Simulation of heat flows in a combined process of plasma spraying and coat hardening

A M Kadyrmetov, S N Sharifullin, E V Snyatkov, A A Plahotin, I A Mandrykin, V V Romanov

1 Voronezh State Forestry Engineering University named after G.F. Morozov, Russia, 2 Kazan (Volga) Federal University, Russia

kadyrmetov.a@mail.ru, Saidchist@mail.ru

Abstract: The simulation technique of heat distribution in a detail for applying plasma coating in combination with electro-mechanical treatment and cooling by water jet is worked out. It is shown that water cooling substantially decreases the workpiece surface temperature and provides the formation of more rugged coat by reducing of internal stresses in it.

1. Introduction

One of the effective method of detail surfaces restoring is the plasma coating with concomitant electromechanical breaking in by the roller (Fig. 1) [1, 2]. However, in such process details can get burned and the coats can accumulate excess internal stresses.

Figure 1. Diagram of combined plasma spraying coating. 1 – coat, 2 – detail, 3 – plasma jets, 4 – plasmatron, 5 – roller, 6, 8 – cooling jet, 7, 9 – injectors, F – roller loading force

Modeling of heat extension in the combined method of plasma spraying coating for the actual shapes of details, several ambients and heat dynamics is exceedingly difficult task [3, 4]. In this paper we developed a model, which is based on the equations of classical thermodynamics. In this case, the task complexity for accounting of all external conditions overcomes by using the disretization of space, the algorithmization by the numerical methods of calculation on the base of the grid finite-difference methods and programming [4-5].
2. Materials and methods

In the three-dimensional case, heat propagation is described by the heat equation:

$$\frac{\partial}{\partial t} T(\mathbf{r}, t) = \nabla \cdot (\kappa \nabla T(\mathbf{r}, t)) + Q(\mathbf{r}, t),$$  \hspace{1cm} (1)

wherein $T(\mathbf{r}, t)$ – the temperature distribution in the space and its variation during some time; $\mathbf{r}$ – radius vector of the investigated point in space; $t$ – is the time; $\nabla = \frac{\partial}{\partial x} \mathbf{i} + \frac{\partial}{\partial y} \mathbf{j} + \frac{\partial}{\partial z} \mathbf{k}$ - differential operator nabla; $x, y, z$ – Cartesian coordinates of the investigated point in space; $\mathbf{i}, \mathbf{j}, \mathbf{k}$ – unit vectors in Cartesian space; $(, , )$ – scalar product; $\kappa(\mathbf{r}, t)$ – substance temperature conductivity coefficient (generally depends on the position in space and time); $Q(\mathbf{r}, t)$ – the thermal field changing over time from the sources of heating and cooling in this coating scheme. Temperature conductivity coefficient can be expressed through the coefficient of thermal conductivity $\kappa$, heating capacity $c$ and substance density $\rho$ by the dependence $\kappa = \rho c / \kappa$ [4].

**Figure 2.** Representation of the geometry of the shaft in the model (a) and the crucial scheme of accounting for adjacent nodes with the grid option of the thermal conductivity equation (b).

For sufficiently adequate repeating of the detail form in the model the space in which the modeling is performing, is discretised in the rectangular grid with a step $h = 1$ mm (Fig. 2, a). The length of the space in each of the three spatial directions $X, Y, Z$ is 100 grid cells (corresponding to a size of 100 mm). In this case, the total number of cells is $100^3 = 1,000,000$.

The grid for the solution of the thermal conductivity equation has the form, represented in Fig. 2, b. Each grid node has six adjacent nodes from which reception or transmission is possible. In the finite-difference statement of the problem, the equation (1) is transformed as follows. For each node $(i,j,k)$ on each step of integration in time temperature $T_{i,j,k}$ depends on the temperature of adjacent nodes as follows.

$$\frac{\Delta T_{i,j,k}}{\Delta t} = \chi_{i,j,k} \left( \frac{\Delta T_{i,j,k}}{(\Delta x)^2} + \frac{\Delta T_{i,j,k}}{(\Delta y)^2} + \frac{\Delta T_{i,j,k}}{(\Delta z)^2} \right) + Q_{i,j,k},$$  \hspace{1cm} (2)

where $\Delta t$ is the time discretization step; $\Delta x = \Delta y = \Delta z = h$ is the discretization step of space; $\chi$ is the temperature conductivity coefficient; $Q_{i,j,k}$ – heat input from the external environment to a given cell or heat removal from it. If we spell out details of finite differences in (2) we obtain the following final formula for thermal calculating [5]:

![Diagram of shaft geometry and grid option](image-url)
\[
\frac{T^\tau_{i,j,k} - T^{\tau+1}_{i,j,k}}{\Delta t} = \frac{\chi}{h} \left( T^{\tau}_{i+1,j,k} + T^{\tau}_{i-1,j,k} + T^{\tau}_{i,j+1,k} + T^{\tau}_{i,j-1,k} + T^{\tau}_{i,j,k+1} + T^{\tau}_{i,j,k-1} + 6T^{\tau}_{i,j,k} \right) + Q_{i,j,k} \quad (3)
\]

This formula enables the calculating of each cell \((i, j, k)\) temperature \(T^{\tau+1}_{i,j,k}\) for the next step of the integration time \(\tau + 1\) based on the actual temperature \(T^{\tau}_{i,j,k}\) of actual integration step \(\tau\).

Heat propagation problem is solved for media of two types: metal of the shaft \((\chi = 0.25\text{W/}(\text{m}\cdot\text{K}))\) and gas surrounding the shaft \((\chi = 0.026\text{W/}(\text{m}\cdot\text{K}))\). At the initial moment of time, all grid nodes have the same room temperature \((T = 20\text{°C})\). Unlike from the actual coating process, a detail in the model is stationary and the heating and cooling spots representing the system of coating, move around the detail in the plane \(x = 0\).

**Figure 3.** Illustration of improved surface cooling of the detail: temperature distribution maps in the cross section of the neck of the crankshaft for plasma spraying

- \(a, c\) - without water cooling;
- \(b, d\) - with cooling of the shaft by one or two water jets;
- \(a, b\) - without electromechanical processing;
- \(c, d\) - with electromechanical processing

Thermal process simulation program is developed in the Object Pascal programming in the integrated programming environment Borland Delphi 7. The essential program technical limitations: a step of integrating for differential equations is not more than 0.01 s; the maximum size of the cube space discretization is not more than 1 mm. The parameters of the computer model were close to the
following real parameters of the coating process: substrate - steel; Ni55%+Ti45% powder; the diameter of the powder particle (model element) is 10 microns; effective roller radius is 10 mm; typical thickness of a single coat layer is 50 microns; the speed of movement of the plasmotron and the roller relative to the surface is 1 sm/s; powder consumption is 10 mg / s; characteristic roller pressure is 100 MPa.

3. Results and discussions

Sing the developed model, five computer experiments were conducted to simulate the main options for the operation of a plasma spraying system (Fig. 3). On the temperature distribution maps dimming level is proportional to temperature. The temperature of the detail surface is reduced from 600 °C (Fig. 3, a, c) to 200 °C with cooling by one water jet subsequently the spraying spot (Fig. 3, b) and up to 150 °C at cooling by two water jets (Fig. 3, c). Fig. 4 represents the calculation example of temperature profile.

Analyzing the cases of coating without additional electromechanical treatment (lanes 1 and 2), it can be concluded that the cooling by water jet reduces the average temperature of the detail surface along the line of movement of the plasmotron to 50-200 °C. In the case of additional electromechanical treatment without the water cooling the average surface temperature is about 200 °C higher than in the case of its absence. And using two water cooling jets allows to maintain the average temperature of the detail at an acceptable level (about 150 °C). Analyzing the profiles of the curves we can conclude that the every single water jet gives the reducing of the average temperature along the line of movement of the plasmotron to about 150-200 °C.

![Figure 4](image)

**Figure 4.** The temperature distribution in the cross section of the shaft (in the "plasma heating spot") during plasma coating without (a) and additional electromechanical treatment (b): 1-5 - number of computer experiment

4. Conclusions

Water cooling substantially reduces the temperature of the detail surface what contributes the formation of a more durable coating by reducing the internal stresses in it. In the case of the additional electromechanical surface treatment it is appropriate to use two cooling water jets: before and after roller pass.

References

[1]. Kadyrmetov, A. M., Pat. Russia №2480533, IPC S23S 4/18, V24V 39/06, 9/00 V23N Method of combined hardening of parts /Kadyrmetov A. M., Posmetyev V. I., Posmetyev V. V., Nikonov V. O., Suhotochev G. A., Maltsev A. F. – No. 2011140996/02; appl. 10/11/2011; publ. April 2, 2013, b Jul. No. 12. – 8 p.

[2]. Suhotochev, G. Computer generated spray coating modeling with simultaneous mechanical and electromechanical processing /G. Suhotochev; A. Kadyrmetov; E. Pamfilov //2015
International Conference on Mechanical Engineering, Automation and Control Systems (MEACS), IEEE Conference Publications, 1-4 Dec. 2015, Tomsk, Russia, DOI: 10.1109/MEACS.2015.7414923. – 2015. – pp. 1-4.

[3]. Sovetov, B. Ya. Modeling of systems: a training manual / B. Ya. Sovetov, S. A. Yakovlev. – M.: Higher School, 1998. – 319 p.

[4]. Polyanin, A. D., Linear problems of heat- and mass transfer: Basic formulas and results / A. D. Polyanin // Theoretical Foundations of Chemical Engineering. –2000. – T. 34. – No. 6. – P. 563-574.

[5]. Grinchik, N. N. To the problem of non-isothermal mass transfer in porous media /N. N. Grinchik, P. V. Akulich, P. S. Kuts, N. V. Pavlyukevich, V. I . Terehov //Engineering physical journal, 2003. – T. 76. – No. 6. – P. 129-142.