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ANALYSIS OF STUDIES OF THE FORMATION OF MULTIFUNCTIONAL COATINGS BY GAS-DYNAMIC SAWING

The article considers a progressive gas dynamic method for functional coatings formation. Theoretical analysis of methods of restoration coatings deposition on worn parts was carried out in order to determine the advantages and disadvantages of these methods, the method of gas dynamic spraying was characterized, the feasibility of implementing the technology in industry was determined. This method has a significant advantage over other spraying methods and can be successfully used to improve the performance characteristics of units and mechanisms of technological equipment. The article determines the optimal size of the sprayed copper and aluminum particles, as well as the required speed for carrying out the technological process. The main stages of coating formation by this method are considered. Inspection of modern gas dynamic spraying equipment was carried out. A general scheme of technological process of coating formation by gas dynamic spraying was developed, dependences of the temperature and particles velocity depending on spraying methods were defined: gas-flame (low-speed); electric arc; gas-flame (high-speed); plasma; detonation; and gas dynamic. The results of calculations and experimental values of dependence of aluminum and copper particles velocity on the obstacle surface on the size of these particles are presented.

The article defines typical characteristics of gas dynamic spraying installations of powder materials, after that these machines are analyzed in order to determine the most versatile, economically feasible and efficient installations used in domestic repair units.

Key words: *gas dynamic spraying, coating formation, surface restoration and protection, melting, composites, powder materials, density, thermal action, gas-flame, electric arc, plasma; detonation, gas dynamic.*

Introduction. *Cold gas dynamic spraying of metal is a spraying method in which solid metal particles, the temperature of which is much lower than their melting point, are accelerated to the supersonic velocity and fixed on the surface in contact with it. The absence of high temperatures can significantly expand the possibilities of powder coating methods and provides a number of important advantages of cold gas dynamic spraying method over known thermal methods, including:*

- possibility to use powders with the size less than 30-50 microns for spraying, including ultradisperse ones, which improves the quality of coating - its density increases, the volume of microvoids decreases, the structure becomes more uniform, it is possible to reduce the coating thickness;

- absence of significant heating of particles and related processes of high-temperature oxidation, phase transitions, etc., which allows achieving coatings with properties close to those of the material of the original particles, as well as composite coatings from mechanical powder mixtures which differ significantly in physical and thermal properties;

- lack of significant thermal influence on the product, which allows applying coating on substrates made of temperature-sensitive materials;

- simplicity of technical implementation and improvement of work safety due to the

absence of high-temperature jets, as well as flammable and explosive gases.

The essence of the method of cold gas dynamic spraying of metal includes the formation of a supersonic gas flow in the nozzle, delivery of powder material with particle size (0,01-50) μm into this flow, its supersonic acceleration in the nozzle and direction of powder particles on the product surface. Particle acceleration is possible among cold or preheated gases, such as air, helium, nitrogen. Temperature values are significantly lower than the melting temperature of the powder material (0,4-0,7) T_m. Cold gas dynamic spraying technology makes it possible to apply metal coatings not only on metals, but also on glass, ceramics, stone, concrete. Coatings deposited by this method are mechanically strong and have high adhesion to the substrate [1].

Analysis of recent research and publications. *A.P. Alkhimov, V.F. Kosarev, A.N. Papyrin, N.I. Nesterovich, S.V. Klinkov, V.M. Fomin et al., made a significant contribution to the study of the coating deposition process by gas dynamic spraying.*

The phenomenon of coatings formation by gas dynamic spraying was first discovered at Khristianovich Institute of Theoretical and Applied Mechanics in the early 1980s of last century. They showed that it was not necessary for the particles to be in a molten or pre-molten state in order to form a coating, and the coating could be obtained from particles with a temperature much lower than their melting point, in contrast to traditional spraying methods.

The main tasks of gas dynamic spraying is to eliminate damage to light alloys parts, primarily aluminum or aluminum-magnesium alloys, arising both during their production and operation, and this is the most efficient way of using this technology. It is important to emphasize that the low energy of the process allows eliminating defects and damage, even to thin-walled parts, the restoration of which in other ways is simply impossible. The reason for this is the lack of heating of the part (the part is not heated above 100-150°C), and hence the absence of oxidation of the sprayed material and substrate, the absence of thermal deformations of the product and internal stress.

Gas dynamic coating is used for the following works: casting repair, mechanical damage elimination, restoration of bearing seats, leak sealing of liquids and gases, application of electrically conductive coatings, anti-friction coatings, anti-corrosion coatings, etc. In addition to the above-mentioned areas, it is effective to use gas dynamic spray technology and equipment to provide protection against high temperature corrosion, prevent "setting" in power threaded connections, sealing of heat exchangers and refrigeration units, electrical equipment housings, creating reflective technical and decorative products.

Purpose and objectives of the research. *To determine the advantages of the gas dynamic method functional coatings formation over other spraying methods, which significantly affects the improvement of performance characteristics of units and mechanisms of technological equipment. To estimate the optimal size of sprayed copper and aluminum particles, as well as the required speed for the technological process. To consider the main stages of coating formation by this method. To inspect modern gas dynamic spraying equipment.*

Presentation of the main material. *Modern technological equipment operates in rather severe operating conditions, which leads to premature failure. It is possible to increase operational characteristics of units and mechanisms of technological equipment using the methods of coatings formation in energy flows [2]. Among these methods, powder spraying methods play a special role, since they possess a wide range of technological capabilities and allow the formation of various coatings (including composite ones).*

In the process of powder spraying, the material particles receive in a fairly wide range from the heating source thermal energy and from the gas flow kinetic energy. Both types of energy are simultaneously and jointly involved in the coating formation and determine the specifics of its structure and operational characteristics.

With the prevalence of thermal energy over the kinetic, the formed coatings have good adhesion, but also have the following technological disadvantages which significantly reduce the prospects for their use:

- unfavorable working conditions of staff providing the technological process of coating application;

- high temperature of heating the processed part surface;

- obtaining high porosity of coating;

- high internal stresses formed in the coatings.

These disadvantages can be eliminated if the coating is formed mainly due to the kinetic energy transmitted by the flow of particles of the sprayed material.

The analysis of powder spraying methods based on the gas dynamic method GDM was performed (Fig. 1).

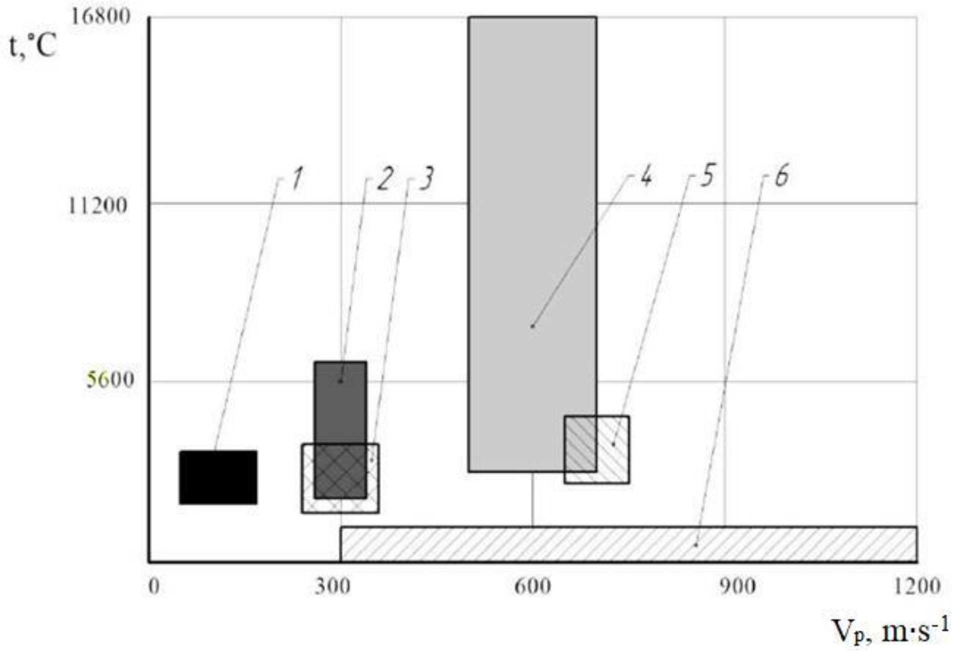

Fig. 1. Temperature (t) and particle velocity (Vp) dependence diagram depending on spraying methods: 1 – gas - flame (low-speed); 2 - electric arc; 3 – gas-flame (high-speed); 4 - plasma; 5 - detonation; 6 – gas dynamic

This method allows forming multilayer composite coatings of soft metal powders on the workpiece surfaces.

The velocity of contact of particles with the substrate material is of great importance in the process of applying coatings by gas dynamic method [3]. Therefore, the determination of this velocity for GDS is one of the main tasks for improving the efficiency of this method.

The velocity calculation was performed for a single particle. It is assumed that the particle motion into the nozzle is carried out along its central axis without turbulent pulsations of gas parameters.

The calculation of the particle acceleration was carried out according to the equation:

$$m_p v_p \frac{dv_p}{dz} = C_x \frac{\rho \cdot (v - v_p)^2}{2} \cdot S_{mid}, \tag{1}$$

where m_p *– mass of the particle;* v_p *– velocity of the particle;* C_x *– particle drag coefficient;* ρ *– gas density;* v *– gas velocity;* S_{mid} *– Midsection.*

To obtain the particle drag coefficient the Henderson approximation was used:

$$C_x = \begin{cases} C_{x1}, M_p, < 1 \\ C_{x2}, M_p, > 1{,}75 \\ C_{x1} + 1{,}33(M_p - 1)\left(0{,}9 + \frac{0{,}34}{1{,}75} - C_{x1}\right), 1 < M_p < 1{,}75 \end{cases} \quad \begin{matrix}(2)\\(3)\\(4)\end{matrix}$$

$$C_{x1} = \frac{24}{Re_p + 3{,}06\sqrt{\gamma}} + \frac{4{,}5 + 0{,}0114 Re_p + 0{,}1825\sqrt{Re_p}}{1 + 0{,}03 Re_p + 0{,}48\sqrt{Re_p}} + 0{,}3 \tag{5}$$

$$C_{x2} = C_{x1} + 0{,}1 M_p^2 + 0{,}2 M_p^8 - 0{,}3 \quad 6)$$

$$M_p = \frac{v - v_p}{\alpha} \qquad 7)$$

$$Re_p = \frac{(v - v_p)\rho d_p}{\mu} \qquad 8)$$

where d_p – particle diameter; μ – gas viscosity; α – local velocity of sound $\left(\alpha = \sqrt{\gamma \frac{p}{\rho}}\right)$; p – static gas pressure; γ – adiabatic index $\left(\gamma = \frac{c_p}{c_v}\right)$; C_p – heat capacity of the gas at constant pressure; C_v – heat capacity of the gas at constant volume.

Experimental determination of particle velocity was performed according to the well-known method, the so-called track method. This method is easy to use and provides satisfactory reliability of measurements at very low concentrations of particles simultaneously at different distances from the nozzle exit, while reliably measuring the velocity of particles up to 5 μm in size in the speed range from 200 to 1200 m/s [4].

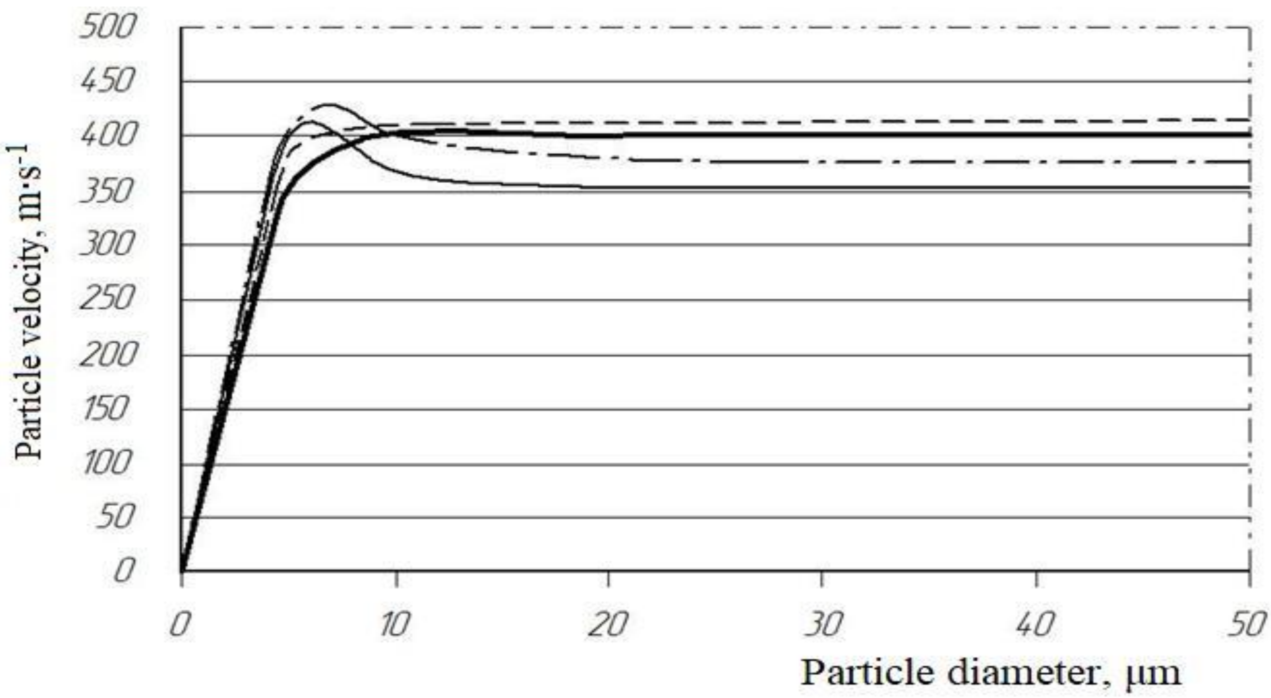

Fig. 2. Results of calculations and experimental values of dependence of aluminum and copper particles velocity at the obstacle surface on the size of these particles (L = 150 mm, p_0= 2 MPa, where L - distance from the nozzle exit; p_0 - gas flow pressure)

Calculation	***Experiment***
- - - - - - - - - - ***copper particles***	-·-·-·-·-·-·-·- ***copper particles***
——— ***aluminium particles***	——— ***aluminium particles***

Analysis of the obtained calculated and experimental studies showed that the results of the values have a good correlation (Fig. 2).

As seen from the graphs, particles smaller than 5 μm immediately before the substrate, lose their initial velocity significantly. Copper and aluminum particles with a size of 5-50 microns, contact with the substrate at approximately the same speed.

It can therefore be concluded that the optimal particle size is at least 10 μm, which should be accelerated to a velocity of 400 m/s.

The general scheme of the technological process of gas dynamic coating formation (Fig. 3) includes: preparing a powder material, preparing a surface for coating, coating, finishing coatings and quality control of the applied coating.

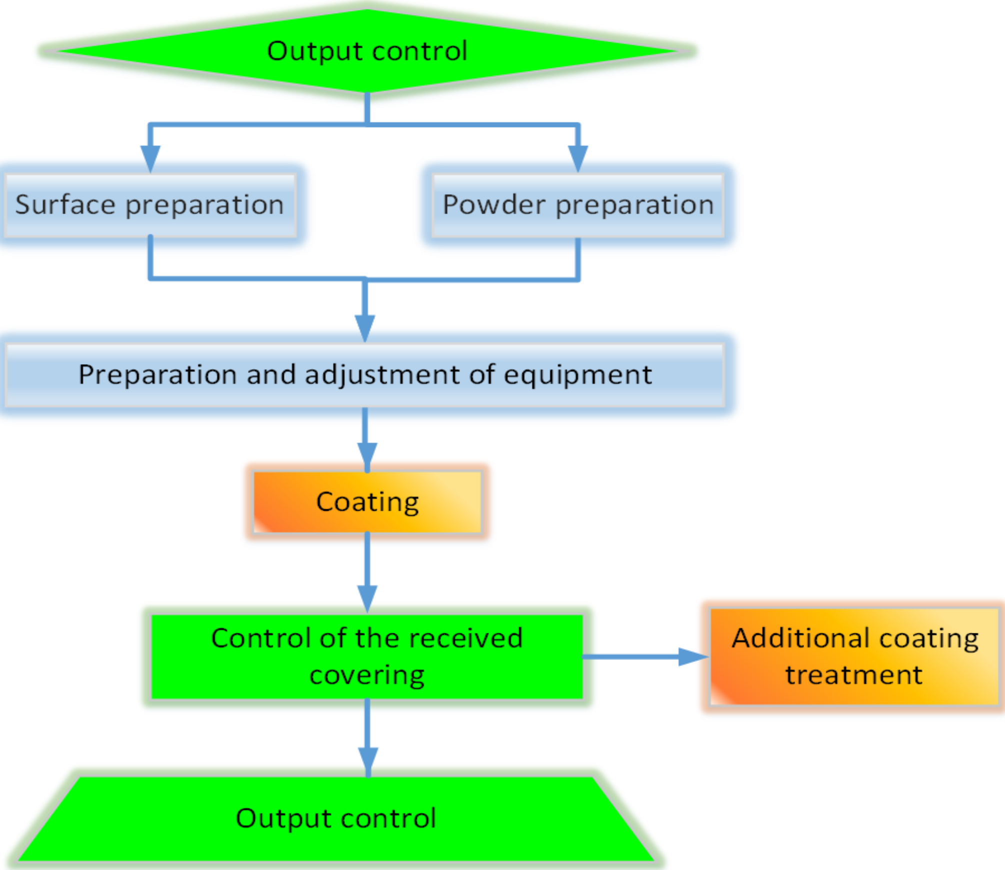

Fig. 3. General scheme of the technological process of gas-dynamic coating formation

At the stage of preparing the powder material, drying of the powder is mandatory, which improves its flowability, promotes moisture removal and various organic impurities. Drying of metal powders is carried out in drying cabinets at a temperature of about 150^{0}C for 5 hours. If several types of powders are planned to be applied simultaneously, the mixture is supposed to be prepared using mechanical agitators.

In preparation for coating, the surface is cleaned from various contaminants by mechanical, chemical and other methods and it is given the necessary roughness.

For high-quality surface preparation it is necessary to follow a number of requirements:

- prepared surface should have a temperature of about + 25 ° C;

- oxide film is removed from the surface with metal brushes, followed by washing with hot water and detergents;

- grease and oil films are removed from the surface with acetone, gasoline or other organic solvents;

- moisture is removed from the surface either by drying under natural conditions or by heating the product to a temperature of +200^{0}C.

Finally, after preparing to coat the surface, the product should be blown off with compressed air to remove dust.

The prepared surface must be protected from moisture, dust, oil and other contaminants.

The coating technology consists of two stages. The first stage is the heating and acceleration of particles. The second stage is the direct interaction of particles with the substrate material.

To prevent intense oxidation of the surface, its heating temperature should exceed +200^{0}C. It should be taken into account that the rate of chemical reactions of bonding is significantly affected by the applied spraying rate [5].

In coatings applied by spraying method, tensile or compression stresses occur. For most materials, the rule is fulfilled: with different coating materials and substrate, residual tensile stresses occur if the thermal expansion coefficient of the sprayed material is equal to or greater than that of the base material. Otherwise, compression stresses arise, leading to the parts damage.

There are known technological methods that regulate residual stresses and adhesion of coatings [6]:

- coordination of temperature coefficients of linear expansion of materials;

- reduction of the thermal effect of gas on the substrate material;

- introduction of plastic components into the structure of the sprayed material;

- use of additional applied sublayers;

- reinforcement of the coating with fibers or wires;

- spraying on parts that are in the pre-stressed state.

Finishing of applied coatings consists in machining of the part surface (brushing, shot, pressing or rolling), sintering, impregnating, melting, etc. As an additional treatment, it is possible to apply a paint-and-lacquer or polymer coating, which significantly increases its corrosion resistance.

Quality control of the obtained coating is carried out on finished products or specially prepared samples. At this stage, the following parameters are controlled [7]:

- external appearance of the coating: the coating must be intact, uniform in color and without cracks;

- minimum coating thickness: it is set depending on a purpose of coating and its operating conditions, established in accordance with State Standards 9.304-87 of the required service life of protective properties;

- coating roughness: should not exceed Rz 100 in accordance with State Standards 2789-73;

- adhesive strength of the coating material with the substrate material: when tested by scratches, no peeling of the coating should occur;

- coating porosity: is set in accordance with the requirements of technological documentation;

- corrosion resistance of the coating: the coating must have the required corrosion resistance in accordance with the requirements of operating conditions.

According to the results of the market research of gas dynamic spraying equipment, it was found that this equipment is produced by both foreign and domestic manufacturers (table 1)

Table 1

Typical characteristics of gas dynamic powder spraying plants.

Manufacturer	**CGT**	**ITPM**	**Intermetcompozyt**	**Inovati**	**OCPN**
Equipment	Kinetiks	UHGN	NGA-5	KM	DIMET
Working gas	nitrogen/ helium	air/helium	air	helium	air
Pressure, MPa	3,0-4,0	1,5-2,5	1,0-1,5	0,35	0,5-0,8
Flow rate, m^3/min	2-4	1,3	2	0,2	0,4
Power, kW	47	15	18	2,5	3,5

Conclusions and prospects for further research. *A progressive gas dynamic method of functional coatings formation was considered. Optimal sizes of sprayed copper and aluminum particles as well as the required speed for carring out the technological process was determined. The main stages of coating formation by this method was considered. Modern gas dynamic spraying equipment was inspected.*

Having carried out the analysis, it can be concluded that for domestic repair units it is reasonable to use DIMET equipment because it is inexpensive and the most versatile compared to other samples presented.

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ВІДОМОСТІ ПРО АВТОРІВ

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