INFLUENCE OF PARTICLE MATERIAL EVAPORATION ON HEAT TRANSFER FROM PLASMA TO FINE-SIZED PARTICLES IN PLASMA SPRAYING

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Fundamental mechanisms of heat transfer from low-temperature atmospheric pressure plasma to the fine-sized particle are studied under plasma spraying conditions. Analysis of the physical processes occurring within the Knudsen layer near the particle surface resulted in derivation of analytical expressions for evaluating the densities of electron and ion currents from plasma to the particle surface, the potential drop between plasma and the particle, as well as electron and ion components of a heat flux from plasma to the particle. The near-surface plasma is assumed to be non-isothermal and multi-component to contain atoms and ions of the evaporated particle material along with the plasma gas particles. The method of determining parameters of the near-surface plasma at the external boundary of the Knudsen layer, which appear in the derived analytical expressions, is proposed. In a wide range of temperature of the non-disturbed argon plasma and temperature of the aluminum particle surface the numerical analysis of plasma composition, electron temperature and temperature of heavy particles of the near-surface plasma is performed, and the corresponding heat fluxes to the sprayed particle are evaluated. The near-surface plasma which is rendered multi-component due to evaporation of the particle in a diffusion mode is shown to substantially influence the total heat flux from plasma to the particle.

Consider the main mechanisms of heat transfer at atmospheric pressure from a plasma flow of an atomic (inert) gas to a fine-sized particle under plasma spraying conditions. The particle being sprayed is assumed to be spherical, its radius a substantially exceeding the mean free path of plasma particles. Under such conditions, the energy balance at the particle surface can be represented as follows:

$$-\left(\chi_m \frac{\partial T_m}{\partial r}\right)\Bigg|_{r=a} = Q_c + Q_r + Q_i + Q_e - Q_v, \qquad (1)$$

where χ_m is the thermal conductivity, $T_m(r)$ is the temperature field inside the particle, Q_c is the convective-conductive heat flux, Q_r is the thermal radiation heat flux, Q_i and Q_e denote the heat fluxes, that are brought onto the particle surface by plasma ions and electrons, and Q_v is the heat flux carried away by the vapor stream. At a high temperature and a high ionization degree of the plasma, its ion and electron components contribute greatly to the above energy balance. Due to the particle material evaporation, the near-surface plasma is rendered multicomponent to contain atoms and ions of the evaporated material along with the plasma gas particles.

To describe the processes within the near-surface plasma and to analyze the Q_i and Q_e heat fluxes, we use the method [1] suggesting that the plasma surrounding a particle can be divided into several zones. The first one adjoining the particle surface is the space charge layer, where the plasma quasi-neutrality condition is not satisfied and the major part of the potential drop between the plasma and the particle is formed. The second zone is the ionization region of a non-isothermal quasi-neutral plasma (presheath), where the charged particles are generated, originating from plasma gas atoms and evaporated atoms of the material ionized by plasma electrons. The Knudsen layer extends from the surface and spans several mean free paths of the plasma particles, its boundary verging on the hydrodynamic flow zone. The latter region can be conditionally divided, in turn, into two zones. They are the thermal boundary layer, wherein the electron temperature T_e and the heavy particle temperature T are leveled, and the undisturbed plasma flow region (Fig. 1).

Under the assumption that the total electric current between the plasma and a particle is zero, the electron and ion flows to the surface of the particle can be defined as

$$j_e - \sum_{\alpha=g,\,m} j_{i\,\alpha} = 0\,. \qquad (2)$$

Here, j_e is the current density of plasma electrons reaching the particle surface, $j_{i\alpha}$ is the current density of ions of the α kind, ($\alpha = g$ indicates the plasma gas, and $\alpha = m$ corresponds to ions of the particle material). The electron current density can be calculated using the known expression

$$j_e = \frac{1}{4}\, e\, n_e^0 \sqrt{\frac{8kT_e^0}{\pi m_e}} \exp\left(-\frac{e\,\varphi^0}{kT_e^0}\right), \qquad (3)$$

where e and m_e are the electron charge and mass, n_e^0 and T_e^0 denote the electron concentration and temperature at the outer boundary of the Knudsen layer, k is the Boltzmann constant, and $\varphi^0 > 0$ is the potential drop between plasma and the particle. The expressions for ion currents to the particle surface are described by [1]

$$j_{i\,\alpha} = e\,n_{i\,\alpha}^0 \exp\left(-\frac{1}{2}\right) \times$$

$$\times \sqrt{kT_e^0 \frac{\sum\limits_{\alpha=g,\,m} \left(1 + T^0/T_e^0\right)\, n_{i\,\alpha}^0}{\sum\limits_{\alpha=g,\,m} M_\alpha\, n_{i\,\alpha}^0}}\,, \qquad \alpha = g,\, m\,, \tag{4}$$

where $n_{i\,\alpha}^0$, T^0 are the ion concentrations and temperature of heavy particles at the Knudsen layer boundary and M_α is the mass of a heavy particle of the α kind. Equations (3) and (4) are substituted in (2) to obtain

$$\varphi^0 = \bar{\varphi} + \frac{1}{2}\frac{kT_e^0}{e}\,;$$

$$\varphi = \frac{kT_e^0}{e} \ln \sqrt{\frac{\sum\limits_{\alpha=g,\,m} M_\alpha n_{i\alpha}^0}{2\pi m_e \sum\limits_{\alpha=g,\,m} \left(1 + T^0/T_e^0\right)\, n_{i\alpha}^0}}\,, \tag{5}$$

where $\bar{\varphi}$ is the potential at the boundary between the presheath and the space charge layer (see Fig. 1).

In the diffusive mode of the particle material evaporation, the composition of a near-surface multicomponent plasma can be defined using the Saha equations, quasi-neutrality condition, and Dalton's law and assuming that the partial pressure of heavy particles of the evaporated material at the outer boundary of the Knudsen layer is equal to the saturated vapor pressure corresponding to the given surface temperature. The electron temperature T_e^0 entering this system of equations can be evaluated by solving the energy balance equation for the electron component of plasma within the thermal boundary layer and the equation for the temperature of heavy particles:

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \chi_e \frac{\partial T_e}{\partial r}\right) - \beta\,(T_e - T) = 0,$$

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \bar{\chi} \frac{\partial T}{\partial r}\right) + \beta\,(T_e - T) = 0. \tag{6}$$

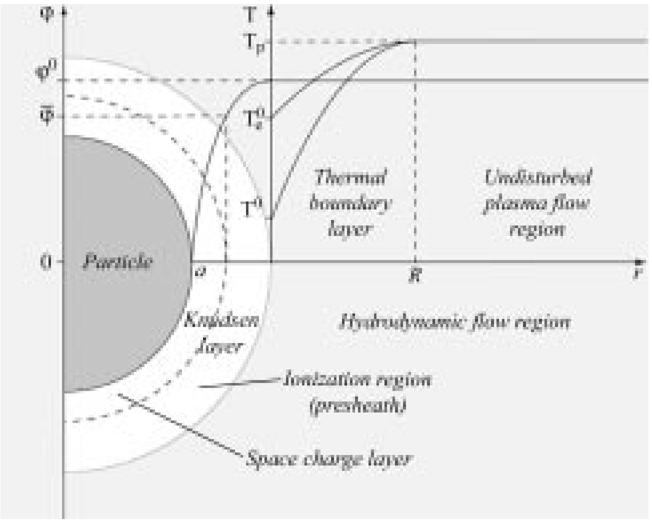

Fig. 1. Near-surface plasma structure

Here, χ_e is the electron thermal conductivity, $\bar{\chi}$ is the thermal conductivity of heavy particles (atoms and ions), and β is the coefficient of heat exchange between electrons and heavy particles [2]. Considering that the Knudsen layer thickness is substantially smaller than the particle radius a, this system of equations can be solved in the interval $a \le r \le R$, where R is the outer radius of the thermal boundary layer (see Fig. 1). The boundary conditions at the border between the hydrodynamic region and the Knudsen layer are specified as

$$\left(\chi_e \frac{\partial T_e}{\partial r}\right)\bigg|_{r=a} = j_e\left(\varphi^0 + \frac{2kT_e^0}{e}\right) +$$

$$+ \sum_{\alpha=g,\,m} j_{i\,\alpha}\left(\frac{kT_e^0}{2e} + U_\alpha\right), \qquad T|_{r=a} = T_{ms}, \tag{7}$$

where U_α are the corresponding ionization potentials and T_{ms} is the particle surface temperature. The boundary condition at $r = R$ is set as the equality of the electron and heavy particle temperatures to the temperature of undisturbed plasma T_p.

Fig. 2 shows the dependence of T_e^0 on T_p at different values of T_{ms} for an aluminum particle (a = 30 μm) in the argon plasma. The results obtained indicate a substantial influence of readily ionized metal vapor atoms rendering the plasma to be multicomponent at the electron temperature and the near-surface plasma ionization degree. With T_{ms} rising and the vapor particle concentration consequently increasing, the electron temperature drop at the Knudsen layer boundary becomes more evident, as opposed to the growth of n_e^0.

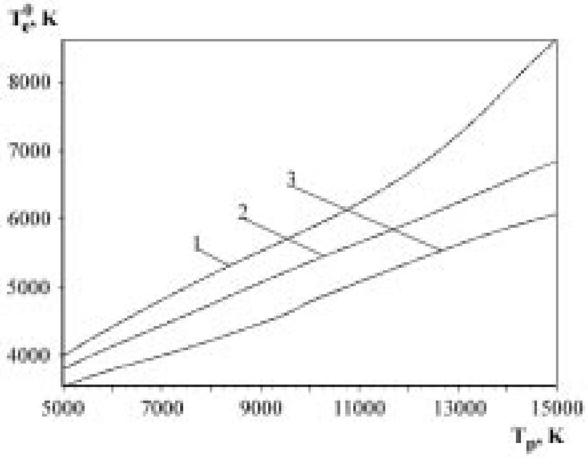

Fig. 2. Plasma electron temperature at the Knudsen layer boundary: *1* — T_{ms} = 2000 K; *2* — 2200; *3* — 2500

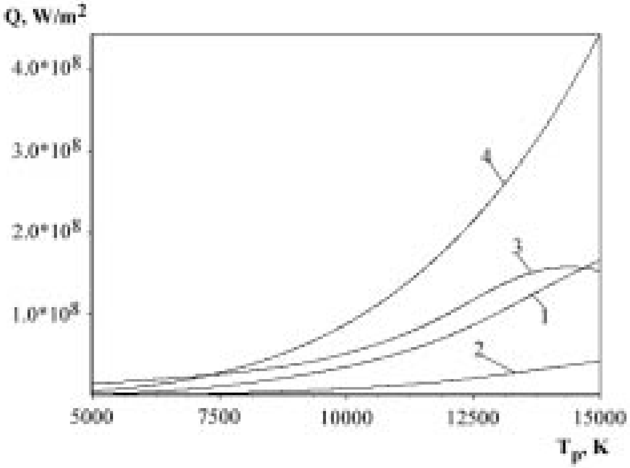

Fig. 3. Total heat flux components for an aluminum particle (a = 30 μm, T_{ms} = 2000 K): *1* — Q_i, *2* — Q_e, *3* — Q_c, *4* — Q_r

The following expressions can be used to evaluate Q_e and Q_i:

$$Q_e = j_e \left(\varphi^0 + \frac{2\,k T_e^0}{e} + \varphi_m\right) ,$$

$$Q_i = \sum_{\alpha=g,\,m} j_{i\,\alpha} (\bar{\varphi} + U_\alpha - \varphi_m) , \qquad (8)$$

where φ_m is the electron work function for a given particle material.

In Fig. 3, the computed dependences of the Q_e, Q_i heat fluxes on the temperature of the undisturbed argon plasma can be seen. The calculation of Q_c and Q_r is pursued following the method described in [1]. The data obtained show that, at higher temperatures of the outer plasma, T_p, the ion and electron components of the heat flux may contribute significantly to the total heat flux from plasma to the sprayed particle surface.

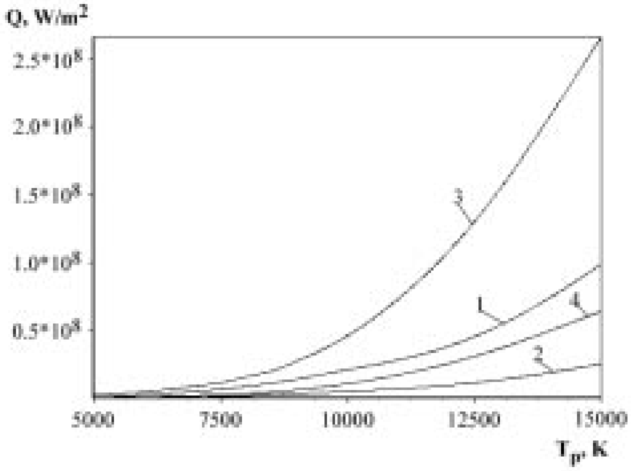

Fig. 4. Ion (*1, 3*) and electron (*2, 4*) heat fluxes to an aluminum particle (a = 30 μm): *1, 2* — T_{ms} = 1800 K; *3, 4* — 2400 K

The influence of the plasma composition, resulting from the presence of atoms and ions of the evaporated material, on Q_e and Q_i is illustrated in Fig. 4. At T_{ms} = 1800 K, the near-surface plasma contains a negligible quantity of metal ions, therefore the mentioned heat fluxes are formed by the charged particles of argon. The vapor partial pressure in the near-surface plasma turns out to be much higher at T_{ms} = 2400 K, implying that plasma becomes substantially multicomponent, which results in higher values of the Q_e and Q_i heat fluxes at $T_p > 10000$ K. This appears to be the case due to the fact that, despite the T_e^0 drops with respect to T_p (see Fig. 2), the growth of the concentration of readily ionized metal atoms with T_{ms} rising leads to the increase in the concentration of charged particles, which determines the considered heat fluxes according to (3), (4), and (8).

1. *Krivtsun I.V.* // Avtom. Svarka. — 2001. — **3**. — P. 3—10.

2. *Zhdanov V.M.* Transport Phenomena in Multicomponent Plasma. — Moscow: Energoizdat, 1982 (in Russian).

3. *Borisov Yu.S., Krivtsun I.V., Muzhichenko A.F. et al.* // Avtom. Svarka. — 2000. — **12**. — P. 42—51.

ПОТІК ІЗ ПЛАЗМИ В ДРІБНОДИСПЕРСНУ ЧАСТИНКУ ПРИ ПЛАЗМОВОМУ НАПИЛЕННІ

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Резюме

Розглянуто основні механізми теплового впливу низькотемпературної плазми атмосферного тиску на частинку дисперсного матеріалу в умовах плазмового напилення. На основі аналізу фізичних процесів, що мають місце в кнудсенівському шарі поблизу поверхні частинки, що напилюється, отримано аналітичні вирази для розрахунку густини електронного та іонного струмів із плазми на поверхню частинки, падіння потенціалу між плазмою й частинкою, а також електронної та іонної складових теплового потоку із плазми в частинку. Вважається, що приповерхнева плазма є неізотермічною й багатокомпонентною та містить, поряд з частинками плазмоутворюючого газу, атоми й іони матеріалу частинки, що випарувався. Запропоновано метод для визначення параметрів такої плазми на зовнішній межі кнудсенівського шару, які входять в отримані аналітичні вирази. В широкому діапазоні зміни температури незбуреної плазми (Ar) та температури поверхні частинки (Al) проведено чисельний аналіз складу, температури електронів та важкої компоненти плазми, обчислено відповідні значення теплових потоків у частинку. Показано істотний вплив багатокомпонентності приповерхневої плазми, що формується при випаровуванні в дифузійному режимі частинки, яку напилюють, на результуючий тепловий потік із плазми в частинку.