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INFLUENCE OF GAS THERMAL SPRAYING PARAMETERS ON THE ADHESION AND POROSITY OF COATINGS

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The article investigates the influence of particle velocity and temperature on the characteristics of coatings obtained by gas-dynamic spraying. This method there are one with the most promising technologies formation protective and functional coatings thanks to opportunities causing material without significant heating substrates that minimizes risk its thermal damage .

Considered main parameters process, in particular speed and temperature particles that determine kinetic energy, level adhesions, density and structure coverage. Carried out analysis interactions particles from surface linings by different modes spraying, which allows to determine optimal technological parameters for achievement the best operational characteristics coatings.

Separately attention given materials that are used for gas-thermal spraying, in particular metals, ceramics, composites and special materials, such as carbide tungsten and carbide chromium. The features of their behavior during the spraying process, the formation of the microstructure of the coatings, and their resistance to wear and corrosion were investigated.

The article also discusses the practical application of gas-dynamic spraying in the aviation, automotive, energy and other industries. In particular, the results of an experimental study of the influence of spraying modes on the utilization rate of aluminum powder, the adhesion strength of the coating to the substrate and its porosity are presented.

The results of the work can be used to optimize gas-dynamic spraying processes, increase the efficiency and durability of coatings, which opens up new prospects for the application of this technology in high-tech industries.

Key words: *spraying, surface layer, particle, application, coating characteristics, working environment, speed, optimization, electric power industry.*

Eq. 5. Fig. 3. Table. 1. Ref. 8.

1. Problem formulation

In modern industry, the need for high-quality coatings that can protect parts from wear, corrosion, thermal effects and mechanical loads is constantly growing. One of the most promising methods for creating such coatings is gas-dynamic spraying - a technology that allows applying materials without significant heating of the substrate, ensuring high adhesion and density of the resulting layer [1].

This technology is based on the use of a high-velocity gas flow that transports solid powder particles and accelerates them to supersonic speeds. At the moment of collision with the substrate, the particles deform and bond at the molecular level, forming a dense and durable coating [2]. The main feature of the method is that the temperature of the particles remains below their melting point, which avoids structural changes and thermal defects characteristic of other coating methods.

One of the key factors affecting the quality of the coating is the speed and temperature of the particles. Optimal spraying modes ensure strong adhesion of the coating to the substrate, uniform distribution of the material and minimal porosity. Excessively high speed can cause particle breakage or surface damage, while insufficient speed reduces the efficiency of coating formation. The temperature of the particles affects their plasticity, which determines the level of deformation during impact and the formation of a solid layer.

Gas-thermal spraying methods, which include gas-dynamic spraying, have found wide application in the aviation, automotive, energy and medical industries. They are used both for the restoration of worn parts and for the creation of protective coatings on new products. Of particular interest is the use of aluminum, titanium, nickel alloys, as well as ceramic and composite materials in this process.

However, despite the active development of the technology, there remain a number of open questions regarding the optimization of gas dynamic spraying processes, in particular, the influence of particle velocity and temperature on the characteristics of coatings. The study of these aspects is necessary to increase the efficiency of the technology and expand its application in industry.

Ensuring wear resistance, corrosion resistance and thermal stability of parts and structures is one of the key tasks of modern mechanical engineering, aviation, automotive and energy industries. Increased operational loads, the impact of aggressive environments and the need to increase the durability of equipment require the use of effective protective coatings.

Among the coating application methods, gas-thermal spraying (in particular, gas-dynamic spraying) is one of the most promising, as it provides the formation of a coating without significant heating of the substrate, which avoids undesirable changes in the structure of the base material. This technology allows the application of metal, ceramic, composite and special materials with high bond strength and minimal porosity.

However, the quality of the resulting coating depends largely on the process parameters, in particular the velocity and temperature of the particles. The influence of these factors remains poorly understood and requires further research. The main problems that arise during the gas dynamic spraying process include:

1. Determining the optimal particle velocity – too low a velocity can result in poor adhesion of the particles to the substrate, while too high a velocity can cause them to break down and damage the surface.
2. Particle temperature control – it is necessary to find a balance between sufficient plasticity of the particles to form a dense coating and avoiding overheating, which can cause the formation of unwanted phases or defects.
3. Studying the interaction of speed and temperature – these parameters are closely related, so changing one factor requires adjusting the other. The lack of an integrated approach can lead to uneven coating or low adhesion.
4. Determining the effect of the process on the microstructure of the coating – the structure of the coating affects its mechanical properties, including hardness, wear resistance and corrosion resistance.
5. Optimization of parameters for different materials – different metals, ceramics and composites have unique physical and mechanical properties, which requires the development of individual spraying modes.

Solving these problems is necessary to increase the efficiency of gas-dynamic spraying, which will allow creating high-quality coatings with improved performance characteristics. That is why the study of the influence of particle velocity and temperature on the characteristics of coatings is a relevant and important task of modern science and industry.

2. Analysis of recent research and publications

Gas-dynamic spraying as one of the methods of gas-thermal deposition attracts considerable attention of scientists and researchers all over the world. Due to its ability to form coatings with high performance characteristics without significant heating of the substrate, this technology has found wide application in mechanical engineering, aviation and energy industries. In this regard, a number of studies have been conducted aimed at optimizing the process and improving the resulting coatings.

Much research has been devoted to determining the optimal particle velocity, as this parameter significantly affects the process of coating deposition and the formation of strong adhesion to the substrate. Works [3] and [4] show that particle velocity approaching the speed of sound (≈300–1200 m/s) is critical for ensuring strong bonding between coating particles and the substrate.

According to [4], too low a velocity (less than 300 m/s) leads to poor adhesion and the formation of porous coatings. At the same time, as noted in [5], too high a velocity (>1000 m/s) can cause particle destruction upon impact with the substrate or even damage to the surface itself. This confirms the need for precise selection of velocity parameters depending on the type of material used.

The particle size plays an equally important role in the coating formation process. Studies [5] indicate that the increased temperature of the particles promotes their plastic deformation, which improves the contact between the particles and the substrate. This allows the formation of denser and more uniform coatings.

However, as noted in [5] and [6], excessive heating of particles can lead to thermal damage to the material, changes in phase composition, or the formation of microcracks in the coating. It is important to find a balance between particle temperature and particle velocity, as these parameters are interrelated.

An important aspect is the choice of the material for sputtering. As noted in [6], aluminum, titanium, nickel alloys, and ceramic materials are most often used. Studies have shown that metallic materials such as aluminum and titanium exhibit good adhesion at medium particle velocities (400–800 m/s), while ceramic materials, such as aluminum oxide (Al_2O_3), require higher velocities to ensure reliable adhesion to the substrate.

Recently, research has been actively conducted into automated control of the gas-dynamic spraying process. This allows for dynamic regulation of the particle velocity and temperature, adapting the process to specific materials and application conditions.

3. The purpose of the article

The aim of the article is to investigate the influence of particle velocity and temperature on the characteristics of coatings obtained by gas-dynamic spraying, in order to determine the optimal technological parameters that ensure high adhesion, density and wear resistance of coatings for further effective use of this technology in various industries.

4. Results and discussion

Gas-dynamic spraying is one of the most modern technologies for creating high-quality coatings, which is widely used in industry. Its uniqueness lies in the fact that the process occurs at relatively low temperatures, which prevents the melting of powder particles and preserves the original properties of the material. Due to the high-speed gas flow, the particles are accelerated to supersonic speeds, which allows them to effectively settle on the surface of the substrate, forming a strong and wear-resistant layer.

One of the key factors affecting the quality of coatings is the velocity of powder particles. It determines their kinetic energy during collision with the surface, and therefore affects the level of deformation, adhesion and density of the coating. Too low a velocity does not provide enough energy to firmly fix the particles, which leads to porosity and insufficient adhesion. At the same time, too high a velocity can cause the destruction of the particles themselves or even damage to the substrate. That is why control of this parameter is extremely important for optimizing the spraying process [7].

The temperature of the particles during transport in the gas stream also plays an important role. It determines the level of plasticity of the material and its ability to deform when in contact with the surface. Moderate heating helps to improve adhesion and form a dense structure, but excessive temperatures can cause the formation of oxides, microcracks and undesirable phase transformations. The optimal temperature regime provides the necessary balance between the mechanical characteristics of the coating and its durability.

The quality of the resulting coatings is assessed using a series of mechanical tests. Analysis of adhesion, microstructure, wear resistance and hardness allows us to determine how effectively the protective layer is formed and whether it meets operational requirements. Tests for adhesion strength to the substrate demonstrate the ability of the coating to withstand mechanical loads, while microstructural analysis allows us to assess the level of porosity and possible defects. Wear resistance studies, in turn, allow us to draw conclusions about the duration of the coating's operation under conditions of friction, abrasion or erosion.

The practical application of gas-dynamic spraying covers a wide range of industries. In the aerospace industry, this technology is used to strengthen parts of aircraft engines, turbines and body elements that are subjected to extreme loads. In the automotive industry, it finds its application to improve the wear resistance of pistons, shafts and bearings. In the energy sector, gas-dynamic spraying allows you to protect heat exchangers, boilers and turbines from corrosion and high-temperature exposure. This technology is no less important in medicine, where it is used to apply biocompatible coatings to implants, which improves their durability and interaction with the human body [8].

Thus, gas-dynamic spraying technology is one of the most promising methods for creating protective coatings. It allows to significantly improve the performance characteristics of parts and structures, increase their wear resistance and extend their service life. Optimization of spraying parameters, such as particle speed and temperature, is a key task for achieving the best mechanical properties of coatings and expanding the possibilities of applying this technology in various industries.

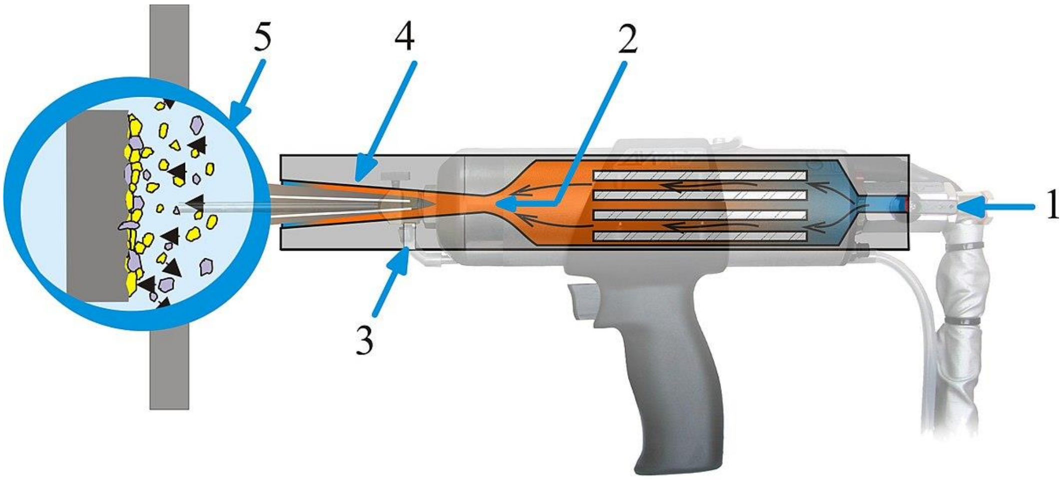

Fig. 1. Scheme of spraying metal coatings:
1 – material supply, 2 – heater, 3 – regulator, 4 – nozzle, 5 – treated surface

The influence of gas thermal spraying parameters on the adhesion and porosity of coatings can be described through several mathematical models and equations that take into account heat transfer, material mechanics, and microstructural characteristics of coatings.

The adhesion of a coating depends on the interaction forces between the molecules of the sputtered material and the substrate, as well as on the degree of local defects or stresses in the coating. This can be described by an equation that includes mechanical and thermal characteristics:

$$\tau_{adh} = \frac{F_{adh}}{F_{adh}} \quad (1)$$

where τ_{adh} – adhesion stress; F_{adh} – adhesion strength; A_{adh} – contact area between the coating and the substrate.

The forms of F_{adh} and A_{adh} may depend on the temperature of the sputtering process T, the deposition rate v, and the chemical composition of the material:

$$F_{adh} = C_1 T^{\beta} \vartheta^{\alpha} (C_2 + C_3\ Cohesion) \quad (2)$$

where C_1, C_2, C_3 – coefficients that depend on materials; α, β – exponential coefficients depending on temperature and deposition rate, *Cohesion* – the internal cohesion of the coating material.

The thermal properties of the coating and substrate that affect adhesion can be expressed in terms of thermal conductivity and thermal expansion:

$$\Delta\in = a_{sub}(T_{sub} - T_{spray}) \quad (3)$$

where α_{sub} – coefficient of thermal expansion of the substrate; T_{sub} – substrate temperature, T_{spray} – gas temperature during spraying.

The porosity of a coating is an important characteristic because it affects the mechanical properties of the coating, such as strength and adhesion. Porosity is determined by the ratio of the pore volume to the total volume of the coating:

$$P = \frac{V_{por}}{V_{total}} 100\% \quad (4)$$

where P – coating porosity; V_{por} – pore volume; V_{total} – total coverage volume.

Porosity can also be modeled through the parameters of gas thermal spraying, which are determined by the deposition rate, gas temperature, and particle size:

$$P = f(v, T, d) \quad (5)$$

where v – particle deposition rate; T – the process temperature; d – the average particle size.

The adhesion stress depends on the temperature and deposition rate. High temperature and deposition rate can increase adhesion, but the contact area and internal cohesion of the material also play an important role.

Porosity depends on particle size. Larger particles can increase the porosity of the coating due to reduced ability of the particles to stick together.

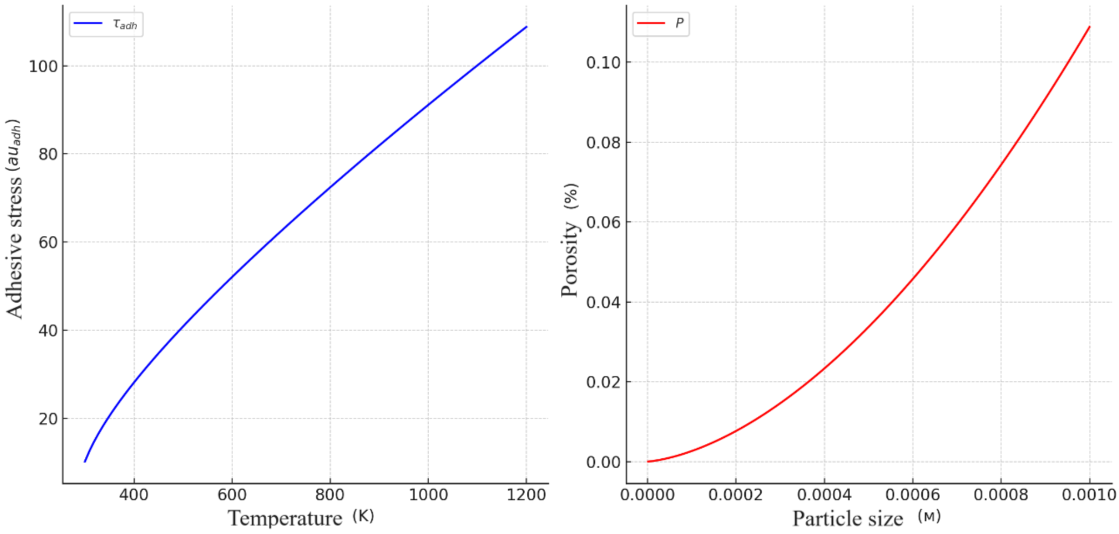

Fig. 2. Graphs of the dependence of adhesion stress and porosity on the parameters of gas-thermal spraying

Table 1.
Numerical data for calculating the influence of gas thermal spraying parameters on adhesion and porosity of coatings

Parameter	Value 1	Value 2	Value 3
Gas temperature (T)	1000°C	1200°C	1500°C
Deposition rate (v)	10 m/s	20 m/s	30 m/s
Particle size (d)	5 microns	10 microns	15 microns
Coefficient of thermal expansion of the substrate (α_{sub})	1.2×10^{-6} /°C	1.5×10^{-6} /°C	1.8×10^{-6} /°C
Substrate temperature (T_{sub})	800°C	1000°C	1200°C
Spray gas temperature (T_{spray})	1500°C	1600°C	1700°C
Internal cohesion of the material (Cohesion)	0.5	0.7	0.9
Adhesion strength (F_{adh})	1000 N	1500 N	2000 N
Contact area (A_{adh})	1 cm²	1.5 cm²	2 cm²
Adhesion stress (τ_{adh})	100 MPa	120 MPa	150 MPa
Porosity (P)	10%	15%	20%
Substrate temperature change ($\Delta \in$)	0.5°C	1°C	1.5°C

The data, presented in the form of graphs, demonstrate the influence of various parameters of gas thermal spraying on the characteristics of coatings. The dependences of adhesion strength, adhesion stress and porosity on gas temperature and deposition rate are displayed. This allows us to investigate how changing one parameter can affect other important characteristics that determine the quality and efficiency of the spraying process.

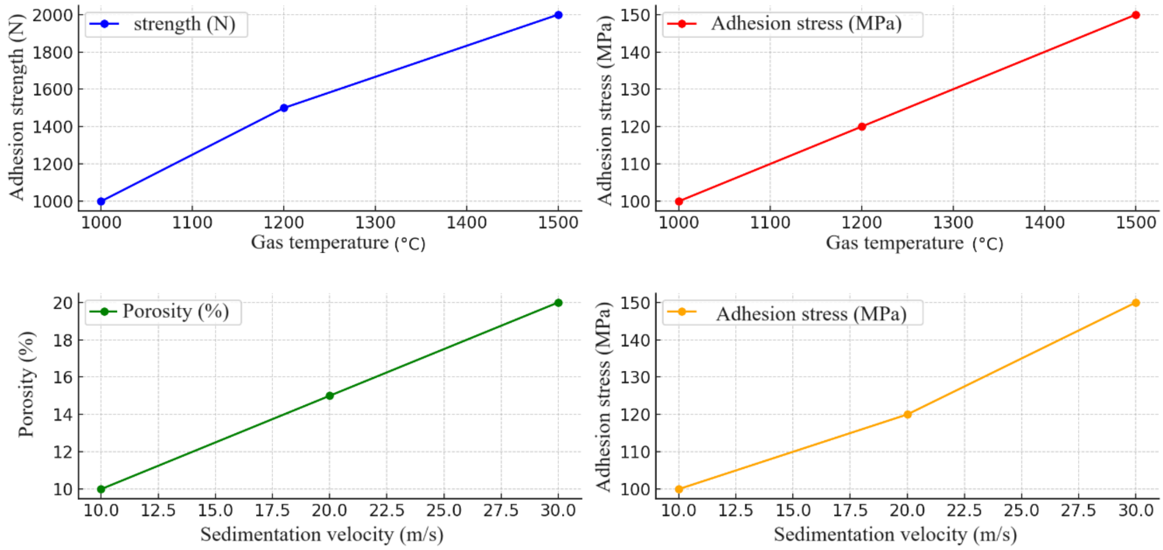

Fig. 3. Influence of gas thermal spraying parameters on coating characteristics

An increase in adhesion strength is observed with increasing gas temperature. This may be due to improved particle-surface interaction at high temperatures, which increases the adhesion force. An increase in adhesion stress is also observed with increasing gas temperature. This may indicate changes in the mechanisms of coating formation at different temperatures, which affects their strength. As the deposition rate increases, the porosity of the coating decreases. This may indicate that faster deposition promotes the formation of more compact coatings with smaller pores. With increasing deposition rate, the adhesion stress also increases. This may be due to the denser deposition of particles on the surface at high deposition rates, which promotes the formation of stronger bonds between the particles and the surface.

5. Conclusion

The results of the graphical dependences show that the gas temperature has a significant effect on the characteristics of the coatings, in particular on the adhesion strength and adhesion stress. With increasing gas temperature, an increase in adhesion strength and adhesion stress is observed, which may indicate an improvement in the interaction process of the coating particles with the surface. This confirms the importance of optimal temperature control during gas thermal spraying to achieve high-quality coatings.

The graphs show that as the deposition rate increases, the porosity of the coating decreases and the adhesion stress increases. This suggests that faster particle deposition can lead to denser and stronger coatings with smaller pores, which provides better mechanical strength and adhesion. This is an important aspect for coatings that must withstand high loads or must be resistant to external factors.

The decrease in porosity observed with increasing deposition rate can lead to an increase in the mechanical strength of the coating, as lower porosity promotes a tighter retention of the coating particles. This makes the material more stable and less susceptible to damage during use.

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ВПЛИВ ПАРАМЕТРІВ ГАЗОТЕРМІЧНОГО НАПИЛЕННЯ НА АДГЕЗІЮ ТА ПОРИСТІСТЬ ПОКРИТТІВ

У статті досліджено вплив швидкості та температури частинок на характеристики покриттів, отриманих методом газодинамічного напилення. Цей метод є однією з найперспективніших технологій формування захисних та функціональних покриттів завдяки можливості нанесення матеріалу без значного нагрівання підкладки, що мінімізує ризик її термічного пошкодження.

Розглянуто основні параметри процесу, зокрема швидкість і температуру частинок, які визначають кінетичну енергію, рівень адгезії, щільність та структуру покриття. Проведено аналіз взаємодії частинок із поверхнею підкладки за різних режимів напилення, що дозволяє визначити оптимальні технологічні параметри для досягнення найкращих експлуатаційних характеристик покриттів.

Окрему увагу приділено матеріалам, що використовуються для газотермічного напилення, зокрема металам, кераміці, композитам і спеціальним матеріалам, таким як карбід вольфраму та карбід хрому. Досліджено особливості їх поведінки під час процесу напилення, формування мікроструктури покриттів та їх стійкість до зношування й корозії.

У статті також розглядається практичне застосування газодинамічного напилення в авіаційній, автомобільній, енергетичній та інших галузях промисловості. Зокрема, наведено результати експериментального дослідження впливу режимів напилення на коефіцієнт використання алюмінієвого порошку, міцність зчеплення покриття з підкладкою та його пористість.

Результати роботи можуть бути використані для оптимізації процесів газодинамічного напилення, підвищення ефективності та довговічності покриттів, що відкриває нові перспективи застосування цієї технології у високотехнологічних виробництвах.

Ключові слова: *напилення, поверхневий шар, частинка, нанесення, характеристики покриття, робоче середовище, швидкість, оптимізація, електроенергетика.*

Ф. 5. Рис. 3. Табл. 1. Літ. 8.

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