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Software Development for a New Robotic Technology of Microplasma Spraying of Powder Coatings

***Abstract**. The paper presents the main results of software development for a new robotic technology of microplasma spraying of powder coatings to protect surfaces of industrial parts. The numerical methods have been implemented for modeling temperature fields induced by the radiation treatment of coatings. The proprietary software products have been developed to perform calculations of temperature fields in two-layer heat absorbers under irradiation and to provide the desired trajectory of a plasma source. The laboratory samples with coatings have been obtained.*

Streszczenie.** W artykule przedstawiono główne wyniki opracowywania oprogramowania dla nowej zrobotyzowanej technologii mikroplazmatycznego natryskiwania powłok proszkowych w celu ochrony powierzchni części przemysłowych. Zastosowano metody numeryczne do modelowania pól temperatury indukowanych przez napromienianie powłok. Opracowano autorskie produkty do wykonywania obliczeń pól temperatur w dwuwarstwowych pochłaniaczach ciepła w warunkach napromieniowania i zapewnienia pożądanej trajektorii źródła plazmy. Uzyskano próbki laboratoryjne z powłokami. **Nowa zrobotyzowana technologia mikroplazmatycznego natryskiwania powłok proszkowych

Keywords: microplasma spraying, robotic technology, software development.
Słowa kluczowe: rozpylanie mikroskopowe, technologia robota, rozwój oprogramowania.

Introduction

Plasma spraying technology is now one of the leading technologies for applying a relatively thick coating (a few hundred of micrometers up to a few millimetres thick) on a substrate to protect its surface or improve its function [1, 2]. Development of processing control algorithms using specialized software allows improving significantly the performance and consistency of plasma spraying.

Amongst various existing plasma-spraying processes for surface protection against corrosion and wear, the Microplasma Spraying (MPS) is very beneficial for the high accuracy deposition of coatings on small parts [1-4].

However, one of the significant challenges remaining is the problem of the formation of coatings with specified structure and properties. Usually combined methods of plasma spraying including deposition of powder on the substrate and additional treatment of the coating surface by irradiation are used [1, 2]. Additional processing of the coatings by irradiation is suggested to melt the coating in order to reduce its roughness and increase the homogeneity of its structure [1, 2, 5, 6].

Based on our previous experience of plasma jet treatment of plasma-sprayed powder coatings [7-9], we proposed an alternative approach to the choice of modes of additional processing. The selection of plasma irradiation processing modes (namely, the power density of the plasma jet on the coating surface, the trajectory and the velocity of the plasma source), is based on the analysis the authors have done in their works [10, 11]. They have shown when Ni-based alloys reach relatively low temperatures of the order of 300 - 400 °C due to irradiation, there can be radiation-enhanced diffusion. Additionally intermittent expulsion of Chromium-Nickel intermetallic compounds may take place with a short exposure time at a given temperature (several minutes). Therefore, it is possible to ensure hardening of the surface due to the processing of coating with a traveling radiation source at relatively low power density of the source. The results of additional processing of plasma-detonation coatings by the direct current (DC) plasma jet are discussed in our works [7 - 9].

The aim of this work was to solve the problem of providing the desired trajectory of the plasma source and to develop the software to perform calculations of temperature fields in two-layer heat absorbers under irradiation by a traveling microplasma source for the deposition of coatings with predicted structure-phase composition and properties.

Mathematical Modelling

Model of heat propagation processes taking place during radiation treatment of coatings.

The model of heat propagation processes is based on nonlinear heat conduction equation (1).

$$\nabla \cdot (k(T)\nabla T) = c(T)\frac{\partial T}{\partial t} \quad (1)$$

Let x, y, z be the moving Cartesian coordinate system, where x – axe is lying along the heat source motion direction and z-axe is perpendicular to surface plane. The velocity of the coordinate system is equal to the velocity of a heat source v. In that coordinate system, the equation (1) becomes the equation (2).

$$\nabla \cdot (\mathrm{k(T)}\nabla \mathrm{T}) = \mathrm{c(T)}\left(\frac{\partial \mathrm{T}}{\partial \mathrm{t}} - \mathrm{v}\frac{\partial \mathrm{T}}{\partial \mathrm{x}}\right) \quad (2)$$

The term $\nabla \cdot (k(T)\nabla T)$ of equation (1) can be linearized using Kirchhoff's transformation.

$$U(T) = \int_{T_0}^{T} k(t)\,dt \quad (3)$$

Assuming the term $\frac{\partial T}{\partial t}$ is negligibly small and applying Kirchhoff's transform to equation (2), we obtain a quasi-steady-state heat conduction equation (4).

$$\Delta U + vF(U)\frac{\partial U}{\partial x} = 0 \quad (4)$$

Boundary value problems for a quasi-steady-state equation.

Let $T_1(x, y, z)$ be a quasi-steady temperature field in the coating, $T_2(x, y, z)$ - quasi-steady temperature field in the base system, and U_1 , U_2 - Kirchhoff's transforms of T_1 and T_2 respectively. Boundary conditions for nonlinear differential equations (5) and (6) are conditions (7)-(10):

$$\Delta U_1 + vF_1(U)\frac{\partial U_1}{\partial x} = 0 \quad (5)$$

$$\Delta U_2 + vF_2(U)\frac{\partial U_2}{\partial x} = 0 \quad (6)$$

$$\left(\frac{\partial U_1}{\partial z}\right)_{z=0} = -P(x, y) \quad (7)$$

(8) $$\left(\frac{\partial U_1}{\partial z}\right)_{z=h} = \left(\frac{\partial U_2}{\partial z}\right)_{z=h}$$

(9) $$U_1|_{z=h} = U_2|_{z=h}$$

(10) $$U_2|_{z=\infty} = 0$$

Description of numerical methods.

Our approach of numerical solving of boundary problems described above is based on the problem splitting into two independent problems described below.

Problem 1. Von Neumann boundary problem for a semi – infinite sheet with finite thickness h with boundary conditions (7) and (11)

(11) $$\left(\frac{\partial U_1}{\partial z}\right)_{z=h} = -Q(x,y)$$

where $Q(x,y)$ is the distribution of the flat heat source.

Problem 2. Von Neumann boundary problem for half-space.

Boundary condition on the surface is:

(12) $$\left(\frac{\partial U_2}{\partial z}\right)_{z=h} = -Q(x,y)$$

With our approach to solving the problem, the equations (1) and (2) are reduced to nonlinear integral equations, which are solved numerically using the iteration method.

The software development and implementation

We have developed the software that implements numerical methods described above for modeling temperature fields raised by the radiation treatment of coatings. The program being written in Python, for the implementation of standard numerical methods a NumPy and SciPy libraries was used.

The temperature fields in the “coating material – item material” model were calculated and analyzed with the variation of the thickness of the upper layer and the travel speed of the source, as well as the power density of the source within the technological capabilities of the MPN-04 device for microplasma treatment of surfaces (produced by E. O. Paton Electric Welding Institute, Ukraine).

In the calculations the following input data were used: the upper layer with the thickness of 50 to 300 µm - Nickel, the lower layer with the thickness of more than 2 cm –Iron.

We have improved the mathematical model of the temperature distribution in bilayer heat absorbers used earlier in software development [12], taking into account the temperature dependence of the coefficients in the heat transfer equation, and developed new software for calculating temperature profiles in two-layer absorbers with variable thermal-physical coefficients at heating by a traveling source.

Based on the results of the calculations, we chose the patterns of the distribution of the temperature fields that correspond to the attainment on the “coating-substrate” boundary temperature of about 673 K and recommended corresponding modes of additional irradiation with microplasma of samples coated with nickel-base alloy of a certain thickness.

Figure 1 shows the screenshots taken during the operation of the program that calculates the thermal field of a traveling source using the next input data: heat source - a Gaussian distribution of surface power density, effective beam diameter - 1 mm, power source - 2 W, travel speed - 6 mm/s. The substrate material in both cases is Iron: density - 7870 kg/m^3, thermal conductivity - 79.9 W/mK, specific heat 447.0 J/kgK. Coating: thickness - 100µm, material - Nickel, density - 8902 kg/m^3.

The dependence of the coefficients of thermal conductivity (Fig.2) and specific heat of Nickel on temperature was taken into account from the experimental graphs of these dependences according to generalized data from background literature sources [13-14].

Since the developed software allows using an arbitrary dependence of the thermophysical properties of material on temperature, we used the constant functions of the dependence for comparison with the results of the calculation of temperature profiles by the patented software [12].

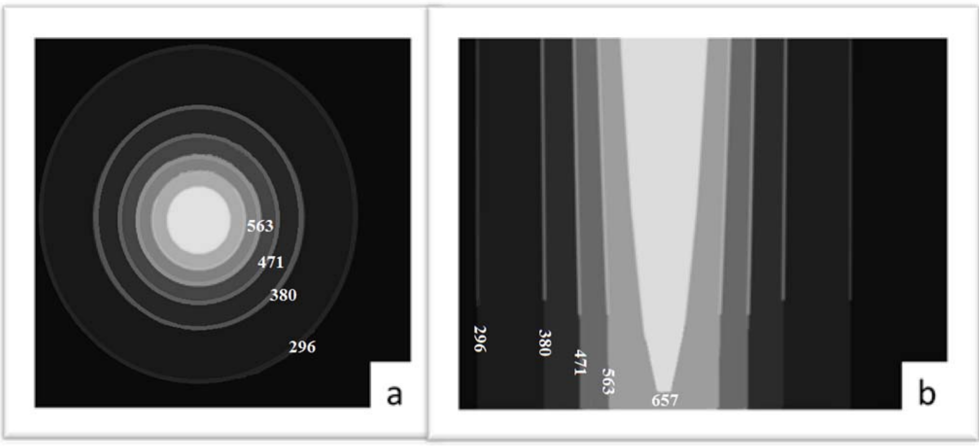

Fig.1. Contour maps of temperature field on the border of the Ni-based coating and the Fe-based substrate: the section cut parallel to the plane of the sample surface (a); the section cut perpendicular to the plane of the sample surface, the vector of the beam velocity is parallel to the plane of the cut (b)

To solve the problem of providing the desired trajectory of the plasma source, we have developed software titled “Converter for DXF drawings into AS language of robot manipulator Kawasaki RS010L” which converts the drawings made in AutoCAD and Compass to the robot controller by selecting the graphics primitives (line, arc, etc.) from the drawings and transferring them into the commands for the robot arm movement [15].

Thus, the choice of trajectory of the plasma source and processing modes has been made on the basis of the optimized condition identified by the initial experimentation and mathematical modelling.

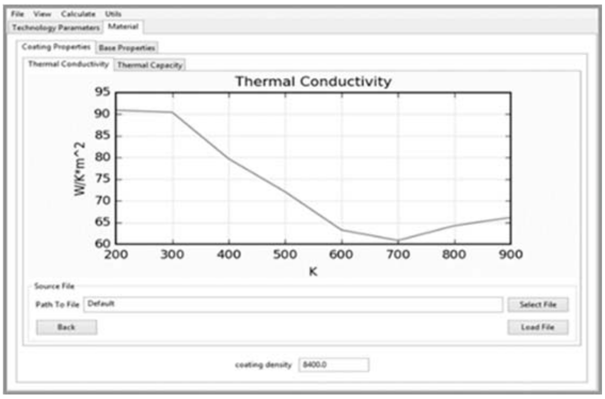

Fig.2. The screenshot of the window of thermophysical properties of the coating material: the graph of Nickel thermal conductivity coefficient dependence on temperature

Materials and Methods

The research material is NiCrBSi alloy PG-10N-01 (Ni-based powder alloy with additives of Cr (8…14%), B (2.3%), Si (1.2…3.2%), Fe (5%), C (0.5%) deposited onto the Steel St3 (Fe – base, C - 0.25 %, Mn – 0.8 %, Si – 0.37 %, P < 0.045%) substrate by a plasma jet. In order to form the desired nanostructures in microplasma coatings we used the same powders as for plasma detonation coatings where we observed these nanostructures previously [7-9]. The average diameter of powders particles is 40 - 45 μm. The substrate surface has been cleaned by grit blasting before microplasma spraying of the powders.

The microplasma deposition of Ni-based powders onto steel substrates was carried out with the help of “MPN-004” micro-plasma deposition unit (produced by E. O. Paton Electric Welding Institute, Ukraine) mounted on the industrial robot arm (Kawasaki Robotics, Japan). Innotech Ltd, Kazakhstan, carried out the mounting of the robot with “MPN-004” in which the powder is fed in a stream of argon onto a substrate of any shape.

The modes of microplasma deposition were as follows: a laminar DC plasma jet; the Ar plasma forming and protective gas; 1…8 mm diameter of the spray spot; 2 W power of plasma source; 2 kg/hour powder flow rate; 0.008 m/s travel speed of the plasma jet. The additional treatment of the samples by a plasma jet was carried out at the power density of $2.0 \cdot 10^9$ W/m^2 with 0.006 m/s plasma jet travel speed. A saw-shaped scanning (the zigzag path of a plasma source) was used to provide uniform surface coating.

Discussion

The laboratory samples with 100 μm thick coatings from Ni-based powders deposited by the microplasma according to the recommended modes onto steel substrates have been obtained. XRD methods allowed establishing that phase compositions of the initial powders PG-10N-01 and the microplasma coatings from them are different. The new $CrNi_3$ intermetallic phase appears in the coating whereas the initial powder does not contain this phase. The volume fraction of Ni-based solid solution in the coatings is on average 5% higher than in the initial powders. At the same time, the phases of chromium oxide and $Cr_3Ni_5Si_2$ completely disappear in the coatings (Fig.3). This is the result of combined MPS of powders and additional treatment of coatings by plasma jet.

As TEM analysis demonstrates, the coating is mainly composed of crystallographically disoriented nanograins of Ni-based solid solution with fcc type of crystal lattice, which precipitates nanoscale lamellae of the $CrNi_3$ intermetallic phase with the fcc structure. Thus, we observed the same structures as we described in our works [7-9].

The average microhardness of the PG-10N-01 coating is 7.3± 0.5 GPa. On average, the microhardness of the PG-10N-01 coating is 4 times higher than that of the substrate. This hardening effect is due to the phase transformations, which take place at lower temperatures.

Thus, we managed to obtain coatings with predictable material structure-phase composition and properties. So the accuracy of computer stimulation of temperature profiles has been implicitly verified. Hence, the model of the process we have developed is correct, and the whole process and the software in particular are reliable.

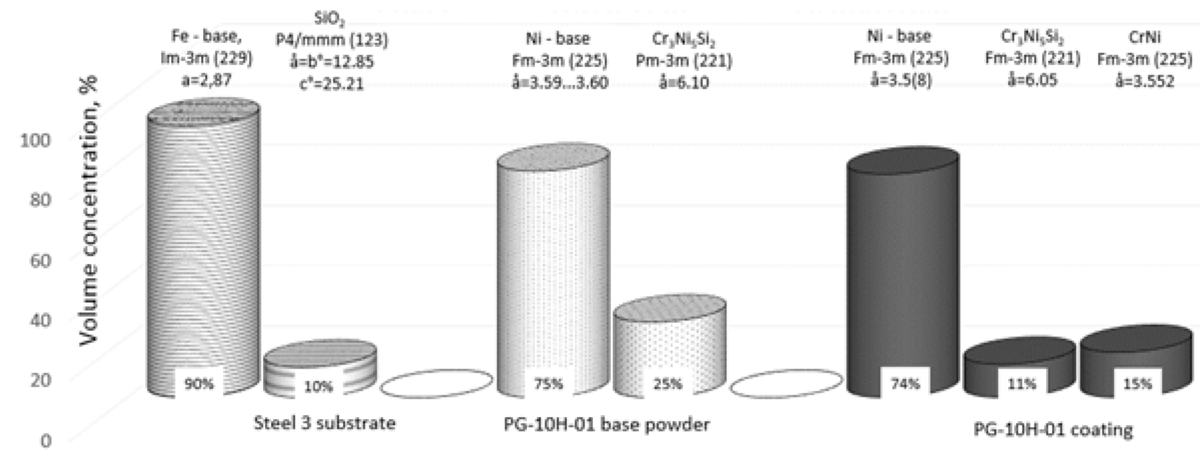

Fig.3. Phase composition of investigated materials: chemical formula, space group, space group number, parameters [Å]

In prospect, the database on thermophysical properties of various metals may be expanded and mathematical modelling in obtaining protective coatings can be more widely used. However, our proposed approach is not universal. It requires a thorough analysis of the coating material and the potential for desirable phase transformations.

We have simulated a number of processes taking place in the coatings to achieve the desired precipitation of $CrNi_3$-phase in Ni-based coatings during the additional treatment by a plasma jet. That involved the accurate selection of an efficient velocity of the microplasma source travelling. As a rule, manufacturers of microplasma spraying units indicate in the documentation such parameter as the effective radius of the plasma spot. It is assumed that the power distribution density is described by a Gaussian distribution, wherein the effective radius and power of the spraying unit completely determine the distribution parameters. Thus, in the calculation of temperature fields, we can vary only one parameter, namely, the velocity of the source. We applied the dichotomy method to adjust the velocity of the source, at which the maximum temperature in the layer separating the coating and the substrate equals approximately 400 °C (673 K). During the trajectory planning the distance between neighbouring lines of the source passage is defined. Using the calculated two-dimensional temperature distribution at the base-coating boundary, we can choose the distance d between the lines so that the temperature at a distance $\frac{d}{2}$ from the maximum point deviates from the maximum by no more than 20%. Thus, a specific temperature field in the system of a coating-substrate has been created to provide the predicted precipitation of hardening $CrNi_3$ phase in the coatings during the additional treatment. Since the mechanical properties of the coating, in particular its microhardness, are determined by the structural-phase state of the coating, we can claim that we predict an increase in the microhardness when the specified temperatures are reached during additional treatment.

Conclusions

The new proprietary software products have been developed to perform calculations of temperature fields in the two-layer heat absorbs under irradiation by a traveling source, and to provide the desired trajectory of the plasma source. The suggestions for the trajectory and velocity of plasma source travelling, the power density of the microplasma are based on the results of original software calculations.

We have received experimental samples of protective Ni-based powder coatings deposited onto steel substrates by the microplasma method according to the modes recommended based on calculations by the software being developed. It was established experimentally that the coatings have a predicted structure-phase composition and higher hardness.

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