmatron, the average-mass initial enthalpy and the plasma jet temperature depending on the plasmatron operation mode: arc current and plasma-forming gas consumption. 12 Ref., 7 Figures.

Keywords: *microplasma wire spraying, wire materials, argon plasma jet, volt-ampere characteristics of plasmatron, temperature and enthalpy of plasma jet, thermal efficiency coefficient, voltage and current of plasma arc, consumption of plasma-forming gas*

As to the type of spraying materials, the technology of thermal spraying (TS) of coatings is divided into powder and wire spraying [1]. The technology of powder TS is distinguished by the variety of types and compositions of spraying materials and possibility of using powders with different granulometric composition. However, it has a number of drawbacks associated with the difficulty in providing the accurate and stable supply of powders into the spraying gas jet, as well as the need in using special powder batchers: complex and expensive devices.

The difference in the size of particles, inherent to all the powders for TS, creates a problem of their nonuniform heating, which influences the quality of coatings. In case of wire TS, by controlling the supply of spraying material (wire), its accurate and stable introduction into the atomizing gas jet and the guaranteed formation of flow of wire spraying molten products are provided. The disadvantage of this process is that the composition of the spraying material is limited by ductile metals. However, recently, the expansion of application of flux-cored wires alleviates this drawback to a certain degree.

In practice, the wire TS is represented by the processes of electric arc metallization, gas flame wire spraying and, in a slightly smaller volume, by plasma TS with the use of «neutral wire» and «wire–anode» spraying systems [2].

The technology of microplasma spraying of coatings (MPS), developed at the E.O. Paton Electric Welding Institute, used the technology of powder spraying at the first stage. For its realization, a design of a plasmatron was made, characterized by a remote anode and presence of a channel for shielding gas supply, protecting plasma jet [3].

The formation of plasma jet, distribution of temperature values and velocities in its volume, is determined both by the plasmatron operation parameters, as well as by its design. In this connection, when creating a new design of a plasmatron, the necessary stage in the development of a spraying technology with its use is the determination of its main characteristics and the limiting levels of temperatures and velocities of plasma jet. This evaluation is necessary to determine the capabilities of the plasmatron for heating and melting the particles of the spraying material.

When developing the technology of microplasma spraying of coatings using a neutral wire, it was necessary to study the characteristics of the microplasmatron and the microplasma jet, generated by it in the conditions of spraying with wire materials.

The aim of the experiment is to investigate the thermal efficiency of the plasmatron operation η and to determine the average-mass initial enthalpy and temperature of the plasma jet depending on the plasmatron operation modes: arc current I_a and plasma-forming gas consumption $Q_{p.g}$.

Procedure for determining characteristics of microplasmatron for conditions of MPS. Plasmatron is the converter of electrical energy into heat one.

Therefore, on the one hand, the arc of the plasma jet as an element of electrical circuit is characterized by electrical parameters (current, voltage), and on the other hand, as a source of heat, it is characterized by thermal parameters (temperature, heat content). There is a complex relationship between the parameters of the first and the second group.

Enthalpy (ΔH) is the amount of heat contained in a unit of volume or mass of the jet, is an important thermal parameter of the plasma jet. The effect of consumption and composition of working gas on the arc voltage is graphically illustrated by the volt-ampere characteristics of plasmatrons (VAC), representing the dependence between the voltage and arc current at the other equal conditions (arc length, plasmatron parameters, external conditions). In the region of low currents, the VACs of plasmatrons are falling, and with the current growth they pass into independent and rising ones. With an unchanged gas composition, the intensity of all sections of the plasma arc column increases with increasing the degree of its compression. The degree of the arc column constriction is growing (to a certain extent) with a decrease in the forming nozzle diameter and an increase in the consumption of working gas. As investigations show, the gas main mass passes through the peripheral regions of the column and, as the consumption increases, it chills and constricts the column ever more intensively. The more intensively the arc is constricted, the lower the value of the current, at which VAC transfers into rising one. Thus, the plasma arc voltage depends on the design dimensions of the plasmatron, on the arc current, composition and consumption of the working gas [4–6].

To determine the range of operating voltages of the plasmatron, the VAC family is plotted, each of which is taken at change in the consumption of the plasma-forming gas $Q_{p.g}$ and unchanged design dimensions of the plasmatron.

For experiments, the plasmatron MP-04, designed by the E.O. Paton Electric Welding Institute, was used. The measurements were carried out with a channel diameter of the plasma-forming nozzle of 1.0 mm and an electrode diameter of 1.5 mm. The distance from the electrode end to the nozzle edge was 1.0 mm, the distance from the nozzle edge to anode was 1.5 mm. As a plasma-forming and shielding gas, argon was used. The plasma-forming gas consumption changed within the limits of 100–300 l/h. The shielding gas consumption in all the experiments was maintained at 400 l / h.

The losses for heating of the plasmatron parts were evaluated according to the methods described in works [7, 8], according to the value of the heat flux Q_f

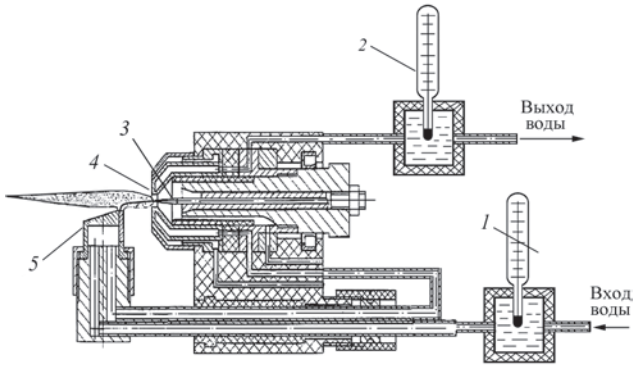

Figure 1. Scheme of experiment for determination of the plasmatron operation efficiency: *1* — thermometer, measuring temperature of water at the inlet to the plasmatron; *2* — thermometer, measuring temperature of water at the outlet from the plasmatron; *3* — cathode; *4* — plasma-forming nozzle; *5* — anode

(J) taken by the water-cooled surfaces of the plasmatron (copper anode, cathode unit and plasma-forming nozzle).

$$Q_f = c\rho Q_w \Delta T, \quad (1)$$

where c is the heat capacity of water, J/(g·K); ρ is the density of water, g/cm^3; Q_w – water consumption, cm^3/s; ΔT is the difference of water temperature at the inlet and outlet from the calorimeter, °C.

The water consumption through the calorimeter (sections of the calorimeter) was measured by rotameters RS-5, the difference in temperatures ΔT was measured by mercury thermometers with a division value of 0.1 °C.

The heat flux was determined by the method of continuous-flow calorimetry in the experimental installation, the scheme of which is shown in Figure 1.

The thermal efficiency of the plasmatron was calculated from the ratio:

$$\eta = 1 - \frac{P_h}{P_a}, \quad (2)$$

where P_a is the arc power, determined as the product of I_a, U_a, W; P_h is the heat flux power consumed for heating the water-cooled surfaces of the plasmatron (copper anode, cathode unit and plasma-forming nozzle), which is determined by the value Q_f and the heat losses for radiation P_{rad}; $P_h = Q_f + P_{rad}$.

Assuming that the plasma is optically thin (transparent for its own radiation), the losses on radiation (taking into account that during operation of the plasmatron MP-04 the arc is burning outside the plasmatron body, i.e. between the remote anode and the cathode tip) can be estimated from the formula:

$$P_{rad} = \frac{\pi d^2}{4} l \psi(\bar{T}), \quad (3)$$

where d is the arc column diameter; l is the open arc section length; $(\pi d^2/4)l$ is the plasma volume; ψ is the

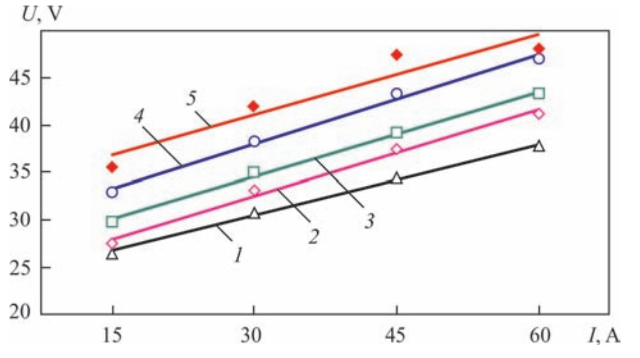

Figure 2. VAC of the plasmatron MP-04 (nozzle diameter is 1 mm, plasma-forming gas is argon, consumption of plasma-forming gas, l/h: *1* — 100; *2* — 150; *3* — 200; *4* — 250; *5* — 300

volume plasma losses for radiation, W/m^3; T is the average mass temperature of the plasma, K.

The enthalpy ΔH (J/l) of the plasma jet was determined from the ratio:

$$\Delta H = \frac{P_a \eta}{Q_{pg}}, \qquad (4)$$

where $Q_{p.g}$ is the consumption of the plasma-forming gas, l/h; η is the thermal efficiency of the plasmatron; P_a is the arc power, J/h.

The jet temperature was determined from the Tables of its relationship with the enthalpy in work [9].

Measurement of VAC of microplasmatron MP-04 during wire spraying. VAC of the plasmatron demonstrates the relation between the voltage of plasma arc and current. VAC allows establishing the range of stable operation of the power source during change in the operation modes of the plasmatron.

The voltage of the plasma arc depends on the design dimensions of the plasmatron (nozzle diameter, nozzle length), arc current, composition and consumption of the working gas and on the value of interelectrode gap.

The main thermal characteristics of the plasmatron are the thermal efficiency of its operation $\eta_{t.o}$, enthalpy ΔH and the temperature of plasma jet.

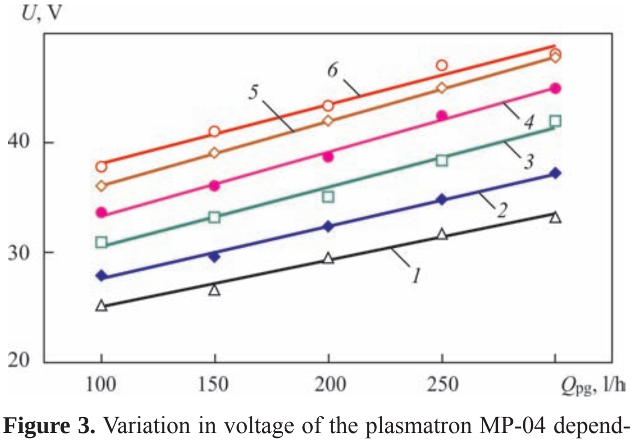

Figure 3. Variation in voltage of the plasmatron MP-04 depending on the consumption of plasma-forming gas at different values of current, A: *1* — 10; *2* — 20; *3* — 30; *4* — 40; *5* — 50; *6* — 60

A calculated evaluation of the influence of parameters of the plasmatron operation mode on the enthalpy of plasma jet was carried out using the expression (4). With the increase in the arc power P_a, the temperature and the enthalpy ΔH of plasma jet increase. The effect of the consumption of plasma-forming gas $Q_{p.g}$ is opposite. The arc power is in its turn determined by two parameters: current and voltage.

To determine the range of operating voltages of the plasmatron MP-04, a family of VAC was plotted, each of which was taken at the unchanged composition and consumption of the working gas, length of the arc open section and constant design dimensions of the plasmatron (Figure 2).

The processing of the experiment results shows that VACs of the plasmatron MP-04 are rising and have a linear form. It is known that in most cases the rising VACs are more energetically advantageous, because during the use of power sources they do not require introduction of additional ballast resistance to the circuit, the voltage drop at which can reach 50 % [10]. Thus, the rising VACs of the microplasmatron MP-04 allow using the power sources with both steep-falling external VAC, as well as with rigid external VAC for operation with it [11].

It was established that at a constant «cathode–anode» distance and constant composition of the gas, the voltage increases linearly with increase in current and consumption of plasma-forming gas (Figures 2 and 3), at the same time, the power of plasmatron increases.

The growth in voltage at the increase in working gas consumption can be explained by the increase in the degree of the arc column constriction. During blowing of arc discharge at its boundary due to intense heat exchange between the gas and the arc column, the deionization process takes place, which leads to reduction in the discharge diameter and growth in the electric field intensity in it. The more intensively the arc is constricted, the lower value of current is required for the VAC to go into rising one.

It is seen from the VAC (Figures 2 and 3) that for operating values of current and consumption of plasma-forming gas, the voltage is in the range of 25–50 V. Using the dependence given in work [12], one can assume that the power source for the arc exciting and stable operation of the plasmatron MP-04 at the modes providing spraying of wire materials, should be capable for smooth regulation of current in the range of 20–80 A and the open-circuit voltage of not less than 60 V.

The investigations of thermal efficiency of microplasmatron showed that a change in current from 15 to

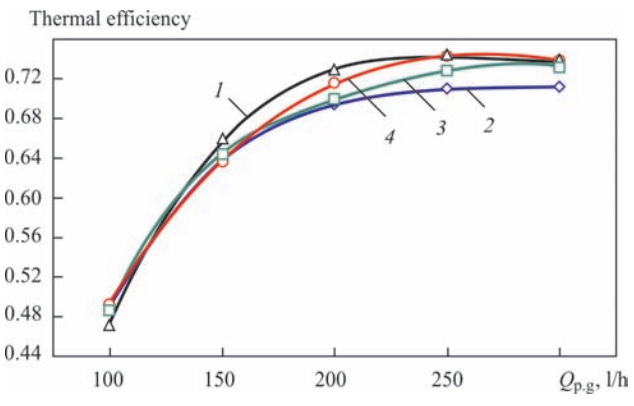

Figure 4. Variation in thermal efficiency of the plasmatron MP-04, depending on the consumption of plasma-forming gas at different values of current A: *1* — 15; *2* — 30; *3* — 45; *4* — 60

60 A in the entire consumption range of plasma-forming gas of 100–300 l/h almost does not result in its change (Figure 4). It was established, that thermal efficiency of the plasmatron grows with the increase in the consumption of plasma-forming gas in the range of 100–200 l/h, and in the range of consumption of 200–300 l/h, the efficiency growth is not observed. This is explained by the balance beginning between the energy, which is taken by the plasma-forming gas and cooling system of the plasmatron, as well as by the beginning of critical conditions, at which the arc constriction is maximum and the losses to the nozzle walls remain at the same level. The maximum efficiency of the microplasmatron MP-04 reaches 75 %, which exceeds the result obtained in the conditions of powder MPS [12].

The carried out investigations showed that the efficiency of the plasmatron MP-04 is almost not changed with a change in the current at the gas consumption, exceeding 100 l/h (Figure 5).

Determination of enthalpy and temperature of argon plasma jet in microplasma wire spraying. During microplasma wire spraying, for improvement of the wire melting conditions and dispersion of the molten metal drop, formed at the end of the neutral

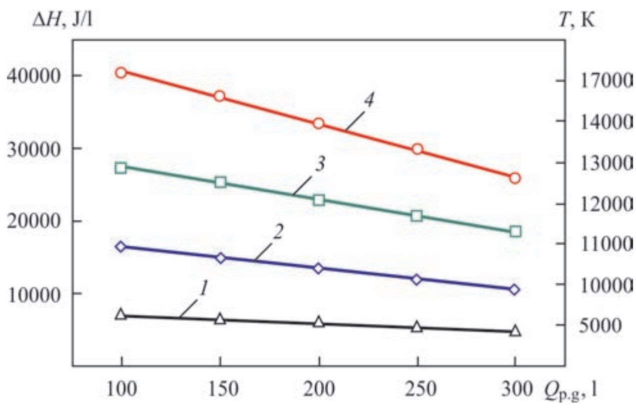

Figure 6. Variation in enthalpy depending on gas consumption for different values of current A: *1* — 15; *2* — 30; *3* — 45; *4* — 60

wire and formation of a jet, containing the particles of the spraying material, an increased gas consumption at a low plasma arc current is used. Therefore, the enthalpy of the plasma jet is much lower than that in microplasma powder spraying. In Figure 6 it is seen that with the increase in gas consumption at a less intensive increase in the jet power, the values of the enthalpy and temperature of the plasma jet are reduced.

The carried out calculation of plasma parameters allowed determining the temperature of microplasma jet from the data of argon temperature dependence on the enthalpy [9]. The maximum temperature of the jet is 17700 K at the minimum gas consumption (100 l/h) and the maximum current (60 A), and the minimum temperature is 5000 K at the maximum gas consumption (300 l/h) and the minimum current (15 A) (Figure 6).

At a fixed voltage, the arc power can be controlled by the more flexible parameter: arc current. The jet enthalpy increases linearly at all the gas consumptions with increase in current and hence, in arc power (Figure 7).

Since the voltage is mainly determined by the design of the plasmatron and the composition of plasma-forming gas, the selection of its operating mode during spraying process consists in establishing the

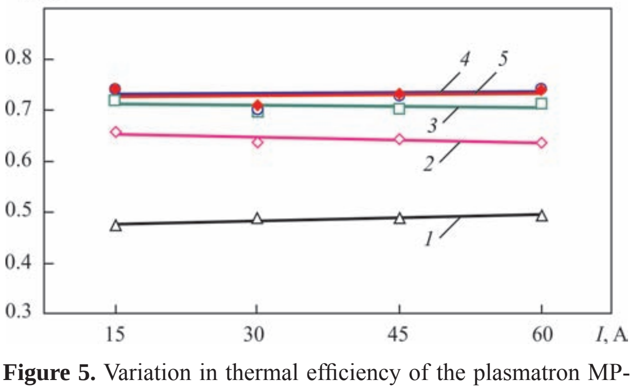

Figure 5. Variation in thermal efficiency of the plasmatron MP-04 as a function of current at different values of consumption of plasma-forming gas, l/h: *1* — 100; *2* — 150; *3* — 200; *4* — 250; *5* — 300

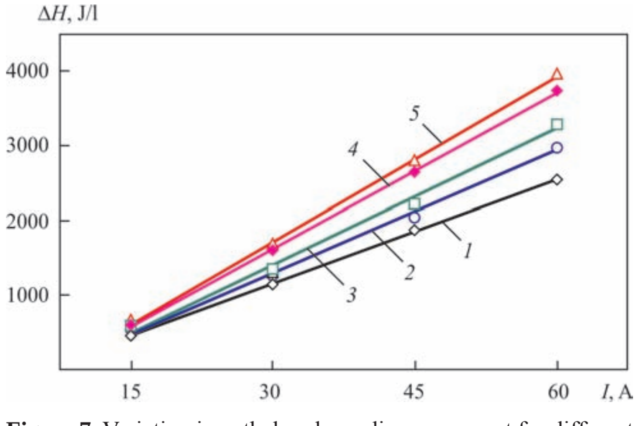

Figure 7. Variation in enthalpy depending on current for different values of consumption of plasma-forming gas, l/h: *1* — 100; *2* — 150; *3* — 200; *4* — 250; *5* — 300

optimal combination of current and consumption of the plasma-forming gas. The lower and the upper level of consumption of the plasma-forming gas is connected with the operating conditions of the microplasmatron (thermal load at the nozzle walls, anode life, process stability).

Conclusions

As a result of measuring the electrical and thermal characteristics of a turbulent microplasma argon jet during spraying the neutral wire, it was established that under these conditions the VAC of a microplasmatron with a remote anode increases linearly in the range of currents of 10–60 A for the consumption of plasma-forming gas of 100–300 l/h, and the efficiency of the microplasmatron is almost independent of the current value and increases from 48 to 73 % with an increase in the plasma-forming gas consumption from 100 to 200 l/h. A further increase in the consumption of the plasma-forming gas to 300 l/h does not lead to a change in the efficiency. The calculated value of the plasma jet enthalpy under these conditions reaches 40 kJ/l, which is equivalent to the argon jet temperature of 17700 K.

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