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PRODUCTION OF COATINGS FROM POWDER MATERIALS WITH THE USE OF A SHORT ARGON ARC. 2. HEAT FLUX FROM THE PLASMA TO A MACROPARTICLE

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The heat flux to a metal particle in the plasma of a short argon arc of atmospheric pressure in depositing metallurgical coatings has been calculated. The limiting approximations of a continuum and free-molecular flow yield comparable results (about $6 \cdot 10^8$ W/m^2). The radiant-flux density has been evaluated. It has been shown that the heating of macroparticles is determined mainly by the conductive mechanism of energy transfer.

The results obtained in [1] demonstrate a substantial improvement of the efficiency of plasma spraying with powder materials using a short argon arc as compared to the cases where traditional methods are used. The development of the technology proposed necessitates a more detailed consideration of the degree of heating of macroparticles and determination of the reliability of the data obtained on the basis of other approaches.

In [1, 2], it has been shown that traditional pyrometric methods are inapplicable to studying the heating of powders in a short argon arc. This is attributed to the fact that direct observation of the particle surface in the flow is impossible because of both the high temperature of the argon plasma and the intense ablation of the macroparticle, resulting in a vapor shell around it. The original method proposed by the authors for determination of the size of particles in a plasma flow is based on the observation of their diffraction images formed by the shadowing of a laser beam. The density of the heat flux to a particle was found from the experimentally determined removal of its mass in motion to the product surface in a plasma formation with a measured temperature field. The regime of the plasma unit [1] ensured generation of a laminar plasma flow (Re ~ 10). The occurrence of an appreciable turbulization of the flow near the macroparticle surface was highly improbable. In this connection, it was difficult to expect a substantial destruction of it by mechanisms other than evaporation, for example, by removal of the small-droplet phase. Consequently, in the algorithm developed for calculation of the particle temperature, we considered the removal of a substance just by evaporation.

Procedures for calculating the heat fluxes to a macroparticle for different flow models determined by the value of the Knudsen number Kn = l/L have been proposed in [3–8]. However, using the value of Kn, it is difficult to reliably separate different regimes of flow about particles, which results in disagreement between the calculated characteristics and the characteristics realized in the plasma formation. At the same time, it should be noted that in [6] there are errors in determining the components of the heat flux.

In this work, we have calculated the densities of the heat flux to a particle in the plasma of a short argon arc using different approaches. The radiant energy flux has also been considered in addition to the conductive flux.

In considering the regime of a continuum where the Knudsen number is very small, one employs the approach based on the Navier–Stokes equations and the Fourier heat conduction law with boundary conditions which disregard a possible temperature jump near the surface of the macroparticle. For this case, in [7] the density of the heat flux to a spherical particle is calculated as

$$Q_c = \frac{S_\infty - S_s}{R}, \quad (1)$$

where

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$$S = \int_{T_r}^{T} \lambda\,(T)\,dT\,, \tag{2}$$

and T_r is the temperature of the reference point selected arbitrarily. Using the data of [9] on the thermal conductivity of an argon plasma, we obtain that the heat flux to a particle with a radius of $4\cdot10^{-5}$ m is $Q_c = 7.5\cdot10^8$ W/m^2 in the short argon arc.

When the Kn number is not negligibly small, consideration is given to the regime of sliding flow or a temperature jump. Using the approach based on a jump in the thermal-conductivity potential, it has been found in [8] for the range $10^{-3} < \mathrm{Kn} < 10^{-1}$ that the heat flux onto a particle can be represented in the form

$$Q_{t.j} = \alpha Q_c = \frac{Q_c}{1 + \left(\frac{\gamma}{\gamma + 1}\right)\left(\frac{4}{\mathrm{Pr}_s}\right)\mathrm{Kn}^*}\,, \tag{3}$$

where γ is specific-heat ratio and the effective number $\mathrm{Kn}^* = l^*/2R$ is determined in terms of the mean free path of plasma particles in a temperature range of T_s to T:

$$l^* = \frac{2\,\langle\lambda\rangle}{\rho_{g,s} V_{Ts}\,\langle c_p\rangle}\,\mathrm{Pr}_s\,. \tag{4}$$

Here $\mathrm{Pr} = \mu C_p/\lambda$. The average values of the thermal conductivity and the heat capacity of the plasma are calculated as $\langle\lambda\rangle = (S_g - S_s)/(T_g - T_s)$ and $\langle C_p\rangle = (H_g - H_s)/(T_g - T_s)$. The surface temperature differs from the plasma temperature because of the Knudsen effect (the difference $T_g - T_s$ represents a temperature jump on the particle surface).

By employing the iteration procedure (see [8]) we can show that for the particle with $R = 4\cdot10^{-5}$ we have $l^* = 3\cdot10^{-6}$ m, Kn = 0.0375, T_g = 11,400 K, and $\alpha = 0.88$ under the considered conditions of a short argon arc. Thus, in the case of flow with a temperature jump the heat-flux density will be $Q_{t.j} = 6.6\cdot10^8$ W/m^2.

To describe the interaction of the macroparticles with the plasma flow at large Knudsen numbers it is necessary to simultaneously solve the Boltzmann equations for the velocity-distribution functions of molecules, ions, and electrons and the Poisson equation for electrostatic potential. From an analysis of the effective interaction potential it follows that in the case of weak ($R < R_D$) and strong ($R >> R_D$) plasma shielding the cross sections of collisions of the ions and electrons with the macroparticle depend just on the potential of its surface φ_s and not on the spatial distribution in the plasma $\varphi(r)$. This enables us to employ the velocity-distribution functions in an undisturbed plasma at a large distance from the macroparticle in computing the flows in the free-molecular regime.

In collisions of the plasma atoms, ions, and electrons with the surface of a heated particle, the energy is transferred as a result of their scattering on the surface, recombination of the electrons, and neutralization of the ions. In the case of a molten metal macroparticle the accommodation coefficient of the gases is close to unity and the efficiency of recombination and neutralization of the charged particles is very high [10]; therefore, in what follows we omit the corresponding coefficients.

Atoms, ions, and electrons moving toward the macroparticle at the external boundary of the space-charge layer and emitted by the boundary surface have the Maxwellian velocity-distribution functions

$$f_n^{\pm}(V) = N_n^{\pm}\left(\frac{m_n}{2\pi k T_n^{\pm}}\right)^{3/2} \exp\left(-\frac{m_n V^2}{2kT_n^{\pm}}\right). \tag{5}$$

The distribution functions of the incoming plasma particles f_n^+ (n = a, i, e) contain the parameters of an undisturbed plasma flow $T_n^+ = T$ and $N_n^+ = N_n$. The distribution functions of heavy plasma particles reflected by the surface f_n^- = (n = a, i) and of emitted electrons (n = e) are characterized by the macroparticle-surface temperature $T_n^- = T_s$. The densities of the ions and the atoms N_n^- (n = a, i) are determined from the condition of absence of their accumulation on the surface, i.e., $N^{-}_{a,i} = \sqrt{T/T_s}\, N^{+}_{a,i}$. The flow of thermoelectrons which are emitted by the macroparticle is found from the Richardson formula (for bronze we assume that $\Phi_e = 4.47$ eV):

$$J^{-}_{e} = \frac{A_R}{e}\, T_s^2 \exp\left(-\frac{\Phi_e}{kT_s}\right). \tag{6}$$

The coordinate system is selected in the following manner. At an arbitrary point of a spherical surface, the z axis is directed toward the center of the macroparticle while the x axis is directed tangentially to its surface. Consequently, the densities of the heat fluxes transferred by plasma particles can be represented as

$$Q^{+}_{n} = \int_{-\infty}^{+\infty} dV_x \int_{-\infty}^{+\infty} dV_y \int_{V_{zn}}^{+\infty} V_z \left[\frac{1}{2} m_n (V_x^2 + V_y^2 + V_z^2) + \delta_n e\varphi_f + W_n\right] f^{+}_{n}(V)\, dV_z\, . \tag{7}$$

In traversing the space-charge layer, the ions gain additional energy while the electrons lose energy $-e\varphi_f$; consequently, $\delta_a = 0$, $\delta_i = 1$, and $\delta_e = 1$. The lower limit of integration of V_{zn} for dV_z is equal to zero for the atoms and the ions (n = a, i) since the latter will not feel the presence of the attracting field because of the small thickness of the shielding layer. For the electrons we have $V_{ze} = (-2e\varphi_f/m_e)^{1/2}$ since when $V_z < V_{ze}$ they cannot reach the surface because of the presence of a negative floating potential in it. The charged plasma particles transfer the energy of their charge state W_n in addition to the kinetic energy. In collision with the surface, the electrons arrive, on the average, at the Fermi level and transfer the energy $W_e = \Phi_e$ to the metal lattice. When the ions are neutralized at the surface, the effective ionization energy $W_i = E - \Phi_e$ is released (E = 15.755 eV for argon).

Thus, we can obtain the following expressions for the components of the heat flux [4–6]: for the atoms

$$Q_a = Q^{+}_{a} - Q^{-}_{a} = J^{+}_{a}(2kT - 2kT_s)\, , \quad J^{+}_{a} = \frac{1}{4} N_a V_{Ta}\, , \tag{8}$$

where J^{+}_{a} is the atomic flow incident on the macroparticle and $V_{Ta} = \sqrt{8kT/\pi m_a}$ is their average thermal velocity in the plasma; for the ions

$$Q_i = Q^{+}_{i} - Q^{-}_{i} = J^{+}_{i}(2kT - e\varphi_f + (E - \Phi_e) - 2kT_s)\, , \quad J^{+}_{i} = \frac{1}{4} N_i V_{Ti}\, , \tag{9}$$

where J^{+}_{i} is the ionic flow incident on the macroparticle and $V_{Ti} = V_{Ta}$; for the electrons

$$Q_e = Q^{+}_{e} - Q^{-}_{e} = J^{+}_{e}(2kT + \Phi_e) - J^{-}_{e}(2kT_s + \Phi_e)\, , \quad J^{+}_{e} = \frac{1}{4} N_e V_{Te} \exp\left(\frac{e\varphi_f}{kT}\right), \tag{10}$$

where J^{+}_{e} is the flow of plasma electrons incident on the macroparticle, $V_{Te} = \sqrt{8kT/\pi m_e}$, and it is taken into account that the energy Φ_e is additionally consumed by the emission of thermoelectrons.

The heat flux from the plasma to a particle strongly depends on its charge state, i.e., the thermal and charge states of the plasma and the body turn out to be related. In the case of the Maxwellian plasma equilibrium at infinity where the electric field is shielded in the boundary layer of the order of a Debye radius that is much smaller than the mean free paths of the plasma particles l_n, we can separate the electrodynamic and thermal problems.

The time of the process of charging of a macroparticle is usually much shorter than the times of thermal and hydrodynamic processes. Therefore, we can describe the interaction of the macroparticle with the plasma in the quasistationary approximation for the equilibrium (floating) potential $\varphi_s = \varphi_f$.

The floating potential of the macroparticle surface is determined using the equation of balance of the charge flows of the ions and electrons from the plasma and of thermoelectrons

$$J^{+}_{e} - J^{+}_{i} - J^{-}_{e} = 0\, ; \tag{11}$$

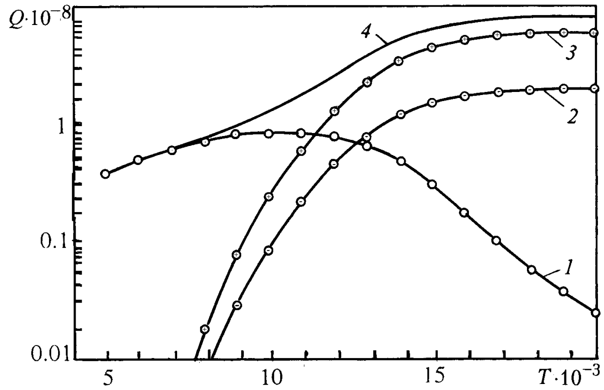

Fig. 1. Temperature dependence of the density of the heat flux from an atmospheric-pressure argon plasma to a macroparticle in the approximation of free-molecular flow: 1) Q_a; 2) Q_e; 3) Q_i; 4) $Q_{f.m}$. Q, W/m^2; T, K.

then

$$\varphi_f = \frac{kT}{e} \ln\left(\sqrt{\frac{m_e}{m_i}} + \frac{4\bar{J}_e}{N_e V_{Te}}\right). \tag{12}$$

For the argon plasma of atmospheric pressure at T = 15,000 K the contribution of thermoemission to the process of charging of a bronze particle becomes appreciable when $T_s > 3500$ K. At T_s = 2800 K [1], the floating potential is φ_f = –7.25 V ($e\varphi_f/kT = -5.6$). For the charge of a spherical particle we obtain $q = Ze = 4\pi\varepsilon_0 R\varphi_f$ (in our case $R = 4{\cdot}10^{-5}$; consequently, $Z = -2{\cdot}10^5$).

Thus, in the approximation of free-molecular flow, the total heat flux to a metal particle in the argon plasma with a temperature of 15,000 K and a concentration of electrons of $2{\cdot}10^{23}$ m^{-3} [11] is found as

$$Q_{f.m} = Q_a + Q_i + Q_e = 6.5{\cdot}10^8 \text{ W/m}^2 , \tag{13}$$

where Q_a, Q_i, and Q_e are equal to $0.2{\cdot}10^8$, $4.7{\cdot}10^8$, and $1.6{\cdot}10^8$ W/m^2 respectively, i.e., the main contribution to the heating of the particle is made by the ions. The results of calculation of the density of the heat flux to the particle as a function of the temperature of the atmospheric-pressure argon plasma are presented in Fig. 1.

The radiant flux to the macroparticle in the short argon arc was determined in the approximation of an optically thin plasma. In this case the expression for the specific heat-flux power has the form [12]

$$B_r = \frac{4\sigma T^4}{L_P} , \quad L_P = \frac{\sigma T^4}{\int_0^\infty \kappa_\nu S_P d\nu} , \tag{14}$$

where κ_ν is the absorption coefficient of the plasma and S_P is the Planck function. The values of the Planckian average L_P for the argon plasma can be found in [12] (L_P = 0.13 m at p = 1 atm and T = 15,000 K).

The corresponding integration with the use of the temperature fields measured in the arc channel yields Q_r = $3{\cdot}10^6$ W/m^2 for the density of the heat flux to the particle, which is two orders of magnitude lower than the density of the conductive heat flux.

CONCLUSIONS

1. The heating of macroparticles in the plasma of a short argon arc is determined mainly by the mechanism of energy transfer.

2. Different methods of calculation of the heat flux within methodological errors yield comparable results:

$$Q_c = 7.5 \cdot 10^8 \ \text{W/m}^2 ; \quad Q_{t.j} = 6.6 \cdot 10^8 \ \text{W/m}^2 ; \quad Q_{f.m} = 6.5 \cdot 10^8 \ \text{W/m}^2 .$$

At the same time, they are in good agreement with the value $Q = 4.3 \cdot 10^8$ W/m^2 obtained experimentally [1, 2].

3. To estimate the value of the heat flux from an atmospheric-pressure argon plasma at $T \sim 15{,}000$ K to a macroparticle, for example, in selecting the technological regime of deposition of coatings, one can employ the simplest procedures corresponding to the regimes of flow with large Knudsen numbers.

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NOTATION

Re, Reynolds number; Kn, Knudsen number; Q, heat-flux density; p, pressure; T, temperature of the plasma; T_s, temperature of the macroparticle surface; S, thermal-conductivity potential; λ, thermal conductivity of the plasma; C_p, specific heat at constant pressure; R, radius of a macroparticle; ρ, density; H, enthalpy; δ, dimensionless parameter; V, velocity; f, velocity-distribution function of plasma particles; l, mean free path; L, characteristic dimension of the body; m, mass; N, concentration; W, energy of the charge state of an electron or an ion; E, ionization potential of the gas; q, particle charge; Z, particle charge in the units of electron charge; Pr, Prandtl number; μ, plasma viscosity; Φ_e, electronic work on escaping from the macroparticle material; φ, potential; α, parameter characterizing the Knudsen effect; J, plasma-particle fluxes; B_r, specific radiant-flux power; ν, radiation frequency; R_D, Debye radius; $A_R = 1.2 \cdot 10^6$ A$\cdot$m$^{-2}\cdot$K^{-2}, Richardson constant; $e = 1.6 \cdot 10^{-19}$ C, electron charge; k = Boltzmann constant; ε_0, electric constant; σ, Stefan–Boltzmann constant. Sub- and superscripts: x, y, z, coordinates; a, atom; i, ion; e, electron; n = a, i, and e; s, surface; f, floating; c, continuum; t.j, temperature jump; f.m, free molecular; r, radiant; P, Planck; D, Debye; R, Richardson; g, plasma; +, in the direction to a macroparticle; –, in the direction from a macroparticle; *, effective.

REFERENCES

1. V. D. Shimanovich, I. P. Smyaglikov, and A. I. Zolotovskii, *Inzh.-Fiz. Zh.*, **75**, No. 6, 8–13 (2002).
2. D. V. Bagino, A. F. Ilyushenko, V. D. Shimanovich, I. P. Smyaglikov, and A. I. Zolotovskii, in: *Progress in Plasma Processing of Materials*, Wallingford, New York (1997), pp. 771–778.
3. A. G. Gnedovets and A. A. Uglov, *Teplofiz. Vys. Temp.*, **29**, No. 6, 1184–1191 (1991).
4. X. Chen and P. He, *Plasma Chem. Plasma Process.*, **6**, No. 4, 313–333 (1986).
5. N. N. Rykalin, A. A. Uglov, Yu. N. Lokhov, and A. G. Gnedovets, *Teplofiz. Vys. Temp.*, **19**, No. 3, 557–565 (1981).
6. A. P. Kuryshev and V. V. Sakhin, *Zh. Tekh. Fiz.*, **71**, Issue 11, 106–109 (2001).
7. X. Chen and E. Pfender, *Plasma Chem. Plasma Process.*, **2**, No. 2, 185–212 (1982).
8. X. Chen and E. Pfender, *Plasma Chem. Plasma Process.*, **3**, No. 1, 97–113 (1983).
9. S. V. Dresvin (ed.), *Physics and Technology of a Low-Temperature Plasma* [in Russian], Moscow (1972).
10. V. V. Gubin, N. P. Reznichenko, and V. A. Shuvalov, *Prikl. Mekh. Tekh. Fiz.*, No. 6, 115 (1979).
11. A. I. Zolotovskii, I. P. Smyaglikov, and V. D. Shimanovich, *Zh. Prikl. Spektrosk.*, **69**, No. 3, 402–405 (2002).
12. S. S. Katsnelson and G. A. Koval'skaya, *Thermophysical and Optical Properties of an Argon Plasma* [in Russian], Novosibirsk (1985).