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MODELING OF HEAT TRANSFER PROCESSES DURING THE FORMATION OF PROTECTIVE COATINGS

Summary. *This paper presents the fundamental principles of mathematical modeling of heat transfer during coating formation using thermal spraying. The main attention is paid to the thermal state of layered heterogeneous systems "coating as a whole – base".*

Key words: *layered heterogeneous systems, thermal spraying, "multilayer coating-sublayer-base", mathematical modeling, high-temperature zone, heat transfer*

Introduction. Problems of creating new and improving existing thermal spraying technologies necessitate an in-depth study of the thermal phenomena observed during the implementation of these technological processes [1-9]. This paper focuses on mathematical modeling of the thermal phenomena under study, since in this physical situation, where the specific nature of the processes under study encompasses both the localization of the high-temperature zone and high velocitys of temperature change, the relatively small sizes of the melt particles and the coating as a whole make it very difficult to obtain the required information using only full-scale experiments.

This paper examines thermal processes in layered, heterogeneous coating-substrate systems. Particular attention is paid to the thermal phenomena observed during the formation of the coating as a whole during high-velocity machining. Some average temperatures in the coating-substrate system are considered; elementary interactions between individual particles and the solid surface are not considered in the mathematical modeling.

The main publications related to the study of the thermal state of the "coating as a whole - base" system, depending on the conditions adopted in modeling for the coating itself, can be divided into the following three cases. The first was characterized by a monotonic increase in the coating thickness δ over time, the second by a discrete growth of δ, and the third by the assumption that the thermal resistance of the coating itself can be neglected. In the first case, the mathematical model of the heat conduction process is formulated in the approximation of L.S. Leibenson [4]. Accordingly, the spraying process is assumed to be quasi-stationary, the average mass flux density from the sprayer is considered constant over the surface of the base and the coating thickness will increase at a constant velocity V, the temperature profile in the coating is assumed to be linear and, accordingly, the heat flux supplied to the coating is assumed to be entirely spent on heating the base. Mathematical models with the specified assumptions are one-dimensional.

In the second case, a three-dimensional non-stationary heat conduction problem is formulated for a multilayer plate. The following assumptions are fundamental. The heat supply source is assumed to move at a constant velocity V, corresponding to the motion of the plasma torch. It is assumed that in the heating spot itself, the heat flux density distribution obeys the Gaussian law. The increase in coating thickness after one plasma torch pass is not taken into account. The problem is formulated in a linear formulation, and all bounding surfaces of the multilayer system are assumed to be adiabatic, excluding the heat supply surface. In the third case, the thermal resistance of the coating was not taken into account in the mathematical modeling, because it is comparatively small.

The mathematical models for each of these three cases have shortcomings. In the first case, they are one-dimensional, significantly limiting the ability to describe the actual physical situation of spraying. Models for the second case are more general. In the third case, the model is a special case, since the thermal resistance of the sprayed layer is not taken into account. Therefore, the development of research based on mathematical models describing the second case is most important.

Based on the analysis of the models presented in the review for various cases, it can be concluded that particular attention should be paid to the development of research on an approach to analyzing the thermal state of layered, heterogeneous "coating as a whole - substrate" systems. The primary focus is on studying the most important principles of the heat transfer process under consideration, as applied to the spraying conditions of two classes of thermal spray coatings: metal-polymer coatings and composite coatings containing graphite.

In both situations, the quasi-stationary heat transfer process during the formation of multilayer coatings is investigated. A layered, heterogeneous system is present, consisting of a base 1 with a pre-applied sublayer 2 and a sprayed multilayer coating 3 (Fig. 1). The heat source moves along the upper surface of the system under study along the z-axis in the positive direction at a constant velocity V in accordance with the movement of the gas torch or plasma torch. Regarding the coating itself, the mathematical modeling assumes that the coating thickness increases with the application of each subsequent coating layer. Heat exchange between all bounding surfaces (except for the *XOZ* surface) and the surrounding medium occurs according to Newton's law, which is a boundary condition of the third kind. The heat transfer coefficients and the ambient temperature are assumed to be constant. Since the system under study has thermal and geometric symmetry with respect to the *YOZ* plane, only half of it is considered in the mathematical modeling.

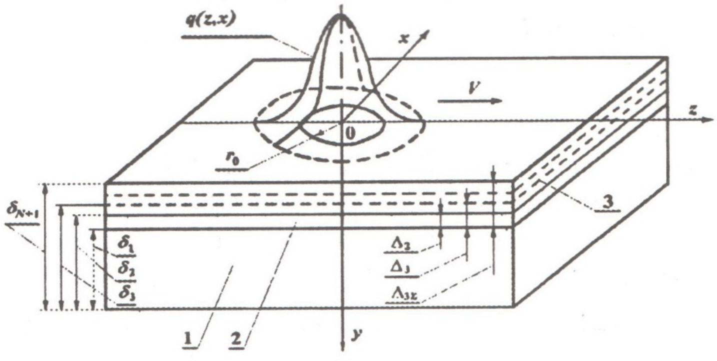

Fig. 1. To the formulation of the heat transfer problem for a layered inhomogeneous system: 1 – base; 2 – sublayer; 3 – multilayer coating

The mathematical formulation of a nonlinear quasi-stationary three-dimensional heat transfer problem for a layered-heterogeneous system "multilayer coating-sublayer-base" in a moving coordinate system, which is associated with an energy source, looks like this:

$$\frac{\partial}{\partial x}\left[\Lambda(y,\theta)\frac{\partial\theta}{\partial x}\right]+\frac{\partial}{\partial y}\left[\Lambda(y,\theta)\frac{\partial\theta}{\partial y}\right]+\frac{\partial}{\partial z}\left[\Lambda(y,\theta)\frac{\partial\theta}{\partial z}\right]-P_e\cdot C_V(y,\theta)\frac{\partial\theta}{\partial z}=0,$$

$$0<x<x_1, \qquad -\infty<z<+\infty,$$

$$0<y<y_1,\quad y_1(n)=\begin{cases}\delta_2 \text{ при } n=0,\\ \delta_3 \text{ при } n=1,\\ \quad . \quad . \quad . \quad . \\ \delta_{N+2} \text{ при } =N,\end{cases}$$

$$\Lambda(y,\theta)\frac{\partial\theta}{\partial x}\Big|_{x=0} = 0$$

$$\left[\Lambda(y,\theta)\frac{\partial\theta}{\partial x}+Bi_{x_1}\theta\right]_{x=x_1} = 0$$

$$\left[\Lambda_i(\theta)\frac{\partial\theta}{\partial y}+Bi_{y_0}\theta\right]_{y=0} = -\,exp[-(x^2+z^2)],$$

$i=2$ при $n=0$; $i=3$ при $n=1,2,\ldots\ldots,N$,

$$\left[\Lambda_1(\theta)\frac{\partial\theta}{\partial y}+Bi_{y_1}\theta\right]_{y=y_1} = 0,$$

$$\left[\Lambda(y,\theta)\frac{\partial\theta}{\partial z}-Bi_{z_0}\theta\right]_{z=-\infty} = 0,$$

$$\left[\Lambda(y,\theta)\frac{\partial\theta}{\partial z}+Bi_{z_1}\theta\right]_{z=+\infty} = 0,$$

$$\lambda(y,\theta)=\begin{cases}\Lambda_1 \text{ при } (y_1-\delta_1)<y\le y_1\\ \Lambda_2 \text{ при } (y_1-\delta_2)<y\le (y_1-\delta_1),\\ \Lambda_3 \text{ при } 0\le y\le (y_1-\delta_2),\end{cases}$$

$$C_V\,(y,\theta)=\begin{cases}C_{V_1} \text{ при } (y_1-\delta_1)<y\le y_1\\ C_{V_2} \text{ при } (y_1-\delta_2)<y\le (y_1-\delta_1),\\ C_V \text{ при } 0\le y\le (y_1-\delta_2),\end{cases}$$

where $\theta=(t-t_c)\cdot\lambda_0/(q_{max}\cdot r_0)$; $P_e=V\cdot r_0/a_0$; $Bi_{x1}=\alpha_{x1}\cdot r_0/\lambda_0$; $Bi_{y1}=\alpha_{y1}\cdot r_0/\lambda_0$; $Bi_{zo}=\alpha_{zo}\cdot r_0/\lambda_0$; $Bi_{z1}=\alpha_{z1}\cdot r_0/\lambda_0$; $x=x_p/r_0$; $y=y_p/r_o$; $z=z_p/r_0$; $\delta_1=\delta_{p1}/r_0$; $\delta_2=\delta_{p2}/r_0$; $\delta_3=\delta_{p3}/r_0$; $\delta_{N+2}=\delta_{pN+2}/r_0$; $\Lambda=\lambda/\lambda_0$; $C_V=c_v/c_{vo}$; $a_0=\lambda_0/c_{vo}$; n is the number of the sprayed coating layer; N is the total number of sprayed coating layers; δ_{p1} is the base thickness; δ_{p2} is the total thickness of the base and the pre-applied sublayer; δ_{p3} is the total thickness of the base, the pre-applied sublayer and one coating layer; δ_{N+2} is the total thickness of the base, sublayer and N coating layers; q_{max} is the maximum value of the heat transfer diagram; t_c is the ambient temperature; a_0 is the thermal diffusivity coefficient, α_{x1}, α_{x2}, α_{x3}, α_{x4} are the heat transfer coefficients on the corresponding surfaces; r_0 is the heat spot radius; λ_0 and c_v are fixed values of the thermal conductivity coefficient and specific heat capacity of the base material, respectively; indices 1, 2 and 3 at the values of Λ and C_V relate the latter to the base, sublayer and coating, respectively.

To solve the problem, the integral method of complete polyargument systems was used [5; 6].

Composite clad powders containing solid lubricants are increasingly used to produce antifriction coatings using various thermal spraying methods. Composites with graphite as the primary particle, or core, are widely used in spraying. This graphite particle is coated with a metal shell, which protects the core from the harmful chemical effects of the environment. Heating the shell to the melting point ensures the core is welded to the base surface. Coatings made from composite powders of this composition are used in friction units operating without lubrication and under boundary friction conditions. Such coatings are used as bearing surfaces for plain bearings, in gas turbine engines for abradable stator coatings, in vane compressors, in ring pump seals, and in specialized military equipment. Therefore, the development and improvement of coating technology necessitates further research into the thermal phenomena observed in these situations. Of considerable interest are the data from mathematical modeling of heat transfer processes during the formation of coatings from clad composite powders containing graphite. These data represent the results of numerical studies examining the key factors influencing the thermal state of the objects under consideration, including spraying distance, the power of the supplied two-phase flow, the plasma torch rate, the cooling conditions of the free surfaces of the system, the preliminary application of sublayers, and other factors.

The main results of the analysis of the peculiarities of changes in the thermal state of the studied layered inhomogeneous system "coating-sublayer-base". The obtained data of the performed computational experiments correspond to the following values of the initial parameters of the system: $x_1=2.56$; $\delta_1=0.34$; sublayer thickness Δ_2=0.0085 ($\Delta_2= \delta_2 - \delta_1$); thickness of a single coating layer Δ_3=0.00425 ($\Delta_3= \delta_3 - \delta_2$); Pe=129.6; $Bi_{x1}= Bi_{y1}= Bi_{zo}= Bi_{z1}=5.96\cdot10^{-3}$; from here on, steel 20 was considered as the base material, sublayer - Ni, coating - clad powder (graphite) - (Cu) with a volume content of components of 30% and 70%, respectively.

To better understand the influence of a pre-applied Ni layer and subsequent layers of composite powder on heat transfer, it is advisable to compare the obtained data with the results obtained for a separate steel substrate. The conducted studies have shown that the temperature fields in comparable objects are qualitatively similar, but can differ significantly quantitatively.

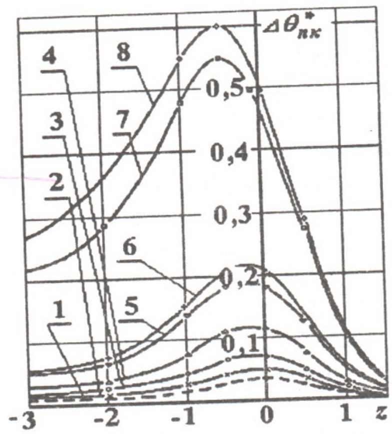

Fig. 2 Dependence $\Delta\theta^*_c = f(z)$ – for x=0, y =0 for systems: 1 – "steel base – Ni sublayer"; 2-7 – "coating-sublayer-base" with the number of coating layers of 1, 2, 4, 8, 9 and 60, respectively; 8 – separate base made of composite material (Cu)- (graphite)

The differences in the compared temperature fields show that the temperature levels of the coated part in the high-temperature zone are lower than the corresponding levels of a separate steel base, and the quantitative difference in the compared temperatures significantly depends on the number of coating layers N. The patterns of change in the value of $\Delta\theta^*_c$($\Delta\theta^*_c=\Delta\theta_c/\theta_{max}$, $\Delta\theta_c=\theta_{st} - \theta_{csb}$, θ_{st} is the dimensionless temperature of a separate steel base, θ_{csb} is the temperature of the coating-sublayer-base system, θ_{max} is the maximum temperature of a separate steel base) are shown in Fig. 2. In the high-temperature zone, the effect of temperature reduction in the coating-sublayer-base system compared to a separate steel base is more rapid, the greater the coating thickness. On the heat supply surface *XOZ*, the largest differences $\Delta\theta^*_c$ of temperatures that are compared are 0.00492 for a coating thickness of 0.00425 (one coating layer) and 0.214 for a coating thickness of 0.03825 (nine coating layers), lines 2 and 6.

The thermal state of an individual steel base differs significantly from the thermal state of the multilayer system under consideration in the general case. Moreover, in cases where the coating thickness Δ_{3c} is small, the temperature discrepancies between the multilayer system and the individual steel base are relatively small. This is due to the fact that the base plays a major role in the heat transfer process under study. At sufficiently large coating thicknesses Δ_{3c}, its role in determining the system's temperature regime is significant, and accordingly, the temperature discrepancies between the individual base and the system increase.

Conclusions. The presented research results demonstrate the validity of using single-layer mathematical models for approximate estimates of the thermal state of a multilayer system for two limiting cases. The first case is for conditions where the coating thickness Δ_{3c} is relatively small, while the second case is for conditions where it is quite large. In the first case, only an isolated steel base was considered. The presence of the coating was ignored due to the coating's very low thermal resistance in the y-axis direction. In the second case, only the isolated coating was considered. In this case, the existence of the base was either completely ignored, or its thermophysical properties were used for the coating. At sufficiently large coating thicknesses, a regional influence of the base on heat transfer in the high-temperature zone of the multilayer coating was observed. This justifies the implementation of the aforementioned substitutions for the uniqueness conditions.

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