https://doi.org/10.15407/tpwj2019.11.04

INVESTIGATION OF ELECTRICAL AND THERMAL CHARACTERISTICS OF PLASMATRON FOR MICROPLASMA SPRAYING OF COATINGS FROM POWDER MATERIALS

Yu.S. BORISOV, S.G. VOINAROVYCH, A.N. KYSLYTSIA, E.K. KUZMYCH-IANCHUK and **S.N. KALIUZHNYI**
E.O. Paton Electric Welding Institute of the NAS of Ukraine
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine. E-mail: office@paton.kiev.ua

The volt-ampere characteristics were studied and the thermal efficiency of the MP-04 plasmatron for the installation of microplasma spraying MPN-004 was determined under the conditions of formation of a laminar argon microplasma jet. The range of operating voltages of the plasmatron was determined and a family of volt-ampere characteristics was plotted, each of which was taken at the constant composition and flow rate of working gas, length of open region of the arc and constant design dimensions of the plasmatron. Analysis of the experimental results shows that volt-ampere characteristics of the MP-04 plasmatron are ascending and linear. It was established that at operating values of current and flow rate of plasma-forming gas, the voltage is in the range of 22–32 V. The thermal efficiency of the plasmatron, the bulk mean initial enthalpy and the temperature of plasma jet were determined depending on the arc current and flow rate of plasma-forming gas by the method of heat flow calorimetry. It was found that under the conditions of microplasma powder spraying process, thermal efficiency of the plasmatron is in the range of 30–55 % and at gas flow rates, exceeding 40 l/h, it practically does not change with the change in current. 16 Ref., 1 Table, 7 Figures.

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

At present, the processes of thermal coating are increasingly used in industry. One of the main methods of thermal coating is plasma spraying. Most often, for this purpose plasmatrons are used, which generate a turbulent plasma jet with an electric power of up to 200 kW and a spot diameter of the sprayed material of 15–30 mm. The use of such plasmatrons for spraying small-sized or thin-walled parts can lead to their overheating and buckling because of a high thermal power of plasma jet. In addition, in the case of spraying small-sized parts or local surface areas (5–10 mm or less), large losses of sprayed material occur, and it also becomes necessary to perform an additional operation to mask the areas which are not subjected to spraying. These circumstances resulted in the development of a new method of thermal coating at the E.O. Paton Electric Welding Institute, which is microplasma spraying (MPS) [1, 2].

For realization of the microplasma spraying method, at the E.O. Paton Electric Welding Institute the microplasmatron was designed and patented, equipped with a stand-off, directly cooled anode with an erosion-resistant insert [3]. The power of the designed MP-04 microplasmatron is up to 2.5 kW.

A specific feature of the microplasma spraying process in the case of coating of powder materials is the mode of laminar plasma jet flow with the use of coaxial blowing of plasma jet with argon for its stabilization.

During the development of the technology of microplasma spraying of coatings using powder as a sprayed material, it was necessary to study both the characteristics of the MP-04 microplasmatron as well as the parameters of the microplasma jet generated by it. In the work, such energy characteristics as coefficient of thermal efficiency of the plasmatron (η), dependence of arc discharge voltage on current during change in gas flow rates — volt-ampere characteristics (VACh) of the arc, enthalpy (ΔH) and plasma temperature were studied.

Investigations procedure. The procedure of heat flow calorimetry, used to determine the characteristics of the MP-04 microplasmatron as applied to the conditions of MPS from wire materials, is described in [4]. The main difference in the operation of the plasmatron for spraying powder materials is the mode of laminar plasma jet flow. It is known that plasma arc voltage depends on the design of the plasmatron, arc current, composition and flow rate of the working gas. In this connection, measuring of VACh was performed at a constant composition and flow rate of the working gas, length of the open region of the arc and constant

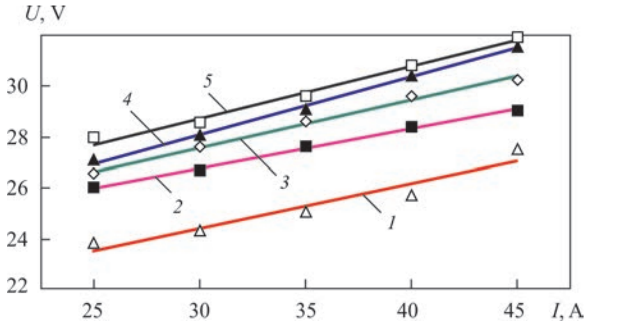

Figure 1. VACh of MP-04 plasmatron. Plasma-forming gas flow rate: *1* — 40; *2* — 60; *3* — 80; *4* — 100; *5* — 120 l/h

design dimensions of the plasmatron: diameter of the plasma-forming nozzle channel was 1.0 mm, electrode diameter was 1.5 mm, distance from electrode end to nozzle end was 1.0 mm, distance from nozzle end to anode was 1.5 mm. As a plasma-forming and shielding gas, argon was used. The flow rate of plasma-forming gas was changed within 40–120 l/h, the flow rate of shielding gas in all experiments was maintained equal to 240 l/h.

The main thermal characteristics of the plasmatron are its thermal efficiency (η_{th}), enthalpy (ΔH) and temperature of plasma jet.

Measurement of VACh of the MP-04 microplasmatron during spraying of powder materials. VACh allows establishing the range of stable operation of the power source at the change in operating modes of the plasmatron. To determine the range of operating voltages of the MP-04 plasmatron, the family of VAChs was plotted (Figure 1).

Processing of the experimental results shows that the VAChs of the MP-04 plasmatron are ascending and have a linear form. The similar VAChs were also obtained during the study of laminar plasmatron in [5]. It follows from [6] that ascending VAChs in most cases are more energetically favourable, since during the use of power sources they do not require the introduction of additional ballast resistance into the circuit, the drop of voltage at which can reach 50 %. Thus, the ascending VAChs of the MP-04 microplasmatron allow using the power sources with it having both a steeply falling external VACh as well as a rigid external VACh [7].

It was found, that at a constant cathode-anode distance and at a constant gas composition, the voltage increases with an increase in current and flow rate of plasma-forming gas (Figures 1, 2), simultaneously increasing the power of the plasmatron. The rise in voltage with the increased flow rate of working gas can be explained by an increase in the degree of the arc column constriction. During blowing of the arc discharge, at its boundary the deionization process occurs due to intense heat exchange between the gas and the arc column, which leads to a reduction in the discharge diameter and an increase in the electric field intensity in it. The more intense the arc is constricted, the lower the current value, when its VACh transfers into ascending one.

From VACh (Figure 1) it is seen that for operating values of current and flow rate of plasma-forming gas, the voltage is in the range of 22–32 V. Using the dependence given in the work [8], it can be assumed that the power source for arc excitation and stable operation of the MP-04 plasmatron should provide the ability to perform a smooth adjustment of current in the range of 20–60 A and open circuit voltage of at least 60 V.

Determination of thermal efficiency of the plasmatron, power, enthalpy and temperature of Ar-plasma jet during microplasma spraying. A growth in voltage at the increase in the flow rate of plasma-forming gas leads to a linear increase both in the arc power (Figure 3) as well as in the thermal efficiency of the plasmatron (Figure 4), determined according to [4].

The obtained thermal efficiency of the MP-04 microplasmatron at the given operating parameters is in the range of 30–55 %. According to literature data and calculations performed using the CASPSP software package for computer simulation of the plasma spraying process, the thermal efficiency of plasmatrons

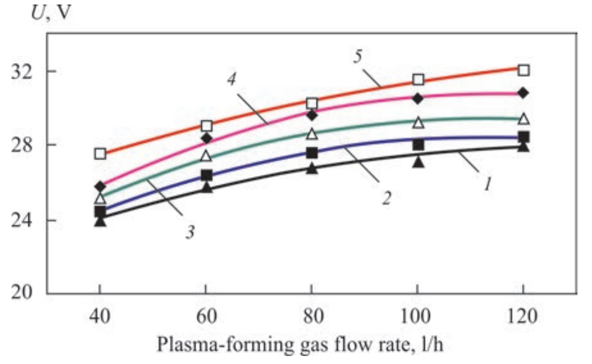

Figure 2. Change of arc column voltage of MP-04 plasmatron, depending on gas flow rate for different values of current: *1* — 25; *2* — 30; *3* — 35; *4* — 40; *5* — 45 A

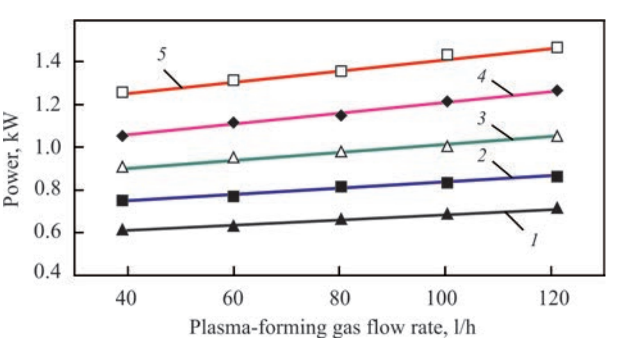

Figure 3. Change of power of MP-04 plasmatron depending on gas flow rate for different values of current: *1* — 25; *2* — 30; *3* — 35; *4* — 40; *5* — 45 A

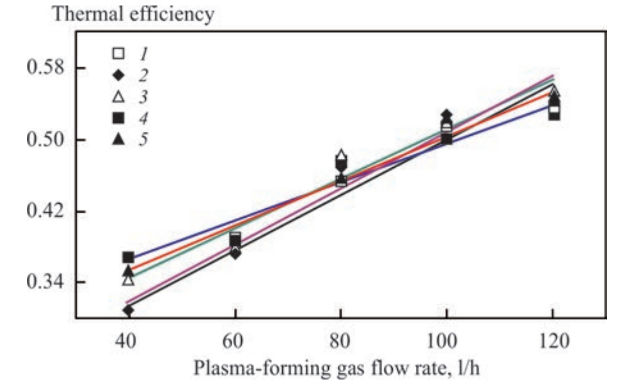

Figure 4. Change of thermal efficiency of MP-04 plasmatron depending on gas flow rate for different values of current: *1*— 45; *2* — 40; *3* — 35; *4* — 30; *5* — 25 A

without an interelectrode insert applied during traditional plasma spraying using argon, is 50–70 % [9].

The increase in thermal efficiency of the MP-04 microplasmatron with a growth in the flow rate of plasma-forming gas is explained by a decrease in heat losses from the arc column to the nozzle walls due to the increase in the degree of the arc column constriction and, as a result, improvement of their thermal insulation from the arc column, as well as due to a more intensive cooling of the anode by a gas flow. Thus, the higher the gas flow rate, the lower the heat load on the nozzle and, therefore, the longer the life of the nozzle.

However, since voltage and, consequently, jet power grow less intensively than gas flow rate, the values of enthalpy and temperature decrease with the growth in gas flow rate (Figure 5). In this case, the maximum calculated enthalpy of 32000 J/l is observed at a minimum gas flow rate (40 l/h) and a maximum current (45 A), and the minimum calculated enthalpy of 11000 J/l is observed at a maximum gas flow rate (120 l/h) and a minimum current (25 A).

Based on the data on the dependence of argon temperature on enthalpy [10], the temperature of microplasma jet is 10000–13500 K. According to literature data and calculations performed using CASPSP for traditional plasma spraying, the initial temperature of

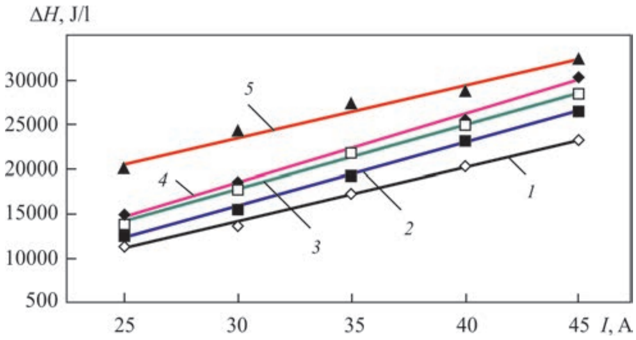

Figure 6. Change of enthalpy depending on current at different values of plasma-forming gas flow rate: *1* — 25; *2* — 30; *3* — 35; *4* — 40; *5* — 45 A

argon plasma leaving the nozzle is 7000–13000 K [7, 11–15].

At a fixed voltage, the arc power can be controlled by a more flexible parameter — arc current. The jet enthalpy with increasing current, and, consequently, the arc power, rises linearly at all gas flow rates (Figure 6).

Since the voltage is mainly determined by the design of the plasmatron and the composition of plasma-forming gas, during spraying a coating of powder material, the choice of the mode of operation of the plasmatron consists in establishing the optimal combination of current and flow rate of plasma-forming gas. The lower and upper levels of the flow rate of plasma-forming gas are associated with the operating conditions of the microplasmatron (thermal load on nozzle walls, anode resistance and process stability).

The carried out investigations showed that the thermal efficiency of the MP-04 plasmatron practically does not change with a change in the current at gas flow rates exceeding 40 l/h (Figure 7). A decrease in the thermal efficiency of the plasmatron with a rise in current in the case of a gas flow rate of 40 l/h is associated with an increase in losses in the nozzle walls due to insufficient arc constriction.

The evaluation of power losses on radiation with the open column region of a microplasma arc was performed using the formula (3) [4].

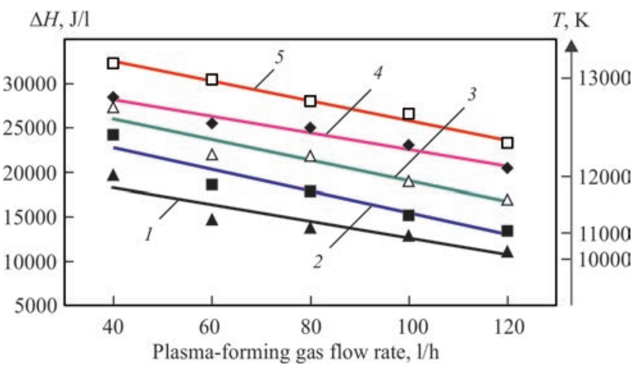

Figure 5. Change of enthalpy depending on gas flow rate for different values of current: *1* — 25; *2* — 30; *3* — 35; *4* — 40; *5* — 45 A

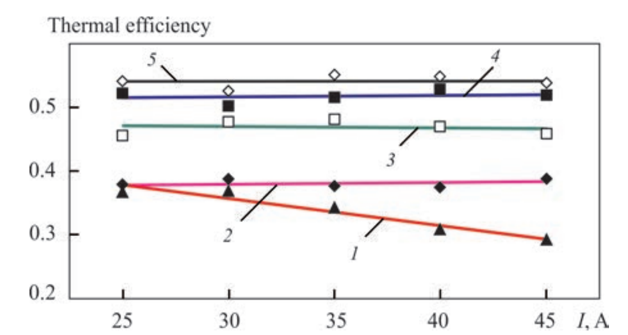

Figure 7. Change of thermal efficiency of MP-004 plasmatron depending on current at different values of plasma-forming gas flow rate: *1* — 40; *2* — 60; *3* — 80; *4* — 100; *5* — 120 l/h

Values of volumetric losses of power of argon plasma of atmospheric pressure on radiation

($\bar{T}$), kK	10	11	12	13	14	15	16
$\psi\cdot10^{10}$, W/m^3	0.0033	0.011	0.030	0.062	0.096	0.118	0.124

The results of a calculated evaluation of the volumetric losses of power of argon plasma of atmospheric pressure on radiation are given in Table.

In the case when l = 3 mm, d = 1 mm, ($\bar{T}$) = 13 kK, the power losses on radiation will be 1.46 W, which corresponds to approximately 0.1 % of the arc power.

The results of experiments on measuring argon plasma radiation given in [16] show that at a temperature of about 13500 K, the radiation correction is about 2 %.

Conclusions

1. As a result of measuring the electrical and thermal characteristics of the laminar microplasma argon jet used in microplasma spraying by powder materials, the volt-ampere characteristics of the MP-04 plasmatron were determined. It is shown that they have a linear form and are ascending, while the operating voltage of the arc in the current range of 25–45 A is 22–32 V.

2. It was found that the thermal efficiency of the MP-04 microplasmatron in the current range of 25–45 A grows with an increase in the flow rate of plasma-forming gas. The maximum thermal efficiency reaches 55 % at a gas flow rate of 120 l/h. The efficiency of the plasmatron practically does not change with a change in the current at gas flow rates exceeding 40 l/h. An increase in current at a gas flow rate of 40 l/h leads to a decrease in the efficiency of the plasmatron, which is associated with an increase in losses in the nozzle walls as a result of insufficient arc constriction.

3. It was found that under the given conditions, the calculated value of plasma jet enthalpy reaches 32 kJ/l and the maximum calculated temperature of microplasma argon jet in the operating range of the MP-04 microplasmatron is 13500 K. Thus, due to the increased ratio of the arc power to the flow rate of plasma-forming gas in the case of microplasma spraying (about 2 kW), as compared to traditional plasma spraying (about 1 kW), the temperature of microplasma jet with a power of 1.5 kW is in many cases higher than the temperature of plasma jet generated by conventional plasmatrons of 10–40 kW capacity.

1. Borisov, Yu., Borisova, A., Pereverzev, Yu., Ramaekers, P.P.J. (1997) Microplasma spraying. In: *Proc. of 5th Europ. Conf. on Advanced Material and Processes*. Netherlands, 237–241.
2. Borisov, Yu.S., Pereverzev, Yu.N., Bobrik, V.G. , Vojnarovich, S.G. (1999) Deposition of narrow-strip coatings by microplasma spraying method. *Avtomatich. Svarka*, **6**, 53–55 [in Russian].
3. Borisov, Yu.S., Vojnarovych, S.G. et al. (2002) *Plasmatron for coating deposition*. Pat. Ukraine 2002076032UA, Int. Cl. B23K10/00 [in Ukrainian].
4. Borisov, Yu.S., Kyslytsia, O.M., Voinarovych, S.G. et al. (2018) Investigation of plasmatron electric and energy characteristics in microplasma spraying with wire materials. *The Paton Welding J*., **9**, 18–22.
5. Zheenbaev, Zh., Engelsht, V.S. (1975) *Laminar plasmatron*. Frunze, Ilim [in Russian].
6. Koroteev, A.S. (1980) *Electric arc plasmatrons*. Moscow, Mashinostroenie [in Russian].
7. Borisov, Yu.S., Kharlamov, Yu.A. et al. (1987) Thermal coatings of powder materials. Kiev, Naukova Dumka [in Russian].
8. Paton, B.E., Gvozdetsky, V.S., Dudko, D.A. et al. (1979) Microplasma welding. Kiev, Naukova Dumka [in Russian].
9. (2007) Software CASPSP-3.12 for computer modeling of plasma spraying process. *Avtomatich. Svarka*, **5**, 5–6 [in Russian].
10. Engelsht, V.S., Gurovich, V.Ts., Desyatkov, G.A. et al. (1990) *Theory of electric arc column. Low-temperature plasma*. Vol. 1. Novosibirsk, Nauka [in Russian].
11. Grey, J., Jackobs, P. (1964) *Rocket technique and cosmonautics*, **3**, 25.
12. Elyashevich, M.A. (1970) *Problems of physics of low-temperature plasma*. Ed. by M.A. Elyashevich. Ins-te of Physics of AS BSSR. Minsk, Nauka i Tekhnika [in Russian].
13. Abdrazakov, A., Zheenbaev, Zh., Karikh, F.G. (1968) *Investigation of electric arc and plasmatron*. Frunze, Ilim [in Russian].
14. Krasnov, A.N., Zilberberg, V.T., Sharivker, S.Yu. (1970) *Low-temperature plasma in metallurgy*. Metallurgiya [in Russian].
15. Morenov, A.I., Petrov, A.V. (1967) Determination of velocities and pulsations of jet in plasmatrons for coating deposition. Svarochn. Proizvodstvo, 2, 3-6 [in Russian].
16. Tankin, R.S., Berry, J.M. (1964) Experimental investigation of radiation from an argon. *Phys. of Fluids*, **7**, 1620–1624.

Received 23.07.2019