Software Development for a New Technology of Precision Application of Powder Coating Multifunctional Systems

D.L. Alontseva, A.L. Krasavin, O.B. Ospanov
East Kazakhstan State Technical University, 69, Protazanov Street, 070004 Ust-Kamenogorsk, Kazakhstan
dalontseva@mail.ru
alexanderkrasavin@mail.ru
ospanovolzhas@gmail.com

Abstract - **The paper presents the main results of software development for a new technology of precision application of powder coating multifunctional systems to protect surfaces of industrial products using microplasma material processing complex with the assistance of an industrial robot. The use of this technology allows receiving multifunctional systems of powder coatings with the predicted nanostructure and a complex set of properties such as microhardness and corrosion resistance. The choice of components for developing multifunctional powder coating systems and the trajectory of the plasma source and processing modes is made on the basis of the optimized condition identified by the initial experimentation and mathematical modeling. The numerical methods have been implemented for modeling of temperature fields raised by the radiation treatment of coatings. A proprietary software product has been developed to perform calculations of temperature fields in a number of industrial materials under irradiation.**

I. INTRODUCTION

Nowadays, various types of thermal spray coating processes for surface protection against temperature extremes, corrosion and wear are actively developing all over the world [1,2]. Among the different existing plasma spraying processes, the Microplasma Spraying (MPS) is particularly characterized by the low plasma power, low plasma gas flow rate, small spray spot (1...5mm), and a possibility of forming a laminar jet with the length of 100 ... 150 mm, which heats the refractory material in a stream of Ar plasma and provides low heat input into the substrate [3-6]. These properties are very beneficial for the deposition of coatings on small parts or with high accuracy. However, there are still a number of challenges, and the most important among them is a problem of the formation of coatings with the specified structure and properties.

The main prerequisites for the development of the study were the analyses of technical issues arising from the application of industrial robot for coating by plasma jets, and the desire to expand the range of tasks solved by the application of an industrial robot. The technologies of plasma spraying of coatings require accurate sustaining **of** the number of technological parameters (the distance from the plasma system nozzle to the surface of a work piece, the nozzle movement speed, etc.) during the entire processing time. Exceeding these parameters beyond the permissible limits can lead not only to rejected products, but also to an accident (a short circuit). In cases when the robot program is generated according to a given geometrical model of a processed work piece or part, the deflection of the real object shape from the model often leads to the violation of technological parameters of processing with all its undesirable consequences.

The aim of this work was to develop the software to perform calculations of temperature fields in a number of industrial materials under irradiation by **a** moving source for the deposition of coatings with the predicted nanostructure and to solve the problem of providing the desired trajectory of the plasma source. Our previous works [7, 8] dealt with the selection of relevant components for developing multifunctional powder coating systems and appropriate trajectory of the plasma source and processing modes. It was based on mathematical modeling of the optimized condition determined by our initial experimentation [9, 10].

II. EXPERIMENT

A. Materials and Methods

The research material is PG-19N-01 (Ni- based powder alloy with additives of Cr (14…20%), B (3.5%), Si (4.3%), Fe (7%), C (0.8%) 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, 8].

The microplasma deposition of powders onto steel substrates was carried out at a pilot production site at the East-Kazakhstan State Technical University equipped with the industrial complex microplasma processing of materials on the basis of Kawasaki RS010L industrial robot (Kawasaki Robotics, Japan). The robot arm has a mounted device for the microplasma deposition of “MPN-004” powder coating (produced by Paton Institute, Ukraine), in which the powder is fed in a stream of argon onto a substrate of any shape. Innotech Ltd, Kazakhstan, carried out the mounting of the robot. To solve the problem of providing the desired trajectory of the plasma source, we have developed the software, 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 transferred them into the commands for the robot arm movement.

B. 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)

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

Let x, y, z be the moving Cartesian coordinate system, where x – axe 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)

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

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

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

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

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

C. 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)

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

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

are conditions (7) - (10):

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

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

$$U_1|_{z=h} = U_2|_{z=h} \tag{9}$$

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

D. 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)

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

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:

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

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

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

We have simulated a number of processes taking place in the coatings with the purpose to achieve the desired precipitation from the melt phase during the deposition and cooling processes, as well as during the additional treatment by a plasma jet (Fig.1). This includes the optimum choice of the power density of a plasma source on the coating surface and also an efficient speed of the source movement. A specific temperature field in the system of a coating-substrate has been created to provide the precipitation of hardening phases in the coating during the added treatment. During this procedure the surface of the coating is melted, whereas the area of the interface of the coating with substrate is exposed to the temperature of about 400°C for several minutes. In our previous study the temperature distribution in two-layer absorbers was calculated using both: a permanent linear case model and a variable thermal parameters non-linear model [9, 10].

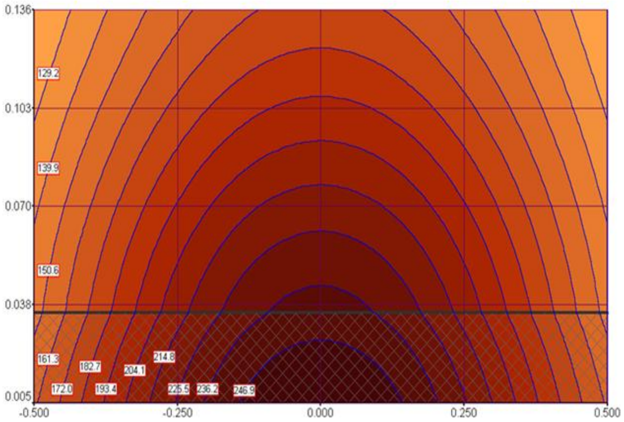


Figure 1. The contour map of the temperature field (cut perpendicular to the plane of the sample surface, the vector of the beam velocity is parallel to the plane of the cut)

E. The modes of surface treatment

Deposition and additional treatment parameters are given in Table 1. The additional treatment of the samples by a plasma jet was carried out at power density of 2.0×10^9 W/m^2.

TABLE I.
REGIMES OF COATINGS SYNTHESIS

Modes	P [W]	U[V]	I [A]	The plasma forming gas (Ar) flow rate [liter/hour]	The protective gas (Ar) flow rate [iter/hour]	The travel speed of the plasma jet [m/s]	The powder flow rate [kg/hour]	The powder utilization rate
Deposition	2	30	40	70	360	0.008	2	0.7
Additional treatment	2	30	40	60	250	0.006	-	-

F. Experimental methods of coating structures analysis

Experimental methods of analysis include Transmission Electron Microscopy (TEM) by JEM-2100 (“JEOL”, Japan) with Energy Dispersive Spectrometry (EDS) INCA Energy TEM 350 (“Oxford Instruments”, Great Britain), Scanning Election Microscopy (SEM) by JSM-6390LV (“JEOL”, Japan), X-ray diffraction (XRD) by X’Pert PRO (“PANalytical”, the Netherlands). M-691 Precision Ion Polishing System (“Gatan”, USA) was used to prepare TEM foils by the Ar ion sputter etching method. Microhardness test of the samples was performed with LM-700 digital microhardness meter (LECO, Russia). Corrosion was tested using the potentiostatic method to measure the sea-water corrosion rate.

III. RESULTS

XRD methods have allowed to establish that phase compositions of the initial powder PG-19N-01 and the microplasma coating are different. A new $CrNi_3$ intermetallic phase has appeared in the coating and the volume concentration of $Cr_{13}Ni_5Si_2$ phase has decreased by 2.5 times compared to the initial powder. As TEM analysis demonstrates, the coating is mainly composed of crystallographically disoriented nanograins of Ni-based solid solution with the fcc type of crystal lattice, which precipitates nanoscale lamellae of the $CrNi_3$ intermetallic phase with the same fcc structure (Fig. 2). The EDX spectrum shows the presence of such elements as Ni, Cr, Fe, that is in a good agreement with XRD results.

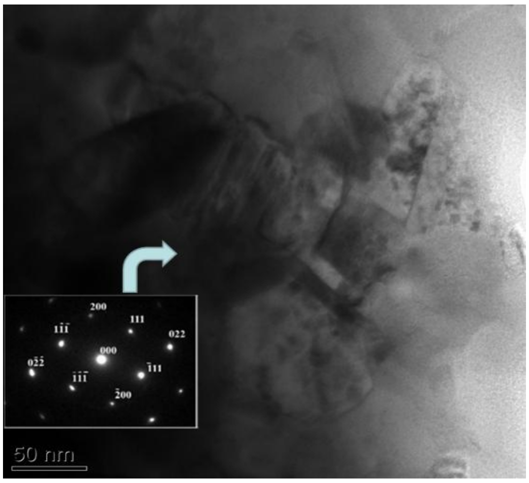
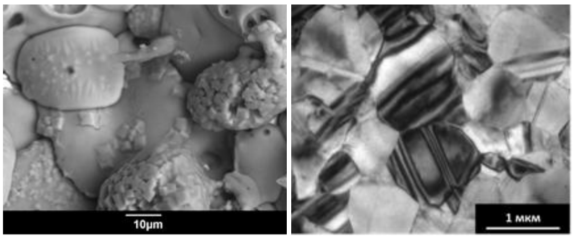


Figure 2. The TEM image of the PG-19N-01 coating with the lamellas of intermetallic phases and the corresponding micro diffraction pattern

SEM images of the coating surface show the broken powder particles (Fig. 3 a). By TEM methods we observe the twins in the substrate grains (Fig. 3 b). Probably, the twins appear for lowering the stress in the surface layer of the substrate due to impact of the plasma jet with powder particles.



a b

Figure 3. The SEM image of the PG-19N-01 coating (a); the TEM image of the substrate Steel 3 (b)

The microhardness of the coating is 7.0 ±0.05 GPa in average. The results of the corrosion resistance test in the seawater confirm the sufficient growth of corrosion resistance for the coated samples compared to an unprotected substrate. Steel 3 substrate and PG-19N-01coating sea water corrosion potential is rather high: $\varphi_{corr}= -0.28$ V and $\varphi_{corr}= -0.35$ V correspondingly. Yet the substrate corrosion rate is considerably higher: i_{corr}(substrate)=3.9 mm/yr, i_{corr}(coating)=2.7 mm/yr.

To sum up, we have managed to obtain the coatings with predicted structure-phase composition and properties for specified materials. We suppose these results are quite important due to the following reasons: firstly, the structure of coatings is similar to the structure of nanocomposite, the coating consists of the ductile base with fcc lattice type which is reinforced by lamellas of hard and heat-resistant intermetallic phase. In perspective, it gives the possibility of creating a protective coating having a combination of such properties as thermal stability, high hardness and good ductility all at once, as noted also by the authors of works [2, 4, 6]. Secondly, the results indirectly confirm the correctness of the computer stimulation of temperature profiles; therefore, we have designed the correct model of the process as the whole process and the reliable software in particular. In the future, we can expand the database on thermal properties of various metals and greater use of mathematical modeling in the practice of obtaining protective coatings.

IV. CONCLUSION

A proprietary software product has been developed to perform calculations of temperature fields in a number of industrial materials under irradiation, and evidence-based recommendations have been provided on the choice of modes of surface modification by the microplasma (the trajectory and speed of the plasma source, the power density of the microplasma). The laboratory samples with protective powder coatings deposited by the microplasma according to recommended modes onto steel substrates have been obtained, and it was established experimentally that the coatings have the predicted structure-phase composition, namely the nanograin Ni-based solid solution with precipitations of strengthening intermetallic lamellas which provide the coatings high microhardness. The coatings have a good corrosion resistance in seawater. Thus, the scientific bases of the surface modification technology have been implemented by microplasma exposure and an automated pilot production site has been developed.

ACKNOWLEDGMENT

The authors thankfully acknowledge the funding provided by the Scientific Committee of the Ministry of Education and Science of the Republic of Kazakhstan for the project 0869/GF titled “Automated precision deposition of powder coating multifunctional systems”.

REFERENCES

[1] S.Kuroda, J. Kawakita, M.Watanabe, H. Katanoda, Warm spraying—a novel coating process based on high-velocity impact of solid particles, Sci. Technol. Adv. Mater. 9 (3): 033002. (2008). DOI:10.1088/1468-6996/9/3/033002.

[2] Mahmood Aliofkhazraei, Comprehensive Guide for Nanocoatings Technology, Nova Science Publishers, Properties and Development, Vol.3, NY, 2015, 481p. ISBN 978-1-63482-647-1.

[3] L.Wang, H.Wang, S.Hua, X. Cao, *Plasma Science and Technology.* 9, 52 (2007). DOI: http://dx.doi.org/10.1088/1009-0630/9/1/11.

[4] E. Lugscheider, K. Bobzin, L. Zhao and J. Zwick, Assessment of the Microplasma Spraying Process for Coating Application Advanced Engineering Materials Special Issue: Thick Coatings for Thermal, Environmental and Wear Protection Volume 8, Issue 7, 2006, p. 635–639. DOI: 10.1002/adem.200600054.

[5] L.Travis, J.Michael, Spray deposition of nanostructured metal films using hydrodynamically stabilized, high-pressure microplasmas J. Vac. Sci. Technol. A 31, 061312 (2013); http://dx.doi.org/10.1116/1.4825129.

[6] A V Andreev, I Y Litovchenko, A D Korotaev, D P Borisov Thermal Stability of Ti-C-Ni-Cr and Ti-C-Ni-Cr-Al-Si Nanocomposite Coatings 12th International Conference on Gas Discharge Plasmas and Their Applications. IOP Publishing Journal of Physics: Conference Series 652 (2015). . DOI:10.1088/1742-6596/652/1/012057.

[7] D.L. Alontseva, A.L. Krasavin, A.V. Russakova, T.A. Kolesnikova, G. S. Bektasova , *Materials Science (Medziagotyra)* 22, 2 (2016). DOI: 10.5755/j01.ms.22.2.7699.

[8] D. Alontseva, E. Ghassemieh The Structure-Phase Compositions of Powder Ni – based Coatings after Modification by DC, *Journal of Physics*, (2015) DOI:10.1088/1742-6596/644/1/012009.

[9] A.L. Krasavin, D.L. Alontseva, N.F. Denisova, Certificate of authorship No.0010558 of the Republic of Kazakhstan for the computer program (entry in the register number 1151 of August 20, 2013).

[10] D.L. Alontseva, A.L. Krasavin, T.A. Kolesnikova, A.V. Russakova, Acta Physica Polonica A 125, 6 (2014). DOI: 10.12693/ APhysPolA.125.1275.