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Multicriteria optimization of heat-resistant coatings detonation spraying technology

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Abstract

The paper presents the multi-criteria optimization results of heat-resistant coatings detonation spraying technology. The following criteria for optimization of detonation spraying technology are chosen: critical deformation of coating fracture, adhesion-cohesion equal strength of coating and specific technological cost of coating application. Dependences of the strength properties values of the studied detonation coatings at change of technological and constructive factors have been obtained. It is proved that the greatest influence on the mechanical properties of the studied detonation coatings is exerted by the material of the hardened part and the material composition of the sprayed coating, which is caused by the difference in their thermophysical, chemical and mechanical properties, as well as by the physical and chemical processes occurring during the formation of the sprayed layer. The optimum technological parameters allowing to obtain coatings with specified mechanical properties have been established.

Key words: detonation spraying, heat-resistant coatings, multicriteria optimization, structural and technological factors, mechanical properties of coatings.

Introduction

The choice of optimal coatings and technologies for their production is complicated [1, 2]. This is largely due to the fact that the composition and structure of the coating thickness, as well as its thickness, optimal in terms of adhesion properties and durability depend on many factors.

The development of any coating technology is inevitably associated with the solution of optimization problems. This should be explained by the large number of coating application methods in combination with different materials from which the coatings are formed, as well as a large number of influencing factors provides technologies with a wide range of alternative solutions [3]. This has contributed to the development of a new direction – technological processes of protective coatings application optimization according to the criteria of durability.

The peculiarity of the new direction lies in the ideology of conducting research according to a single experiment planning matrix taking into account design and technological factors, a complex of mechanical and operational characteristics. Thus, were optimized according to the complex criterion of fatigue resistance strength, wear and corrosion resistance (gas-thermal coating technologies), adhesion-cohesion equal strength and critical deformation of the base (detonation spraying technologies), isothermal and thermocyclic creep (technologies of electron-beam application of heat protective coatings), strength, stress-deformed state and wear resistance (electrochemical technologies, electrospark alloying) [4].

The work [5] shows the indisputable advantages of detonation coatings, which ensured their widespread use in the world practice of aircraft engine building, as well as in other branches of mechanical engineering.

Literature review

Detonation coating technologies are becoming more and more widespread in industry, including gas turbine construction, and are used both in manufacturing and repair [5, 6]. Detonation spraying technologies are constantly being improved, industrial complexes of modern automated equipment are being developed, mathematical models of this method and optimization approaches have been obtained [4, 7]. Ukrainian scientists have made a great contribution to the development of detonation spraying technology [8]. The V.N. Bakul Institute of Superhard Materials of the National Academy of Sciences of Ukraine has developed the Perun-C unit, the peculiarity of which is the presence of a device for coating and abrasive treatment of the sprayed surface.

At the same time, the efficiency of this technology is hampered by the difficulties in optimizing its modes due to the lack of qualified scientific analysis of research results. Multicriteria optimization of spraying modes will ensure its wider use in all industries.

Let us consider the factors (criteria) that can be used in the multi-criteria optimization of detonation spraying technology of protective coatings.

Parts with heat-resistant coatings characterized by high indicators of wear and corrosion resistance can malfunction due to their delamination (insufficient adhesion of the coating with the part) and cracking of coatings (low cohesion of the coating itself) under the influence of operational loads. It is noted in work [9] that the main criterion that determines the strength of the coating adhesion with the base is the critical deformation of coating fracture (ε_r).

In the practice of creating protective coatings prevails the desire to provide higher adhesion strength of the composition "base – coating" is the main condition for its functionality. Adhesion strength of the system "base – coating" is provided by the technology of coating spraying (temperature of spraying process, jet speed, powder fraction, required quality of the sprayed surface pre-treatment) and selected finishing treatment. It is the coating technology that influences the adhesion strength of the "coating – base" system and has a decisive effect on the load-bearing capacity of the base material. However, by hardening the part by applying a coating, we can get the opposite effect – to unstrengthen it. In order to create an equal-strength composition with minimal de-strengthening, the criterion of adhesion and cohesive strength was chosen in work [10]. This criterion allows to provide simultaneously the necessary indicators of adhesion and cohesive strength of the system "coating – base", and, thus, to exclude delamination and cracking of coatings with minimal de-strengthening of the hardened or restored part material.

The cost of coated parts and the economic effect from the use of detonation coatings depend on a number of factors: type of production, equipment used, materials, part configuration, required dimensional accuracy, etc.

The authors [11] propose to assess the economic efficiency and feasibility of using detonation coatings for restoration and hardening of parts by the criterion of specific technological cost of coating application (C_T):

$$C_T = \frac{C}{S \cdot h}, \tag{1}$$

where $C = C' \cdot K_S$ – cost of coating thickness *h* and area *S*, due to the consumption of powders and gases; $C' = V_f C_f + V_o C_o + V_i C_i + m_p C_p$ – cost per shot; C_f, C_o, C_i – respectively, the unit volume costs of fuel, oxidizer and inert gas; C_p – cost per unit mass of powder; V_f, V_o, V_i – volumes of fuel, oxidizer, inert gas per shot; $K_S = \frac{S \cdot h \cdot \gamma_c}{m_p \cdot K_{mu}}$ – number of shots; m_p – powder weight per cycle; γ_c – coating density; K_{mu} – material utilization rate.

Thus, the following criteria were selected for multi-criteria optimization of detonation spraying technology:

- critical fracture deformation of the coating (ε_r);
- adhesion-cohesion equal strength;
- specific technological cost of coating application due to the consumption of powders and gases (C_T).

Purpose

The aim of the work is the selection of optimal modes of detonation coatings application taking into account technological and constructive factors, providing the obtaining of protective coatings with the required mechanical properties.

Research Methodology

Taking into account the above arguments, a multicriteria optimization of the detonation spraying technology of heat-resistant coatings applied to the parts of tribocouplings of the aviation gas turbine engine hot path has been carried out in the paper, taking into account such criteria as critical deformation of coating fracture, technological cost of the process and adhesion-cohesion equal strength.

According to the estimates of various researchers, the properties of detonation coatings are influenced by 20 to 150 factors [4, 5]. The selection of the most significant factors, on the one hand, should have a dominant influence on the coating properties (optimization parameters), and, on the other hand, should allow their control by the operator. Applying the methods of expert evaluation, using the results of a number of researchers works on optimization of detonation spraying process [6, 9, 12], as well as in order to clarify the specific technological cost of coating application, we selected technological and design parameters for optimization of detonation spraying technology (Fig. 1).

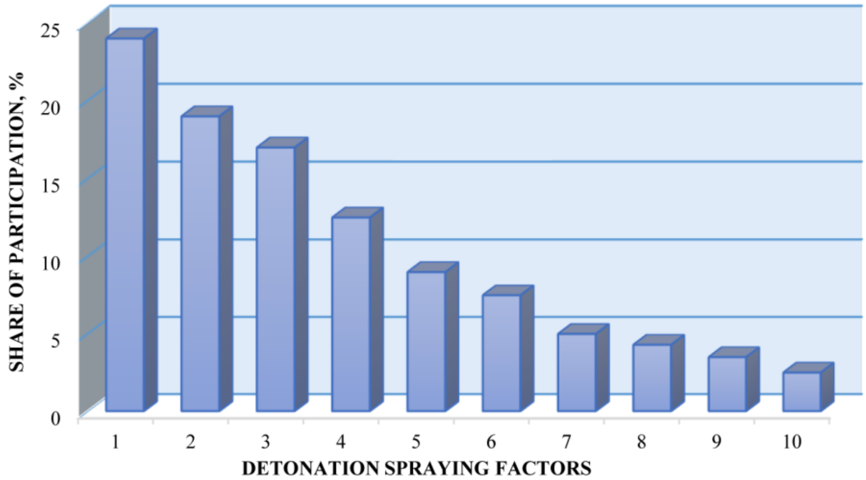


Fig. 1. Ranked series of detonation spraying factors: technological parameters (1 – powder material; 2 – base material; 3 – powder weight per cycle; 4 – spraying distance; 5 – volume of detonating mixture; 6 – number of shots per second; 7 – temperature of water for barrel cooling; 8 – speed of part movement), constructive parameters (9 – coating thickness; 10 – powder granulation).

For modeling the detonation spraying process, based on the analysis of the technological and design parameters presented in Fig. 1, the input parameters that have the greatest influence on the properties of coatings (the value of optimization parameters) were selected. A similar methodology was used in works [13-15].

Table 1 presents the input parameters of the detonation spraying technology (coating material, base material, coating thickness, powder weight per cycle, spraying distance, cost per cycle) that were included in the planning matrix for the optimization of this technology.

Table 1

Levels of design and technological factors variation of detonation spraying technology

Name and designation of the factor	Factor No.	Levels in natural units	Matrix level designation	Levels		
				F_i	X_i	Z_i
Base material, *M*	1	VT-20	VT	0	-1	0,5
		EP-648	EP6	1	0	-1
		EP-718	EP7	2	1	0,5
Coating material, *C*	2	VK-25M	VK	0	-1	0,5
		PG10N01	PG	1	0	-1
		PS12NVK-01	PS	2	1	0,5
Spraying distance, *L*, mm	3	130	130	0	-1	0,5
		170	170	1	0	-1
		210	210	2	1	0,5
Powder weight per cycle, m_p, mg	4	150	150	0	-1	0,5
		225	225	1	0	-1
		300	300	2	1	0,5
Coating thickness, *h*, µm	5	150	150	0	-1	0,5
		250	250	1	0	-1
		350	350	2	1	0,5

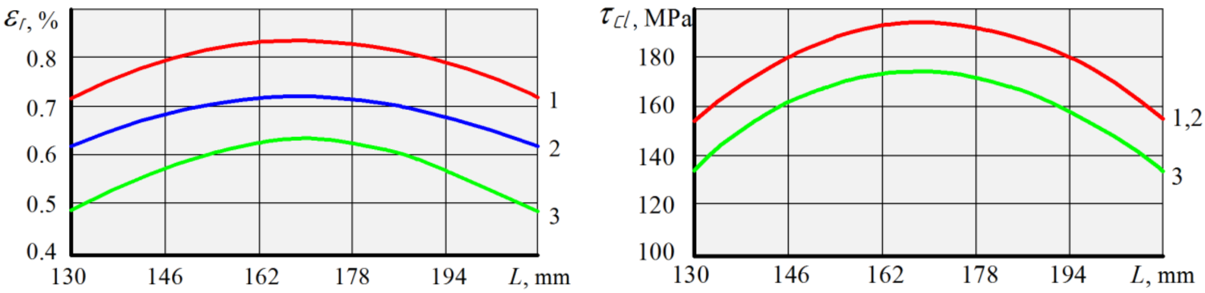
Such powder materials as titanium alloy VT-20, alloys EP-648 and EP-718, which are most often used in the manufacture of tribocouplings parts of the aviation gas turbine engine hot path, were chosen as the base material for research.

Standard powders VK-25M, PG10N01 and PS12NVK-01 were used as materials of heat-resistant coatings. The feasibility of their use for application of coatings by detonation spraying was confirmed in work [12] for hardening of heavily loaded tool materials.

Results

As a result of experimental studies, the strength properties values of the studied detonation coatings at changing technological and constructive factors according to the experiment plan were obtained (Table 1).

Experimental dependences of strength characteristics on spraying distance are shown in Fig. 2 – 5.

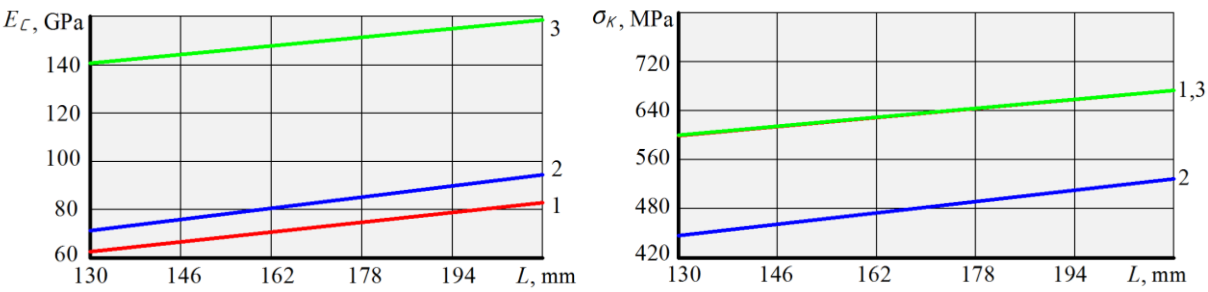


a) b)

Fig. 2. Dependence of critical coating fracture deformation ε_r (a) and shear bond strength τ_{cl} (b) on spraying distance *L*: 1 – VK-25M; 2 – PG10N01; 3 – PS12NVK-01

As a result of the research it was found that ε_r of the base material hardened by detonation spraying has a minimum value (Fig. 2, a), and τ_{cl}, sprayed coating with the base reaches the maximum value (Fig. 2, b) at L = 170 mm.

It has been established that high τ_{cl} of the coatings obtained by detonation spraying with the base is achieved due to not only adhesion bonds at the interface "base – coating", but also chemical ones. This was confirmed by the study of the chemical composition of the transition zone between the coating of powder alloy VK-25M and titanium substrate. Double chemical compounds of cobalt and titanium and triple compounds of tungsten, cobalt and titanium are formed at the interface "powder alloy VK-25M – titanium substrate".

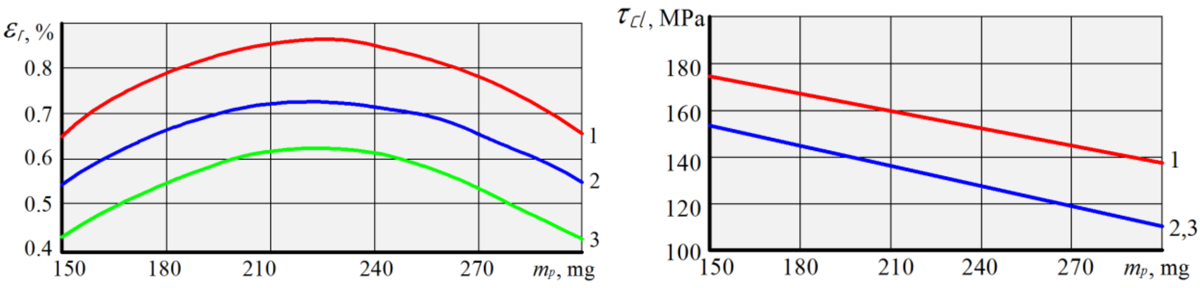


a) b)

Fig. 3. Dependence of elastic modulus of coating E_C (a) and shear bond strength σ_K (b) on spraying distance *L*: 1 – VK-25M; 2 – PG10N01; 3 – PS12NVK-01

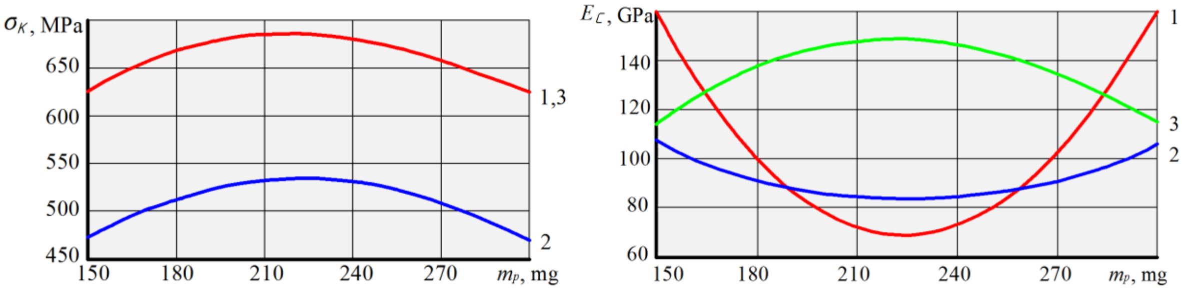
When reducing the spraying distance L to 130 mm, there is a noticeable decrease in the cohesive strength of the coating, and excessive, up to 210 mm, increase of this parameter increases porosity in the interface zone and reduces the adhesive strength of the system "coating – base". There is an overheating of the coating and its cracking under the action of thermal stresses. Note, however, that the increase up to 210 mm leads to a slight increase of E_C (Fig. 3, a) and σ_K (Fig. 3, b) of the coating. This is obviously due to the improvement of cohesive and chemical bonds between the layers during the formation of multilayer coating.

Such a technological parameter of detonation spraying, such as powder weight per cycle m_p, also has a significant effect on the properties of coatings (Fig. 4-5).



a) b)

Fig. 4. Dependence of critical coating fracture deformation ε_r (a) and shear bond strength τ_{cl} (b) on powder weight m_p: 1 – VK-25M; 2 – PG10N01; 3 – PS12NVK-01



a) b)

Fig. 5. Dependence of shear bond strength σ_K (a) and modulus of coating elasticity E_C (b) on powder weight m_p: 1 – VK-25M; 2 – PG10N01; 3 – PS12NVK-01

Moreover, ε_r (Fig. 4, a), τ_{cl} (Fig. 4, b), σ_K (Fig. 5, a), E_C (Fig. 5, b) have extreme values at the weight m_p, about 225 mg/cycle. When increasing the powder weight m_p, from 150 to 300 mg/cycle, there is a decrease (by 26-30%) in the adhesion strength of coatings τ_{cl} (Fig. 4, b), because the location and nature of the powder cloud distribution in the barrel of the unit changes, which significantly affects the speed and temperature of the sprayed powder particles.

It was found that the dependence of E_C on the coating thickness h, has an extreme character (Fig. 6). This should be explained by the influence on this characteristic of the uneven distribution of multicomponent coating chemical elements over the thickness, as well as changes in the chemical composition at the interface "coating – base", associated with the occurrence of diffusion interaction of chemical elements included in the coating and the material of the hardened part.

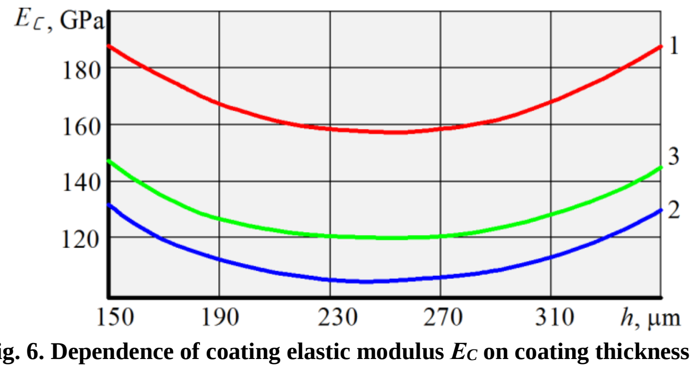


Fig. 6. Dependence of coating elastic modulus E_C on coating thickness h: 1 – VK-25M; 2 – PG10N01; 3 – PS12NVK-01

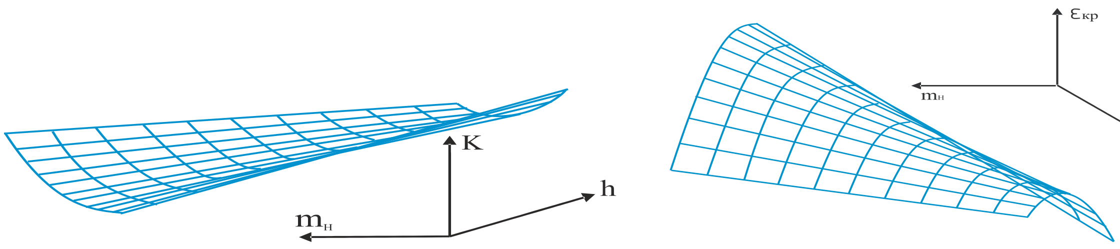
Based on the results presented above, it can be concluded that the greatest influence on the mechanical properties of the studied detonation coatings is exerted by the material of the hardened part and the composition of the sprayed coating material, which is due to the difference in their thermophysical, chemical and mechanical properties, as well as physical and chemical processes occurring during the formation of the sprayed layer.

The experimental results were analyzed and mathematical models were verified according to the methodology described in work [16]. The models were calculated using a package of application programs.

Dependences of coating fracture critical deformation, modulus of coatings elasticity, adhesive shear strength, cohesive strength, specific technological cost of coating application, criterion of adhesion-cohesion equal strength on technological and constructive factors were obtained by regression statistical analysis and presented in work [4]. The experimental-statistical approach, which was applied to the study of the coating application process by detonation spraying, allowed to obtain dependences of coating properties on technological and design factors.

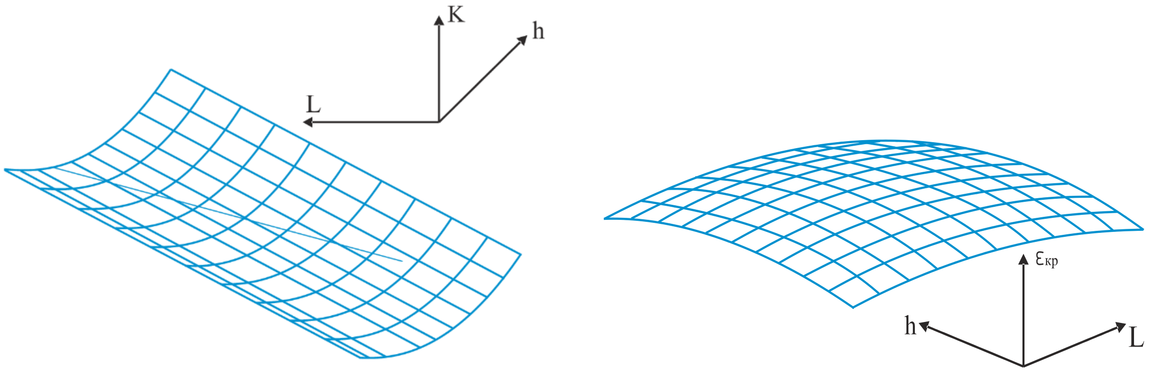
The complex analysis of the obtained data makes it possible to evaluate the influence of the studied factors on the properties of coatings.

The technological process of detonation spraying is characterized by a significant number of technological and design parameters that affect the obtaining of the required properties of coatings. Establishment the optimal technological parameters of detonation spraying is the most important task, the solution of which will make it possible to obtain coatings with the required properties. Fig. 7-8 show the response surfaces of the selected criteria of detonation spraying technology, from which we can see a rather complex influence of the input parameters (factors) of this coating technology on the dependent variables.



a) b)

Fig. 7. Response surface of the regression dependence *K=f(Xᵢ)*. (a) and *εKP=f(Xᵢ)* (b)



a) b)

Fig. 8. Response surface of the regression dependence *K=f(Xᵢ)*. (a) and *εKP=f(Xᵢ)* (b)

When selecting optimal spraying modes for detonation spraying, it was found that the quality of coatings obtained by this spraying method is characterized not by one, but by several significant coating properties. Therefore, multicriteria optimization of this technology is necessary by determining some compromise point equally satisfying all requirements (Pareto compromise).

Table 2 shows the results of the multi-criteria optimization.

Table 2

Results of multi-criteria optimization of detonation spraying technology

Values of independent variables					Values of dependent variables	
Base material, *M*	Coating material, *C*	Spraying distance, *L*, mm	Powder weight per cycle, m_p, mg	Coating thickness, *h*, µm	ε_r, %	*K*
VT-20	PG10N01	189,4	287,1	164	0,793	0,42
EP-648	PG10N01	208,75	292,9	265	0,43	0,23
EP-718	PG10N01	201,25	278,9	172	0,73	0,543
VT-20	VK-25M	155,6	158,2	242	0,774	0,437
VT-20	PG10N01	151,25	297,7	341	0,639	0,525
VT-20	PS12NVK-01	208,75	293,0	266	0,442	0,106

Comparison of coatings properties obtained in this work with the properties of analogues showed that optimization of detonation spraying technology provided an opportunity to increase the adhesion strength of heat-resistant coatings made of powder alloy VK-25M by 25%, cohesive strength – by 23%, as well as to propose the use of powders PG10N01, PS12NVK-01 for detonation spraying, which are 2...3 times cheaper than those used industrially, while providing a sufficient level of products strength.

Thus, the conducted studies of the technological process of heat-resistant coatings detonation spraying have allowed to obtain multifactor mathematical models that allows to select technological and design factors that ensure the obtaining of detonation coatings with given mechanical properties.

Conclusions

The presented studies of multi-criteria optimization of heat-resistant coatings detonation spraying technology allowed us to draw the following conclusions:

1. The expediency of detonation coatings optimization taking into account the critical deformation criteria of coating fracture, technological cost of the coating process and adhesion-cohesion equal strength of the coating has been substantiated.

2. Taking into account the methods of expert evaluation, as well as in order to clarify the specific technological cost of coating application, technological and design parameters for optimization of detonation spraying technology were selected.

3. The obtained values of strength properties of the studied detonation coatings at change of technological and constructive factors have shown that the greatest influence on the mechanical properties of the studied detonation coatings is exerted by the material of the hardened part and the composition of the sprayed coating material.

4. Multicriteria optimization of heat-resistant coatings detonation application technology provided the possibility of increasing the adhesion and cohesive strength of coatings, as well as significantly reduce the cost of the coating process.

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Солових Е.К., Шепеленко І.В., Черновол М.І., Шумляківський В.П., Солових А.Е., Катеринич С.Е. Багатокритеріальна оптимізація технології детонаційного напилення жаростійких покриттів

Представлені результати досліджень багатокритеріальної оптимізації технології детонаційного напилення жаростійких покриттів. Як критерії оптимізації технології детонаційного напилення обрано: критичну деформацію руйнування покриття, адгезійно-когезійну рівноміцність покриття та питому технологічну собівартість нанесення покриття. Отримано залежності значень міцнісних властивостей досліджуваних детонаційних покриттів при зміні технологічних і конструктивних факторів. Встановлено, що найбільший вплив на механічні властивості досліджуваних детонаційних покриттів мають матеріал деталі, що зміцнюється, і склад матеріалу напилюваного покриття. Це зумовлено відмінністю їх теплофізичних, хімічних і механічних властивостей, а також фізико-хімічними процесами, які відбуваються під час формування напилюваного шару. На підставі дослідження технологічного процесу нанесення детонаційних покриттів отримано багатофакторні математичні моделі, які дають змогу визначити поєднання технологічних і конструкційних факторів, за яких можливе отримання детонаційних покриттів із заданими механічними властивостями.

Ключові слова: детонаційне напилення, жаростійкі покриття, багатокритеріальна оптимізація, конструкційні та технологічні фактори, механічні властивості покриттів.