Study of thermal and electrical parameters of workpieces during spray coating by electrolytic plasma jet

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Abstract. In this paper the results are presented of thermal and electrical parameters of products in the system bottom layer – intermediate layer when applying protective coatings of ferromagnetic powder by plasma spray produced in an electric discharge with a liquid cathode, on steel samples. Temperature distribution and gradients in coating and intermediate coating were examined. Detailed descriptions of spray coating with ferromagnetic powder by plasma jet obtained in electrical discharge with liquid cathode and the apparatus for obtaining thereof is provided. Problem has been solved by using of Fourier analysis. Initial data for calculations is provided. Results of numerical analysis are provided as temporal functions of temperature in contiguity between coating and intermediate coating as well as temporal function of the value $Q=q–\phi$, where $q$ is density of heat current directed to the free surface of intermediate coating, $\phi$ is density of heat current in contiguity between coating and intermediate coating. The analysis of data given shows that in the systems of contact heat exchange bottom layer-intermediate layer with close values of the thermophysical characteristics of constituting materials is observed a slow increase of the temperature of the contact as a function of time.

1. Introduction

Durability and surface hardening of protective coating applied using plasma spray produced in the electric discharge containing a liquid cathode [1], and its adhesion to the bottom layer is largely dependent on the presence of residual stresses in the coating – bottom layer system. Residual tension in welded joints is extensively studied worldwide [2]. Residual tension has considerable influence on operational properties of machine parts subjected to cyclic mechanical and thermal action.

Nowadays spray coating is widely used in manufacturing of those machine parts [3]. Advantages of this process include quality and precision of resulting surface but this process also creates stretching residual tension. To reduce the level of residual stresses one may by applying an additional intermediate layer to the bottom layer [4]. Since the bottom layer and the intermediate layer have different thermal properties, then with the thermal effect on the system bottom layer – intermediate layer the thermal stresses arise in coating [5].

Therefore, in the development of the coating technology (bottom layer + intermediate layer) the information becomes important about the temperature distribution and temperature gradients in the bottom layer and the intermediate layer, and in contact area.

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2. Statement of the problem

In this paper the results are presented of thermal and electrical parameters of products in the system bottom layer – intermediate layer when applying protective coatings of ferromagnetic powder by plasma spray (Figure 1) produced in an electric discharge with a liquid cathode, on steel samples [6 – 8]. Ferromagnetic powder is obtained in the high-voltage electric discharge with voltage $U = 1000 – 1300$ V, current $I = 0.6 – 10$ A, between the anode of steel and liquid cathode at an interelectrode gap $S = 5 – 10$ mm, at atmospheric pressure.

![Diagram of the deposition process of the powder by the plasma spray](image)

Thermal effect of grains of the coating on the free surface of the intermediate layer is accepted equivalent to heating of the surface by heat flow of given power $q = \text{const}$. The temperature $t_0$ of the bottom layer and of the intermediate layer at the initial moment are the same, and the thickness of the bottom layer $(l – d) >> d$ – the thickness of the intermediate layer.

We can assume that the distribution of temperature fields in this system is carried out by heat conduction as follows:

\[
\frac{\partial t_1(x, \tau)}{\partial \tau} = a_1 \cdot \frac{\partial^2 t_1(x, \tau)}{\partial x^2} \quad (0 < x < d, \quad \tau > 0),
\]

\[
\frac{\partial t_2(x, \tau)}{\partial \tau} = a_2 \cdot \frac{\partial^2 t_2(x, \tau)}{\partial x^2} \quad (d < x < l, \quad \tau > 0),
\]

\[t_1(x,0) = t_2(x,0) = t_0 \]

\[t_1(d, \tau) = t_2(d, \tau) \]

\[-\lambda_1 \cdot \frac{\partial t_1(d, \tau)}{\partial x} = -\lambda_2 \cdot \frac{\partial t_2(d, \tau)}{\partial x} = \varphi(\tau) \]

\[-\lambda_1 \cdot \frac{\partial t_1(0, \tau)}{\partial x} = q \]

\[\frac{\partial t_2(l, \tau)}{\partial x} = 0 \]

where $t_1(x, \tau)$, $t_2(x, \tau)$ are the temperatures of respectively intermediate layer and bottom layer at a point $x$ at a moment $\tau$; $d$ – the thickness of the intermediate layer, $l – d$ – the thickness of the bottom layer, $a_j$ and $\lambda_j (j = 1, 2)$ – are respectively the temperature conductivity and heat conductivity
coefficients; \( q = \text{const} \) – heat flow of given power; \( \varphi(\tau) \) – the density of heat flow in contact of bottom layer with intermediate layer; \( t_0 \) – initial temperature.

The challenge is to find the temperatures \( t_j(x, \tau), j = 1, 2 \), and the density \( \varphi(\tau) \) from (1) – (7).

3. Research method

In solving the problem (1) – (7) we use the Fourier method [9]. First, we find the solution of equation (1) satisfying the conditions of (3), (5), (6), temporally considering \( \varphi(\tau) \) as known. This solution we obtain in the form

\[
t_j(x, \tau) = \sum_{k=0}^{+\infty} T_j(\tau) X_k(x) + t_j^*(x, \tau), \quad 0 \leq x \leq d, \tau > 0,
\]

where the functions \( t_j^*(x, \tau), X_k(x), T_k(\tau) \) are defined by following formulas:

\[
t_j^*(x, \tau) = \frac{q - \varphi(\tau)}{2d\lambda_1} \cdot x^2 - \frac{q}{\lambda_1} \cdot x;
\]

\[
X_k(x) = \cos(\mu_k x), \mu_k = \left( \frac{\pi \cdot k}{d} \right)^2, k = 0, 1, \ldots;
\]

\[
T_k(\tau) = \begin{cases} 
\frac{-a_k^1}{e^{a_k^1 \mu_k \tau}} \int_0^\tau b_k(t) e^{a_k^1 \mu_k t} dt + a_k \cdot t_0, & k = 0; \\
\int_0^\tau b_k(t) dt + a_k \cdot t_0, & k = 1, 2, \ldots;
\end{cases}
\]

In the derivation of the decision (8) we have taken into account that \( \varphi(0) = 0 \).

Similarly, we find the solution of equation (2) satisfying the conditions of (3), (5), (7), which has the form:

\[
t_2(x, \tau) = \sum_{k=0}^{+\infty} \tilde{T}_2(\tau) \cdot \tilde{X}_k(x) + t_2^*(x, \tau), \]

where

\[
t_2^*(x, \tau) = \frac{\varphi(\tau)}{2l(d - x)} (x^2 - 2lx);
\]

\[
\tilde{X}_k(x) = \cos[\tilde{\mu}_k (x - d)], \quad \tilde{\mu}_k = \left( \frac{\pi \cdot k}{l - d} \right)^2, \quad k = 0, 1, 2, \ldots;
\]
\[ T_k(\tau) = \begin{cases} \frac{-a_k}{2} \int_0^\tau e^{z_k t} dt, & k = 1, 2, \ldots \\ \int_0^\tau b_k(t) dt + t_0, & k = 0; \end{cases} \]

\[ \tilde{b}_k(\tau) = \begin{cases} \frac{(-2)\phi'(\tau)}{\lambda_2 (l - d) \tilde{\mu}_k}, & k = 1, 2, \ldots, \\ \frac{a_2}{\lambda_2 (l - d)} \phi(\tau) + \frac{2l^3 - 3d^3 + d^3}{6 \lambda_2 (l - d)^2} \cdot \phi'(\tau), & k = 0; \end{cases} \]

Now the solutions (8), (9) we substitute in the condition (4). As a result, to determine the density \( \phi(\tau) \) we obtain the Volterra integral equation of the first kind [10] of the form

\[ \int_0^\tau \left[ \frac{\pi_1}{d^2} (\tau - t) + \frac{\pi_2}{(l - d)^2} (\tau - t) \right] \phi(t) dt = \psi(\tau), \quad (10) \]

where \( \theta(x) \) - theta function, defined by the formula

\[ \theta(x) = 1 + 2 \sum_{k=1}^{\infty} e^{-x^2 k}, \]

\[ \psi(\tau) = \phi(\tau) - \frac{d^2 q}{6 \lambda_2} - \frac{2d^2 q}{a_2 \pi^2} \sum_{k=1}^{\infty} (1)^k \cdot e^{-a_k k} \]

\[ \beta_0 = \frac{d \lambda_2 a_2}{a_2 \lambda_2} \]

The integral equation (10) we solve computationally [11]. Assume \( \tau \in [0, T], \quad \tau_j = j \cdot h, \quad j = 1, N, \quad h = T / N \). To find the values of \( \phi(\tau_j) \) in junction points \( \tau_j, \quad j = 1, N \), we obtain the recurrent equations (11)

\[ \psi_m(\tau_{j+1}) - h \left[ \phi(\tau_j) \cdot k_m(\tau_{j+1}; \frac{\tau_j + \tau_{j+1}}{2}) + \phi(\tau_j) \cdot k_m(\tau_{j+1}; \frac{\tau_j + \tau_{j+1}}{2}) + \ldots + \phi(\tau_j) \cdot k_m(\tau_{j+1}; \frac{\tau_j + \tau_{j+1}}{2}) \right] \]

\[ \phi(\tau_{j+1}) = \begin{cases} \psi_m(\tau_{j+1}) - h \left[ \phi(\tau_j) \cdot k_m(\tau_{j+1}; \frac{\tau_j + \tau_{j+1}}{2}) + \phi(\tau_j) \cdot k_m(\tau_{j+1}; \frac{\tau_j + \tau_{j+1}}{2}) + \ldots + \phi(\tau_j) \cdot k_m(\tau_{j+1}; \frac{\tau_j + \tau_{j+1}}{2}) \right] \\ h \cdot k_m(\tau_{j+1}; \frac{\tau_j + \tau_{j+1}}{2}) \end{cases} \]

\[ j = 0, 1, \ldots, N - 1, \]

where

\[ k_m(\tau; t) = \theta_m \left[ \frac{\pi_1}{d^2} (\tau - t) \right] + \frac{\beta_0}{l - d} \theta_m \left[ \frac{\pi_2}{(l - d)^2} (\tau - t) \right], \]

\[ \theta_m(x) = 1 + 2 \sum_{k=1}^{m} e^{-x^2 k} \]


\[
\psi_m(\tau) = q \tau - \frac{d^2 q}{6 \lambda_1} - \frac{2d^2 q}{a_i \pi^2} \sum_{k=1}^{m} \frac{(-1)^k e^{-a_i k \tau}}{k^2},
\]

where \( m \) is a reasonably large natural number.

4. Results and discussion

Computational scheme (11) is implemented with the following input data:

\[
\begin{align*}
a_1 &= 12.5 \cdot 10^{-6} m^2/s, \quad \lambda_1 = 20 W/m\cdot K \\
a_2 &= 12.8 \cdot 10^{-6} m^2/s, \quad \lambda_2 = 46 W/m\cdot K \\
m &= 100, \quad d = 10^{-3} m, \quad q = 4 \cdot 10^7 W/m^2, \quad t_0 = 20 \degree C.
\end{align*}
\]

Results of numerical computations are shown in Figures 2, 3.

![Figure 2](image1.png)

**Figure 2.** Variation with time \( \tau \) of temperature \( t_1 \) in the contact area of intermediate layer and bottom layer: 1 – when \( l = 1 \) cm; 2 – when \( l = 2 \) cm.

![Figure 3](image2.png)

**Figure 3.** Time law of variable \( Q = q - \phi \) (\( q \) is the density of heat flow falling on free surface of the intermediate layer; \( \phi \) is the density of heat flow in the contact area of intermediate layer and bottom layer): 1 – when \( l = 1 \) cm; 2 – when \( l = 2 \) cm.

The analysis of data given shows that in the systems of contact heat exchange bottom layer-intermediate layer with close values of the thermophysical characteristics of constituting materials is observed a slow increase of the temperature of the contact as a function of time \( t_1 \). In such systems, heat flow density in the region of contact of the intermediate layer with the bottom layer (\( \phi \)) differs slightly from the density of the flow (\( q \)) causing heating of the free surface of the intermediate layer, and with time \( \phi \) and \( q \) tend to equalization (corresponding to falling curves \( Q = q - \phi \) in Figure 3). The specified time laws \( t_1(\tau) \) and \( Q(\tau) \) have caused by the condition that, in this case, the thickness of the bottom layer is much greater than the thickness of the intermediate layer.

5. Conclusion

Thus, in the process of applying protective coatings on the two-component facilities the solution of the problem of the regulated control of thermal parameters is directly dependent on the appropriate selection of components of a system in terms of optimizing the ratio between their sizes and thermal properties.
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