vective and radiant heat fluxes, kW/m²; q_0, heat flux delivered to the heated surface, kW/m²; q_0', heat flux delivered to the heated surface with allowance for the loss to radiation, kW/m²; q_{av}', mean integral heat flux during the establishment of a constant surface temperature, kW/m²; I_e, stagnation enthalpy of the gas flow, kJ/kg; P_e, stagnation pressure of the gas flow, Pa; I_w, $I_{x.st}$, enthalpy of the gas at the temperatures of the heated surface and calorimeter, kJ/kg; T_0, temperature of the material before heating, K; T_w, temperature of the surface being heated, °K; $\bar{c}_p$, mean integral specific heat, kJ/kg·K; ΔQ_w, total thermal effect of the surface processes, kJ/kg; γ, injection parameter; ε, emissivity of the surface; σ, Stefan–Boltzmann constant, kW/(m²·K⁴); I_{ef}, effective disintegration enthalpy, kJ/kg; $(\alpha/c_p)_0$, heat-transfer coefficient, kg/(m²·sec); P_d, dynamic pressure of the gas flow, Pa; α, oxidant excess coefficient.

LITERATURE CITED

1. Yu. V. Polezhaev and F. B. Yurevich, Thermal Protection [in Russian], Énergiya, Moscow (1976).
2. G. A. Frolov, V. S. Dvernyakov, V. V. Pasichnyi, and F. I. Zakharov, "Experimental study of heat transfer between subsonic and supersonic plasma jets and a flat surface," Inzh.-Fiz. Zh., 40, No. 6, 965-969 (1981).
3. G. A. Frolov, V. S. Dvernyakov, and V. V. Pasichnyi, "Some results of an experimental study of heat transfer on a surface under the combined influence of radiative and convective heat sources," Teplofiz. Vys. Temp., 16, 221 (1978). Submitted to VINITI, No. 4217-77 Dep.
4. G. A. Frolov, V. V. Pasichnyi, V. S. Dvernyakov, and K. B. Isaev, "Reflectivity of thermally protective materials with radiative–convective heating," Inzh.-Fiz. Zh., 42, No. 5, 792-797 (1982).
5. R. E. Krzhizhanovskii and Z. Yu. Shtern, Thermophysical Properties of Nonmetallic Materials (Oxides) [in Russian], Énergiya, Leningrad (1973).

INTERACTION OF THE ELECTRIC ARC IN A TWO-JET PLASMATRON WITH THE SURFACE OF A SOLID BODY

N. V. Livitan and S. P. Polyakov

UDC 533.9

The electrical and thermal characteristics of a magnetically controlled arc in a two-jet plasmatron interacting with a flat surface are presented.

Increased attention has been devoted in recent years to the problems of studying the interaction of concentrated energy fluxes with materials [1]. In many other energy sources, electric-arc plasmatrons, the thermal flux density from which and the nature of whose action on the surface being worked depend substantially on the structural peculiarities of the plasmatron and the conditions under which the electric arc burns, are widely used.

For example, the so-called indirect action plasmatrons, in which the electric arc burns between the cathode and the nozzle-anode, transferring heat to the plasma-forming gas blown past it, are characterized by a relatively low heat flux density of the order of 0.2-0.6 kW/cm² [2]. Moreover, the significant gas-dynamic head, characteristic for plasma jets, often also makes it difficult to use them.

The so-called direct-action plasmatrons, in which the electric arc burns directly between the cathode (or anode) of the plasmatron and the surface being worked, are distinguished by their high heat flux density in the substrate – up to 15-20 kW/cm² [3, 4]. At the location of fixing, however, the arc is, as a rule, contracted, which destroys the surface layer of the material being worked, and makes it difficult to work thin-walled structures and layers of protective coatings.

L. I. Brezhnev Dnepropetrovsk Metallurgical Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 50, No. 4, pp. 635-640, April, 1986. Original article submitted December 5, 1984.

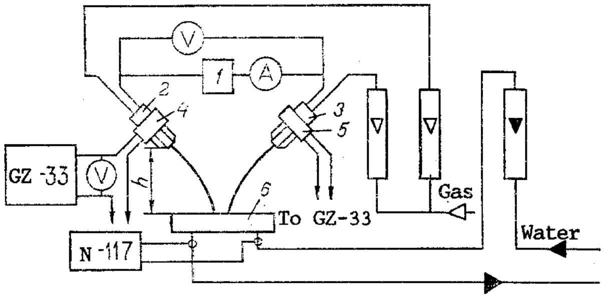


Fig. 1

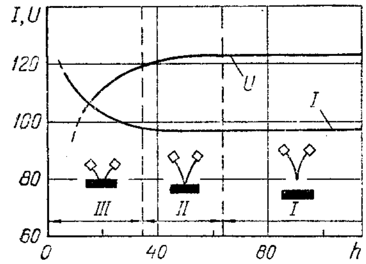


Fig. 2

Fig. 1. Diagram of the experimental arrangement: 1) specialized power supply; 2, 3) anodic and cathodic elements of the two-jet plasmatron, 4, 5) magnetic deflecting systems; 6) calorimetric sensor.

Fig. 2. Change in the magnitude of the current and voltage in the electric arc of a two-jet plasmatron as a function of its height above the surface of the solid. I, A; U, V; h, mm.

Studies in which the interaction of the surface of a solid with an arc plasma filament, stabilized by a rotating cylinder positioned parallel to the surface, is studied have been performed [5]. Specific heat flux from the electric arc reaches in this case 2 kW/cm^2 [6]. Such an electric arc setup is efficient primarily when working flat surfaces and is ineffective for working parts with a complicated surface relief.

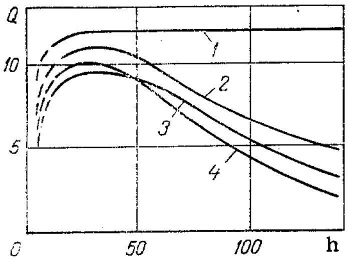
Based on what was said above, it seems promising to use for technological and scientific purposes two-jet plasmatrons whose distinguishing feature is the presence of an external arc; these plasmatrons have the advantages of previously studied plasma-arc devices and are largely free of their deficiencies [7-10]. Indeed, the heat-flux density has a moderate magnitude, characteristic for indirect-action plasmatrons, at the point of convergence of the anodic and cathodic plasma jets. By ensuring direct contact of the beam with the surface being worked it is possible to achieve extremal heat-flux densities, characteristic for direct-action plasmatrons. To this we should add that the surface being worked can be both electrically conducting and nonconducting, flat and with a complicated relief, as well as dense and porous.

The electrical and thermal structure of the electric arc in a two-jet plasmatron has been studied in great detail (see, for example, [7-10]), whereas the questions of its interaction with the surface being worked, the effect of the nature of this interaction on the electrical indicators of the arc, and the magnitude of the heat fluxes from it on the surface have thus far not been studied. This work is devoted to the study of these questions.

The experiments were performed on the setup described in [11]. The setup included (see Fig. 1) a specialized power supply, anodic and cathodic elements of the two-jet plasmatron, equipped with magnetic deflecting systems, which are connected to a power supply supplying alternating voltage with a regulatable frequency (regulated with a GZ-33 acoustic generator). The plasmatron was fastened to the coordinate setup with the possibility of motion in three planes. The electric characteristics of the plasmatron were recorded with the help of an N-117 loop oscillograph. Argon was used as the plasma-forming gas.

The heat fluxes were determined with the help of a copper water-cooled diskotic sensor, at whose input and output thermocouple banks were placed (Fig. 1). The sensor was 110 mm in diameter.

The investigations performed confirmed that under the action of the electric arc from a two-jet plasmatron on the surface of a solid several characteristic working states can be realized depending on their mutual arrangement. These states can be conditionally divided into three basic states, presented below in order of increasing intensity of working: without the electric arc directly touching the surface being worked, with the electric arc touching the surface being worked but without current contact with the surface, working directly with the electric arc with partial or total shunting of the current of the arc through the worked layer of the work piece. It should be noted that in the case when electrically nonconducting work pieces are being worked, only the first two regimes can, as a rule, be realized.



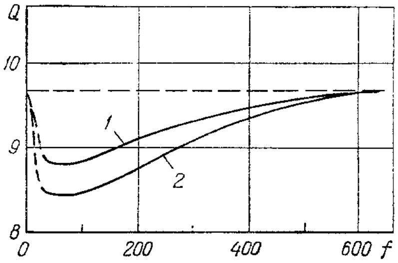


Fig. 3 Fig. 4

Fig. 3. Electric power of the arc of a two-jet plasmatron (1) and the heat fluxes from it in a flat water-cooled calorimetric sensor, depending on the height of the arc above it; 2) without an external magnetic field imposed on the electric arc; 3, 4) with an external transverse magnetic field with a frequency of 100 Hz with synchronous oscillation of its anodic and cathodic sections in opposite directions and in the same direction, respectively, imposed on the arc. G = 0.12 g/sec. Q, kW; h, mm.

Fig. 4. Heat flux from the electric arc of a two-jet plasmatron in a calorimetric sensor as a function of the frequency of its oscillations in an external magnetic field: 1, 2) with synchronous oscillation of the anodic and cathodic sections of the arc in opposite directions and in the same direction, respectively. G = 0.12 g/sec; h = 60 mm; f, Hz.

In accordance with the working conditions indicated above, before the arc touches the surface its electrical characteristics do not change (see Fig. 2, zone I). At the moment the electric arc touches the surface being worked its overall length gradually decreases. This increases the current and reduces the voltage on the arc (zone II), which becomes especially noticeable at the moment that the anodic and cathodic sections of the arc are shunted through the calorimeter and two freely burning arcs with the direct and reverse polarity are formed (zone III). The jumplike change in the length of the arc when it is shunted through the calorimeter does not cause a sharp change in the voltage on the arc, since it is apparently compensated by some increase in the potential in the regions of the newly formed anodic and cathodic spots of the arc [12].

Analysis of the measurements of the heat fluxes presented in Fig. 3 shows that the heat flux in the flat sensor from the arc of a two-jet plasmatron depends substantially on their mutual position. Curve 1 corresponds to the electric power liberated in the arc, defined as the product of the current in the arc by the voltage drop across it. The other curves in Fig. 3 correspond to a heat flux in the calorimeter from a stationary electric arc (2) and an arc oscillating in an alternating transverse magnetic field (3, 4). It follows from the form of the curves that when the arc approaches the calorimeter the magnitude of the heat fluxes increases and reaches a maximum at distances characteristic for the transition region from the surface-working regime without current contact between the electric arc and the surface to the regime in which the arc current is shunted through the worked layer of the work piece, i.e., in the region of transition from zone II into the zone III. Then the heat flux drops as the length of the arc decreases.

In this case, the total measured heat flux from the oscillating electric arc of a two-jet plasmatron is 15-20% lower than the heat flux in the calorimeter from the unperturbed arc. This result is apparently attributable to the peculiarities of the interaction of the oscillating electric arc with the surrounding medium, in the course of which, together with an increase in the uniformity of heat-working of the surface, the physical volume of the gas-plasma flow increases and its temperature potential decreases somewhat, which is what ultimately decreases the intensity of the heat-transfer processes at the worked surface. The results obtained are in qualitative agreement with the results of investigations of heat transfer between a pulsating gas jet and a flat plate [13].

The nature of the oscillations of the arc also affects the magnitude of the heat flux (curves 3 and 4). If at large distances the magnitude of the heat flux from the arc with the anodic and cathodic sections oscillating synchronously in opposite directions is higher than for synchronous oscillation in the same direction, then at short distances the picture changes (see Fig. 3). This can be explained by the fact that in the case of synchronous oscillation of sections of the arc in opposite directions (curve 3) the region of coalescence of the anodic and cathodic plasma jets moves periodically perpendicularly to the heat-absorbing surface, and in the case of oscillations of the arc in the same direction (curve 4) it moves along the surface. At large distances, for oscillations of sections of the arc in the same direction, the heat flux from them is to a large extent dissipated. It is also dissipated with oscillations of sections of the arc in opposite directions. In this case, however, the magnitude of the heat flux into the heat-absorbing surface in different phases of motion of the region of coalescence is different: the heat flux is higher as the region approaches the worked surface and lower as the region moves away from the worked surface. The average heat flux in this case is higher than for oscillations of sections of the arc in the same difection and motion of the region of coalescence along the surface of the body. At short distances the pattern changes, however, since when the region of coalescence of sections of the arc slips along the surface the dissipation of heat from the arc into the surrounding medium is lower than when the region of coalescence moves periodically perpendicularly to the worked surface, when there exists a phase in which the arc moves away from the surface.

Depending on the frequency of the magnetic field applied to the electric arc the heat flux from it to the calorimeter also changes (Fig. 4). The broken curves in Fig. 4 show the magnitude of the heat flux to the surface of the calorimeter from the electric arc without the imposition of an external magnetic field on it. As pointed out above, the imposition of such a field on the arc lowers somewhat the magnitude of the total heat flux. Minimum heat flux is observed at frequencies of the external magnetic field which ensure a minimum amplitude of deflection of the arc in the applied field, and in general, the reverse dependence of the magnitude of the heat flux studied on the amplitude of oscillations of the electric arc is observed.

The efficiency of the process of heat-working of the surface of materials with the arc of a two-jet plasmatron, i.e., the fraction of the electrical energy of the arc transformed into a heat flux in the solid, as also the magnitude of the heat flux itself, depends on the working regime used. The efficiency of the process reaches 90-95% when the surface is worked with the arc current shunted through the surface of the work piece, 70-80% when the surface is worked with the arc touching the surface, and 40-50% when the arc does not touch the surface.

Thus, the results obtained indicate that when the electric arc of a two-jet plasmatron interacts with the surface of a solid the heat fluxes in it depend on the mutual position of the arc and the worked surface, the frequency of the external magnetic field oscillating the arc, and the nature of its effect on the arc. On the other hand, contact between the electric arc and the worked surface has the opposite effect on the arc, changing its electric and energy characteristics, whose values depend both on the conditions under which the material is worked and on the properties of the worked material.

NOTATION

I and U, current and voltage on the electric arc; f, frequency of the external magnetic field; B, induction of the magnetic field; G, flow rate of the plasma-forming gas; h, height of the anode and cathode elements of the two-jet plasmatron above the worked surface; and Q, heat flux.

LITERATURE CITED

1. N. N. Rykalin and A. A. Uglov, "Action of concentrated energy fluxes (CEF) on materials. Problems and prospects," Fiz. Khim. Obrab. Mater., No. 5, 3-18 (1983).
2. A. V. Donskoi and V. S. Klubnikin, Electroplasma Processes and Setups in Machine Building [in Russian], Mashinostroenie, Leningrad (1979).
3. N. N. Rykalin, Calculations of Thermal Processes in Welding [in Russian], Mashgiz, Moscow (1951).
4. P. F. Bulanyi and S. P. Polyakov, "Effect of the conditions of burning of an arc on the distribution of the specific thermal flux and current density at the anode," Zh. Tekh. Fiz., 51, No. 3, 541-546 (1981).

5. A. I. Zolotovskii, A. D. Shimanovich, and A. K. Shipai, "Study of the heating of the surface of ceramic and silicate materials by an arc plasma filament," Inzh.-Fiz. Zh., 42, No. 4, 604-607 (1982).
6. A. B. Demidovich, A. I. Zolotovskii, and V. D. Shimanovich, "Study of the heating of the surface of solids by an electric arc," Inzh.-Fiz. Zh., 46, No. 3, 461-466 (1984).
7. Zh. Zh. Zheenbaev and V. S. Éngel'sht, Two-Jet Plasmatron [in Russian], Ilim, Frunze (1983).
8. S. P. Polyakov and M. G. Rozenberg, "Study and generalization of the current–voltage characteristics of the two-jet plasmatron," Inzh.-Fiz. Zh., 32, No. 6, 1043-1052 (1977).
9. M. K. Asanaliev, "Study of the plasma flow in a two-jet plasmatron," Author's Abstract of Candidate's Dissertation, Physicomathematical Sciences, Frunze (1980).
10. S. P. Polyakov and V. I. Pechenkin, "Study of electric and thermal structure of an argon arc in a two-jet plasmatron," Inzh.-Fiz. Zh., 43, No. 5, 833-837 (1982).
11. S. P. Polyakov and N. V. Livitan, "Electric arc in a two-jet plasmatron in an alternating magnetic field," Inzh.-Fiz. Zh., 46, No. 3, 476-480 (1984).
12. V. Neiman, "Electrodic processes in a high-pressure gas discharge," in: Experimental Studies of Plasmatrons [in Russian], Nauka, Novosibirsk (1977), pp. 853-892.
13. R. G. Nevins and H. D. Ball, "Heat transfer between a flat plate and a pulsating impinging jet," Proceedings of the 2nd International Heat Transfer Conference, ASME (1962), pp. 510-516.

ANGULAR COEFFICIENTS IN SYSTEMS OF BODIES OF REVOLUTION

M. M. Mel'man

UDC 536.33

The apparatus of differential geometry is used to calculate angular coefficients. Examples are given.

1. The angular coefficients between surfaces of revolution are widely used in calculating the radiant heat transfer in various metallurgical and power units: converters, vacuum units for degassing steel, furnaces for heating tubes and rolls of steel strip, recuperaters for heating air and gas, boiler units, etc.

The expression for the angular coefficient with an elementary area dS_M at an area dS_P (Fig. 1) in a diathermal medium takes the form

$$\varphi_{dM-dP} = \frac{\cos\alpha\cos\beta}{\pi|\mathbf{MP}|^2}dS_P. \tag{1}$$

The quantities cos α, cos β, and |MP| are found from the formulas [1]

$$\cos\alpha = \frac{(\mathbf{N}_M,\ \mathbf{MP})}{|\mathbf{N}_M|\ |\mathbf{MP}|},\ \cos\beta = -\frac{(\mathbf{N}_P,\ \mathbf{MP})}{|\mathbf{N}_P|\ |\mathbf{MP}|}, \tag{2}$$

$$|\mathbf{MP}| = (\mathbf{MP},\ \mathbf{MP})^{1/2}, \tag{3}$$

where N_M, N_P are the vectors of the normals to the areas dS_M, dS_P.

Consider the case when dS_M and dS_P belong to surfaces of revolution S_M and S_P. Suppose that $S_M(S_P)$ is formed by revolution around the axis $Z_1(Z_2)$ of some curve in the plane $X_1O_1Z_1$ $(X_2O_2Z_2)$ of the rectangular Cartesian coordinate system $O_1X_1Y_1Z_1$ $(O_2X_2Y_2Z_2)$.

Introducing the spherical coordinates R, θ, φ, let $M = M(R(\theta), \theta, \varphi) = M(\theta, \varphi)$ be the radius vector of the point M. Then $N_M = M_\theta \times M_\varphi$, where M_θ, M_φ are vectors directed along the tangents to the coordinate lines φ = const and θ = const [2]. The projections of the vectors M, M_θ, M_φ, and N_M on the axes of the system $O_1X_1Y_1Z_1$ are given in Table 1. Knowing the projection N_M, it is simple to find $|N_M|$:

All-Union Scientific-Research Institute of Metallurgical Thermoengineering, Sverdlovsk.
Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 50, No. 4, pp. 640-645, April, 1986. Original article submitted January 9, 1985.

