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Calculation of Particles Flow Temperature during Plasma Spraying of Mixture Consisting of Self-Fluxing Powder and Ceramics

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Abstract. Plasma spraying is one of the most effective methods allowing both to restore worn surfaces of parts and create wear-resistant coatings on new parts aiming the increase of their service life. Properties of the produced coatings depend on number of parameters, such as a plasma temperature, a chemical and fractional composition of the sprayed mixture, a distance from a plasma torch to the surface of a part, etc. Mathematical modeling of the process can significantly reduce the cost of processing of technological modes and is widely used at present for a calculation of technological parameters. The paper is devoted to mathematical simulation aiming to determine an effect of the injected ceramics content on the change in a temperature of a particles flow, as well as finding the modes in which the particles of high-temperature ceramics will be in the liquid state when they are deposited on the surface of a product. A mathematical model of particles heating in plasma has been formulated and a system of equations has been compiled. The system of equations has been solved numerically in Mathcad by a standard procedure using the Rkadapt function. Calculations have been carried out for a volume concentration of Al_2O_3 ceramics in a mixture from 5 to 50 % and for a plasma temperature at the exit from the plasma torch in the range from 6000 to 10000 K. Calculations have shown that the concentration of ceramics does not significantly affect the temperature of a mixture. The temperature of the particles depends to a large extent on the temperature of the plasma and the diameter of particles. It has been determined that for the entire range of calculated values the temperature of the self-fluxing powder in contact with the substrate exceeds a melting point. Fractional particle size has a strong effect on the temperature of particles at the moment of contact with the substrate. The dependences of a temperature of the ceramic phase on the particle size at different concentrations and plasma temperature have been determined. Analysis of the coatings microstructures has shown a good correlation with the results of the calculation.

Keywords: plasma spraying, ceramic phase, mathematical modeling, temperature of particles, microstructure

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Расчет температуры потока частиц при плазменном напылении смеси самофлюсующегося порошка и керамики

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Реферат. Плазменное напыление является одним из эффективных методов, позволяющих как восстанавливать изношенные поверхности деталей, так и создавать износостойкие покрытия на новых деталях с целью увеличения срока

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их службы. Свойства создаваемых покрытий зависят от ряда параметров, таких как температура плазмы, химический и фракционный составы напыляемой смеси, расстояние от плазмотрона до поверхности и др. Математическое моделирование процесса позволяет значительно снизить стоимость отработки технологических режимов и широко используется в настоящее время для расчета технологических параметров. В настоящей работе была поставлена цель проведения математического моделирования для определения влияния содержания вводимой керамики на изменение температуры потока частиц, а также нахождения режима, при котором частицы высокотемпературной керамики будут в жидком состоянии при осаждении на поверхность изделия. Сформулирована математическая модель нагрева частиц в плазме и составлена система уравнений, которая решалась численно в пакете MathCad стандартной процедурой с использованием функции Rkadapt. Расчеты проводились для объемной концентрации керамики Al_2O_3 в смеси от 5 до 50 % и для температуры плазмы на выходе из плазмотрона в интервале от 6000 до 10000 K. Вычисления показали, что концентрация керамики не влияет значительно на температуру смеси. Температура частиц в большей мере зависит от температуры плазмы. Определено, что для всего диапазона расчетных величин температура самофлюсующегося порошка при контакте с подложкой превышает температуру плавления. Фракционный размер частиц оказывает сильное влияние на температуру частиц в момент соприкосновения с подложкой. Определены зависимости температуры керамической фазы от размера частиц при различных концентрациях и температуре плазмы. Анализ микроструктур покрытий показал хорошую корреляцию с результатами расчета.

Ключевые слова: плазменное напыление, керамическая фаза, математическое моделирование, температура частиц, микроструктура

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Increasing the wear resistance of working surfaces is an important scientific and practical task for surface engineering. One of the methods of the wear resistance increase of steel surfaces is plasma spraying of self-fluxing Nickel-chromium-based powder [1]. From the point of view of reducing of the coating cost while maintaining its high wear resistance, the practical interest is the introduction into the sprayed mixture of ceramic powder based on aluminum oxide [2].

The properties of the coatings created depend on several parameters such as plasma temperature, chemical and fractional composition of the sprayed mixture, the distance from the plasma torch to the part's surface etc. Experimental determination of optimal regimes of plasma spraying process requires big expenditures of time and money, so mathematical modeling is widely used to save time and money.

Mathematical simulation and computer experiments can significantly reduce the cost of the processing technological modes and determine optimal spraying parameters. For example, the simulation of the main parameters of plasma arc burner: non-equilibrium thermodynamic and chemical models of plasma formation, energy transfer during plasma motion, boundary conditions, etc. was performed [3].

It is known from practice that the deformation of particles and their cooling significantly affects the adhesion of the deposited layer to the base and the occurrence of stresses. The conducted computer simulation allowed determining the optimal temperature conditions for the formation of high-quality coatings [4].

Various programs are developed to simulate the plasma spraying process. Thus, in the work [5] the efficiency of the IPS Virtual Point program developed in Fraunhofer-Chalmers Centre for calculating the thickness of the plasma coating on parts for the automotive industry is considered. The possibility of application of this program for the analysis of the thickness of the layer deposited is shown.

A model for assessing the thickness non-uniformity of the layer deposited during plasma spraying is presented in [6]. On the basis of the developed model a theoretical study of the influence of process parameters on the cross-sectional character of the layer is carried out.

To estimate the influence of the modulation mode of the plasma torch electrical parameters on the plasma spraying process, a mathematical model was developed. This model allowed optimizing parameters of the plasma torch and the deposition process. Using the model it was possible to predict process parameters when a strong and continuous coating on the part surface with good adhesion was formed [7]. The problems of mathematical modeling of different stages of the plasma spraying process are considered in [8–10], first of all, the process of formation of the structure and porosity of the coating.

Despite the large number of publications, mathematical simulations of plasma spraying process are of considerable interest, especially in relation to specific conditions, because there are no models that completely describe this process. For example, an important aspect is the analysis of changes in the temperature of the particles' flow in the presence of a ceramic phase, which is characterized by a high melting point.

So, to determine the influence of the volume fraction of ceramic powders in sprayed mixture on changes in the temperature of the particle flow it is advisable to carry out mathematical simulateon that allows you to choose the optimal modes of plasma spraying without conducting a large number of experiments.

In this paper, the purpose of mathematical simulation was set to determine the effect of the content of the injected ceramics on the change in the temperature of the particles flow, as well as finding the modes in which the particles of high-temperature ceramics will be in the liquid state when deposited on the surface of the product. Taking into account the complexity of the mathematical description of the real plasma spraying process, we introduce a number of simplifications.

1. The particles are uniformly distributed over the volume of the flow and there is no density stratification during the flight.
2. A mixture of powders is injected into the plasma jet at the plasma torch slice.
3. There is no change in the trajectory of the plasma jet and powder material.
4. Plasma properties do not change when the temperature decreases.

The mixture of the sprayed material consists of a self-fluxing nickel-chromium powder and aluminum oxide powder Al_2O_3. The diameter of the self-fluxing powders in the calculations adopted was equal to 100 μm and ceramic particles were in range from 25 to 100 μm. The distance from the plasma gun to the surface of part is 100 mm.

In the flow of plasma-forming gas (nitrogen), the speed of which is 47 m/s and the volume flow rate is 40 l/min, particles of self-fluxing Nickel-chromium powder are introduced with a mass flow rate of 5 kg/h. To improve the wear resistance, a ceramic powder based on aluminum oxide was injected into the self-fluxing powder. Calculations were carried out for the volume concentration of Al_2O_3 ceramics in a mixture of 5 to 50 % and for the plasma temperature at the exit from the plasma torch in the range of 6000 to 10000 K.

Equations for the change of particles' temperature and gas one taking into account convective heat exchange have the following form:

$$m_1 c_1 u \frac{dT_1}{dy} = \alpha F (T_3 - T_1); \quad (1)$$

$$m_2 c_2 u \frac{dT_2}{dy} = \alpha F (T_3 - T_2); \quad (2)$$

$$M c_3 u \frac{dT_3}{dy} = \alpha F \left[n_1 (T_1 - T_3) + n_2 (\mathrm{T}_2 - T_3) \right], \quad (3)$$

where m_1, m_2 – masses of particles; c_1, c_2 – specific heat capacity of materials; T_1, T_2 – temperature of particles; F – surface area of the particle; M, c_3, T_3 – mass flow, specific heat and temperature of the gas, correspondingly; α – coefficient of convective heat transfer; u – flow speed of gas and particles; y – distance from the nozzle exit of the plasma torch; n_1, n_2 – number of particles of self-fluxing alloy and ceramics that interact with the gas flow; subscripts 1, 2, 3 – devoted to self-fluxing powder, ceramic powder and gas, correspondingly.

The form of equations (1) and (2) is close to the equations given in [1]. Calculations for the particle velocity using the expressions given in [2] showed that the particle velocity does not differ from the gas flow velocity. The convective heat exchange coefficient α can be written as follows

$$\alpha = \frac{\lambda}{D} \mathrm{Nu},$$

where λ – thermal conductivity of the gas; D – diameter of particles; Nu – Nusselt number that determines the convective heat exchange of the particle surface with the gas flow around it.

In the case of a spherical particle flow by a uniform gas stream with constant properties it is possible, as in [2], to use known dependence of the Ranz – Marshall

$$\mathrm{Nu} = 2 + 0{,}6\,\mathrm{Re}^{0{,}5}\,\mathrm{Pr}^{0{,}33}.$$

Equations (1)–(3) can be simplified by substituting the values of mass and surface area of particles:

$$\frac{dT_1}{dy} = \frac{6\alpha}{c_1^* u D_1}(T_3 - T_1);$$

$$\frac{dT_2}{dy} = \frac{6\alpha}{c_2^* u D_2}(T_3 - T_2);$$

$$\frac{dT_3}{dy} = \frac{6\alpha m}{c_3 u M \rho_1}\left[\frac{1-x}{D_1}(T_1 - T_3) + \frac{x}{D_2}(T_2 - T_3)\right].$$

The resulting system of equations was solved numerically in the MathCad package by a standard procedure using Rkadapt function – the solution of a system of ordinary differential equations by Runge – Kutt method with automatic step selection.

In the case when the replacement of self-fluxing powder with ceramic one is carried out by volume fractions, the mass of the material introduced into the flow is decreased, since the density of the main component (self-fluxing alloy) is more than twice the density of ceramics. It is worth to note that the volume specific heat capacities (product of density and specific mass heat capacity) differ slightly, as:

$$\rho_1 c_1 = c_1^* = 4{,}8332 \ \text{kJ/(m}^3 \cdot \text{K)};$$

$$\rho_2 c_2 = c_2^* = 4{,}7697 \ \text{kJ/(m}^3 \cdot \text{K)}.$$

That is, the difference in the products of density and heat capacity does not exceed 1.5 %. Therefore, the content of ceramics in the mixture, as shown by calculations, does not significantly affect the nature of the temperature distribution and its values (fig. 1). By increasing the volume content of ceramics in the mixture from 5 to 50 %, the temperature of aluminum oxide particles decreases only by 50–60 °C, that is, by 2.3–3.0 %. More significantly the temperature of the particles depends on the temperature of the plasma.

Analysis of calculation results (fig. 1) indicates that when the plasma temperature increases from 7000 to 10000 K, the temperature of the ceramic particles increases by about 800 degrees. At the size of ceramic particles of 100 microns, they reach a melting point for plasma temperature not lower than 7400 K at a concentration of 5 % and 7700 K – for a concentration of 50 %.

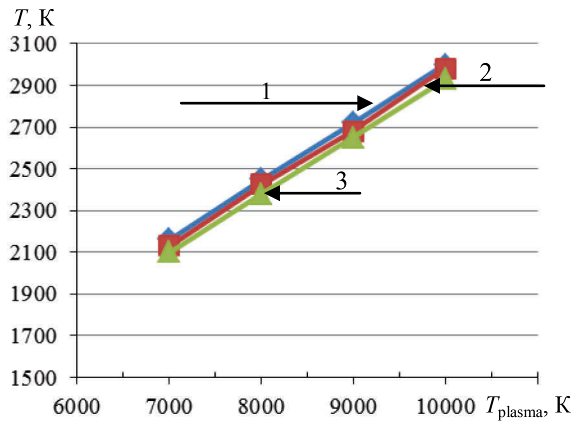

Fig. 1. Effect of plasma temperature on temperature of Al2O3 particles at the time of their contact with a sample surface for different volume content of ceramics in the mixture: 1 – 5 % of ceramics; 2 – 25 % of ceramics; 3 – 50 % of ceramics; particle diameter – 100 μm

Analysis of temperature change calculations at different distances from the plasma gun shows that a noticeable difference in the temperature of metallic and ceramic particles is observed at a distance of more than 5 cm from the outlet, when the temperature of the heated particles is higher by 10 degrees than the less heated ones. Temperature dependence of ceramic and self-flux particles is exponential (fig. 2). Moreover, for the entire range of calculated values, the temperature of the self-fluxing powder in contact with the substrate exceeds the melting point.

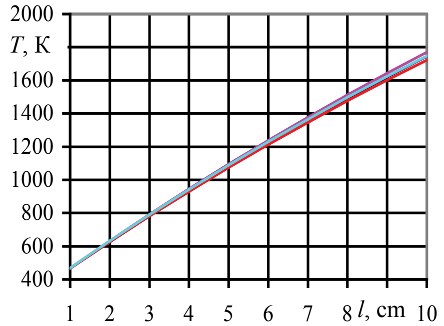

Fig. 2. Calculated temperature change in mixture components from the moment of entering into plasma to the contact with the substrate for particles of 100 microns in size and plasma temperature of 6500 K

Analysis of the calculation results shows that the average volumetric flow temperature decreases by about 15 degrees with an increase in the proportion of ceramic particles from 5 to 25 vol. %. The consequence of the decrease in the flow temperature can be deterioration in the adhesion of the developed layer to the substrate, as well as a weaker relationship between the particles of Nickel-chromium alloy and aluminum oxide.

Particle size has a strong effect on the temperature of the particles at the moment of contact with the substrate (fig. 3). For T_{plasma} = 7000 K and the content of ceramics in the mixture is equal to 25 % the melting temperature is reached by only particles with size less than 40 microns. When the plasma temperature rises to 9000 K, the melting point is reached by particles with a diameter equal to or less than 63 microns. Moreover, when the plasma temperature rises, the dependence curve has a flatter character (fig. 3).

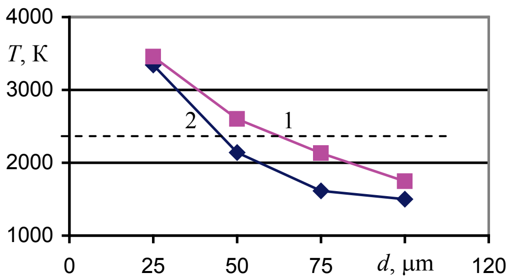

Fig. 3. Influence of ceramic particles size on their temperature at the moment of contact with the surface for volumetric content of ceramics 25 %; 1 – T_{plasma} = 9000 K; 2 – T_{plasma} = 7000 K (dashed line shows the temperature of ceramics melting point)

To check the adequacy of the calculation results some experiments were carried out on the coating formation made of Nickel-based alloy (system Ni–Fe–Cr–Si–B–C) containing oxide ceramics using the plasma spray installation UPU-3D with the plasma torch PP-25. The plasma temperature was 7500 K.

Optical and electron microscopy were used for microstructure analysis. The microstructure of the coating with the volume content of ceramics 20 and 33 % is shown in fig. 4.

Analysis of microstructures shows that at such plasma temperature not all ceramic particles have melted (fig. 4a), that confirms the calculation results. From fig. 3 it follows that at such plasma temperature the size of the ceramic particles for complete melting should not exceed 50 microns, and in experiments the ceramics particles had diameter up to 63 microns. The increase in the volume content of ceramics leads to a decrease in the average temperature of the particle flow and, as a consequence, the presence of larger number of unmelted particles can be seen (fig. 4b).

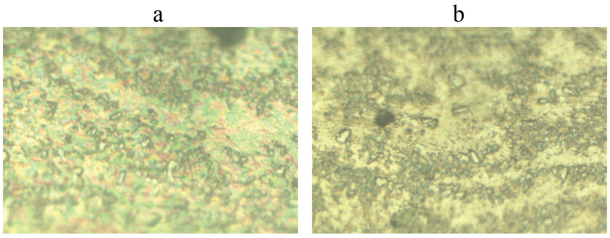

Fig. 4. Microstructure of plasma coatings with different content of ceramics: a – 20 %; b – 33 % (×500)

This is confirmed by SEM-microscopy as well. With the increase in ceramics concentration one can observe not only more non-uniform structure but also marks of tungsten particles (light particles in fig. 5b) confirmed by spectral analysis.

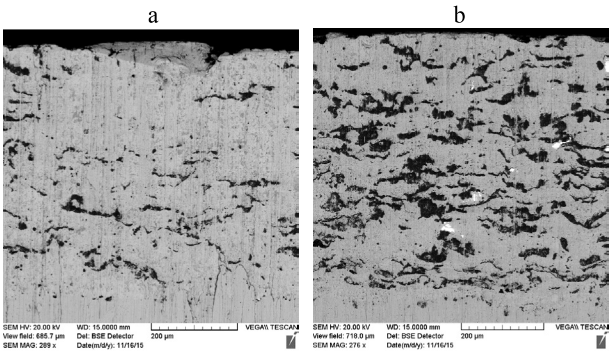

Fig. 5. SEM-microstructure of plasma coatings with different ceramics content: a – 15 %; b – 33 %

So, microstructural studies of deposited coatings are in good correlation with predicted temperature of particles establishing relations between some process parameters and particles temperature during deposition. Based on these results it is possible to estimate a formed coating structure which depends on temperature.

CONCLUSION

In the present work the mathematical simulations of temperature of the particles flow consisting of self-fluxing powder and oxide ceramics in plasma spraying process have been considered. It is determined that the plasma temperature and granulometric composition of ceramics are main factors for the formation of a high-quality coating.

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