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COMPARATIVE MULTI-CRITERIA ASSESSMENT OF NANO-COATING TECHNOLOGIES

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The paper presents an approach of the comparative assessment of alternative nano-coatings technologies using AHP method. The system of 24 criteria has been suggested for assessing the efficiency of nano-coatings technologies. As an example the comparative assessment of two alternative methods of applying nano-coatings (method of ionic condensation and bombing and method of magnetron dispersion) is considered. The vectors of priorities for two levels of criteria hierarchy are calculated for these methods. The practical recommendations on implementation of the considered technologies are developed on the basis of the obtained results.

Keywords: nano-covering, nano-coating technology, alternative methods, multi-criteria analysis, criteria hierarchy

1. Introduction

Increase in safety of modern technique, reduce in cost of its maintenance, providing the competitiveness, prolongation of the exploitation resource as well as technique renovation with employment of state-of-the-art technologies for recovering the functionality and operability of the blocks up to the level of new items – these directions have become the first-priority ones for technologies development. Implementation of technologies of applying the protective coatings comprising the gas-thermal processes as very significant ones is one of the cardinal ways of solving this task. Employment of up-to-date equipment, materials, and technologies of gas-thermal sputtering has allowed significantly decrease or even eliminate the impact of such factors as erosion, corrosion (including the high-temperature one) and others, having influence on details depreciation. On the purpose of solving the ecological problem, mastering the technology of gas-thermal sputtering takes place, which crowds out the "dirty" galvanic technologies.

Nowadays various technologies based on different fundamentals and employing different methods and tools are used for applying the nano-coverings. They embrace the following technologies: cold gas-dynamic spray coating; gas-thermal deposition: ion-plasmas, vacuum and high-velocity, and detonating gas-flame; application of suspensions, electrodeposits; electro-arc deposition and others [2-4, 8]. The choice of suitable technology for the certain case is determined by the whole set of factors, both objective and subjective ones. Moreover, there are usually several technologies for every certain object of applying the coating. The research under consideration suggests using the method of multi-criteria analysis, namely Analytic Hierarchy Process (AHP) method for evaluating and choosing the nano-coating technologies; this method allows grouping the employed criteria and evaluating the importance of each of these groups for the objects under consideration [7]. Moreover, it allows attracting the experts with corresponding qualification for providing the evaluation of certain groups.

The present paper considers the employment of AHP method for assessing the efficiency of two different technologies of applying the nano-coverings and choosing the optimal one. The description of the technologies under investigation is presented in the following paragraph.

2. Technologies of Applying Nano-Structural Coatings

2.1. Magnetron deposition method

It is reasonable to separate the methods of cathode sputtering and ion deposition into plasmas and ionic-radial. The first one uses directly the ions of plasma produced by electric discharge in gas under pressure of 10^{-3}- 10^{-1} Pascal. The ionic-radial technologies employ the ionic flow produced in the ionic source and directed to the field of high vacuum.

Ion-plasma methods of applying coatings comprise the magnetron dispersion, vacuum-arc vaporization and thermal evaporation. The magnetrons and vacuum-arc evaporators present ample opportunities for applying the coatings [1].

Magnetrons show lower deposition rate compared to vacuum-arc vaporizers; nevertheless, it is possible to employ them for producing coatings under lower temperature of processing surface.

The principle of magnetrons functioning (the method of magnetron dispersion) is based on using the transposed magnetic and electric fields for increasing the efficiency of working gas ionization and producing the area of dense plasma above the surface of cathode-target. The magnetic field is used for plasma forming; the lines of this field are perpendicular to the lines of electric field, have significant curvature and pass the surface of cathode-target. The zone of glow discharge of dense low-pressure plasma has locked configuration and is localized above the certain part of cathode-target surface in the area of magnetic field, where the intensive dispersion of material takes place.

The magnetron sputterer comprises as follows: air working chamber with platinum heater, magnetron units of dispersion, transportation system, gateway systems of loading and unloading, vacuum system with pump, gas system. The body of working chamber is cooled and heated with water. The plate's heater is placed on the zone of layer application. The magnetron system is a combination of several magnetrons.

The most widely-spread magnetrons are ones with flat cathode of disc or rectangle shape (see Figure 1). The cathode material can contain various chemical compounds, starting with metals (Ti, Cr, Al, Mo, W) and finishing with compound chemical combinations, obtained as a result of sintering of powder materials. Nevertheless, the cathode of magnetron is implemented by 30% due to narrow annular zone of intensive material dispersion. The industrial production also employs the rotating cathodes with magnetic system inside cathode for increasing till 80% the degree of material utilization.

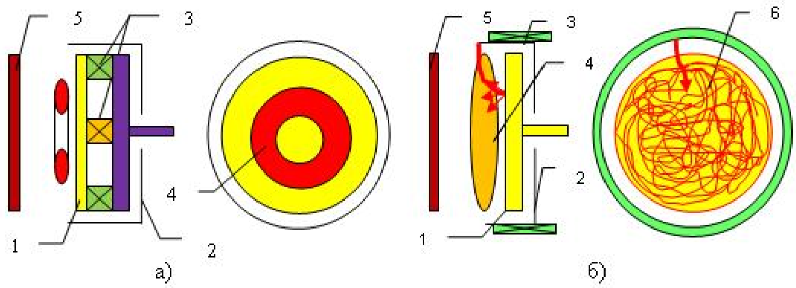


Figure 1. Plasma sources for coating application: a) – magnetron, b) – vacuum-arc vaporizer, 1 – cathode, 2 – anode, 3 – magnet, 4 – plasma, 5 – padding, 6 – arc mechanical trajectory.

Advantages of magnetron method are the following:

- any substances can be dispersed and applied;
- process implementation under the low temperature conditions;
- high material utilization ratio;
- absence of drop-phase;
- rather simple apparatus;
- high speed of sputtering with low working voltage (600-800 volt) and with not big pressure of working gas (5 10-1 - 10 Pascal);
- absence of padding overheating (formation of high-temperature phases on non-hot padding;
- low degree of layers pollution;
- simplicity of sputtering alloys and their compositions, such as nitrides and carbides;
- possibility of producing even in depth layers on big area of paddings;

Main disadvantages of magnetron method:

- low speed of coating application (10-10 – micron/minute);
- difficulties in applying the coating on the complex parts.

2.2. Method of ion condensation and bombardment

Vacuum-arc application (cathode-arc deposition) is a physical method of applying the coatings (thin layers) in vacuum by the way of condensation of material of plasma flows on the base (item, product, detail); the plasma flows are generated on the cathode-target inside the cathode spot of vacuum arc of high-current low-voltage discharge developed in the electrode material steam only. The method is implemented for applying metallic, ceramic and composite layers on various items. This method is also known as cathode-arc deposition (Arc-PVD), method of cathode-ion bombardment or method of substance condensation from the plasma phase in vacuum with ion bombardment of surface (the last one is the original name from the method developers).

Not only magnetrons but also vacuum-arc vaporizers have the ample opportunities for applying coatings [1, 6]. The cathode spot in arc vaporizers relocates on the cathode surface and provokes the local overheating; evaporation and ionization of the cathode material steam (see Figure 1). Plasma flow, moving towards the processed detail, is almost fully ionized, and plasma has high temperature. Sputtering speed and layer adhesion to the processed surface are high. Nevertheless, the cathode spot erupts also micro drops of metal of 1-10 micron; they deposit on the surface degrading the coating quality. The rotary magnetic filters are used for decreasing the number of drops; the separation of plasma flow and rectilinear flow of micro particles takes place in these filters; there also used the rotating cylindrical cathodes for persistent relocating the cathode spot on the surface of the cathode. The intensive heating of processed detail surface takes place in the process of coating application due to the high temperature of plasma of arc vaporizer.

The conditions on the basis, under which the procedure of atoms and molecules deposition takes place, have impact on the structure of protective layer. They comprise the temperature of basis, as well as bombardment of growing layer with ions, accelerated from plasma till energy (30-200 eV), if the negative electrical displacement is applied towards the basis. The ions transmit the energy to the atoms of growing layer, increasing their mobility for enhancing efficiency of diffusive processes on the surface.

The simplest way of producing the nano-structural coatings with perfected properties is employment the cathodes made of materials with alloy additives preventing the growth of crystals (Ti-Al-Si, Ti-Si) in plasma sources. Multi-component cathodes are obtained by the way of hot sintering the powders or by the method of high-temperature synthesis.

The presence of the layer of cathode potential drop, replicating exactly the shape of detail, allows quite efficient processing the surfaces of any unconditioned shape. The size of processed detail is practically limited by the size of vacuum chamber only. Evaporation of depositing material can implemented via vaporizer heating or via bombardment of its surface with ions of inert gas, the electrons. This fact provides the opportunities for covering the basis not only with pure metals but also with various alloys as well as non-metallic coatings. The electrodes erosion processes in cathode spot of vacuum arc are used for generating the plasma flows of various operating substances in production units (plasma accelerator).

Employment of plasma accelerators differs from ion deposition in glow discharge due to the fact that the accelerators generate the directed flow.

The process of ion deposition goes in two stages: coating cleaning and coating deposition.

On the stage of cleaning the basis serves as a dispersed cathode of glow discharge and is subjected to the bombardment with positive ions of residual gases (or with metals ions), as well as the influence of ultraviolet rays from the area of glow discharge.

The bombardment of basis with metal positive ions and residual gases takes place in the process of coating deposition; this process results in activating the surface and generating the conditions for forming the pore-free coating with perfect adhesion towards the basis; ions of metal accelerating in the electric field of basis (and also in accelerator) reach it; having bigger energy and penetrating into the basis they increase the strength of coating adhesion, and form the pseudo diffusive transitive layer with high degree of concentration of deposition material. Combination of ion bombardment of the basis in the process of applying the coating with dispersion of metal steam and high kinetic energy of condensed metal ions accounts the principal advantages of ion deposition method – the perfect coating adhesion towards the basis and possibility of applying coating on complex profile details. Ion deposition with high accelerating potential (3-7 kilovolt) allows generating the layers in the near-surface area; these layers have properties similar to the properties of implanted layers by ion implantation.

Coatings, obtained by ion deposition method, demonstrate density of structure and decreased porosity; consequently, they have the increased resistance to corrosive attack. It has also been established that the coatings of this type have fine-dispersed structure. The investigations, provided by many researchers, demonstrate that the ion coatings have high adhesion towards the basis and do not deteriorate the mechanical properties but sometimes even improve it.

Nowadays the method of ion deposition is widely implemented for producing coatings from various high-melting metals, alloys, oxides, carbides, nitrides, and so on.

Advantages of method of ion condensation and bombardment:

- the coatings demonstrate high physical and chemical properties;

- it allows processing the details of various shapes with high evenness of application;
- high speed of coating application (till I micron /minute);
- high level of controllability and capability of reproducing;
- simplicity of methods of protecting the non-processed surfaces.

Disadvantages of the method:

- the complex equipment requirements;
- restriction of the speed of coating application due to high level of surface heating;
- existence of drop phase;
- rather high temperature (300°C - 600°C) necessary for the process implementation;
- low rate of material utilisation.

3. Multiple-Criteria Analysis and Choice of Nano-Coating Technologies Using the AHP Method

3.1. System of criteria formation

Choice of the best method of nano-coatings of the surface of different objects must be performed taking into account various quantitative and qualitative criteria. This research offers a system of 24 criteria, which are distributed in five following groups:

1. *Physical properties of coating*: adhesive strength, depth, homogeneity;
2. *Functional properties of coating*: micro-hardness, durability, resistance to corrosion, wear resistance, heat resistance;
3. *The process of applying the coating*: start time, duration, labour intensiveness, ecological impact, level of automation;
4. *Resources*: materials consumption intensity, power-intensity, amount of personnel, financial expenses;
5. *Equipment:* total dimensions, weight, cost, supporting equipment, personnel qualification, velocity of reconfiguration, safety, maintainability.

Note that the priorities of these criteria may differ substantially depending on a particular type of coverings. In the article the authors have been focused on heat-resistant and abrasion-resistant covering. The hierarchical structure of the criteria is shown on Figure 2.

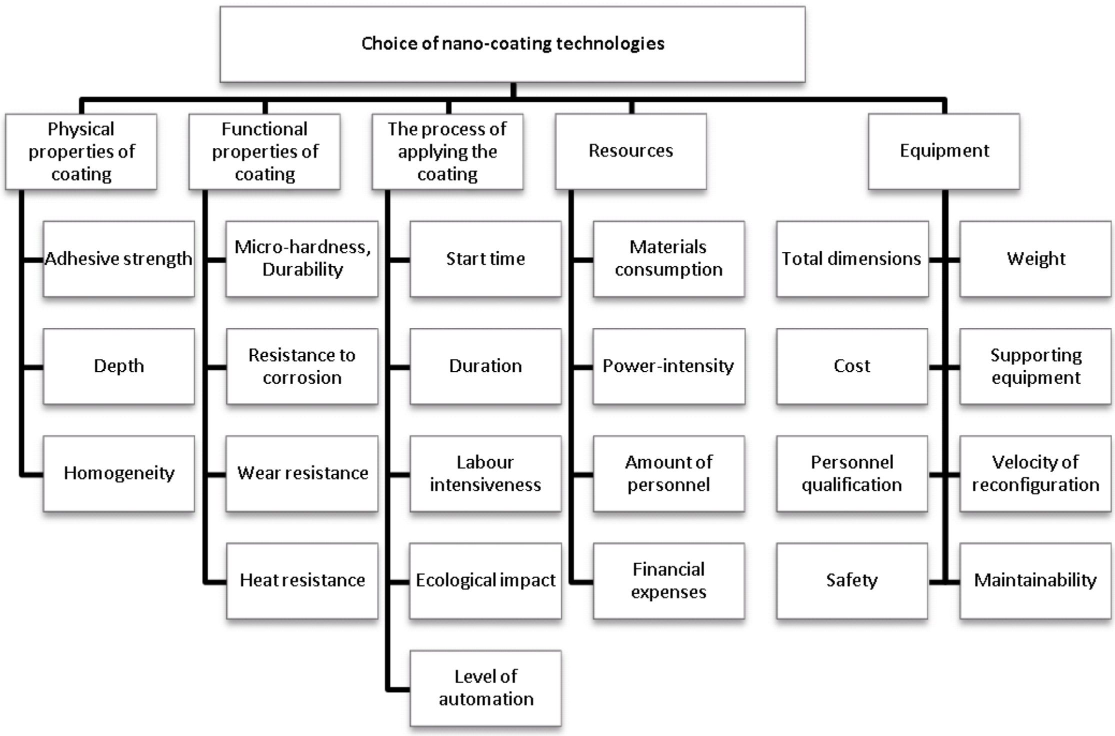


Figure 2. Hierarchical structure of the criteria

To perform the calculations of criteria, the authors have used standard algorithms of the AHP method with the commonly used pair-wise comparison scale 1-9 [7]. This scale proposed by Saaty has the following values for two alternatives A and B: "1" – if A and B are equal in importance; "3" – if A is slightly more important than B; "5" – if A is significantly more important than B; "7" – if A is very significantly more important than B; 9 – if A is absolutely more important than B. And 2, 4, 6, and 8 are intermediate values between the two adjacent judgments. The evaluations of the pair wise comparisons of criteria and the summary results of the comparative assessment of two alternative methods of applying nano-coating are presented in the next sections.

3.2. Assessment of nano-coating efficiency

There are currently various methods that have been developed and implemented to analyze and choose from a range of alternatives [9]. The authors have analysed the possibility of employing one of the most popular multiple-criteria decision analysis method the Analytic Hierarchy Process (AHP) [7] to solve the problem of choosing the best method of nano-coatings.

The results of the experts' pair-wise comparisons for groups of criteria are presented in Table 2. The importance of the groups of criteria is evident from the evaluation of the criteria priority vector. It is easy to notice that criteria "Functional Properties of Coating" with value 0,5052 of priority vector are more important for nano-coating methods.

Table 1. The summary data of the pair-wise comparisons for the criteria of the first hierarchy level

Groups of Criteria	Physical properties of coating	Functional properties of coating	Process of coating	Resources	Equipment	Priority vector
Physical properties of coating	1	1/3	3	5	4	**0,2534**
Functional properties of coating	3	1	5	7	6	**0,5052**
Process of coating	1/3	1/5	1	3	3	**0,1257**
Resources	1/5	1/7	3	1	1/2	**0,0478**
Equipment	1/4	1/6	1/3	2	1	**0,0680**

It is worth mentioning that the significance of one part of criteria depends on the purpose of the coating, and the significance of other part is the same for different type of coating. In presented research the authors suppose the significance of each separate criterion of four groups "Physical Properties of Coating", "The Process of Applying the Coating", "Resources", and "Equipment" is the same for different types of coating, and the significance of separate criteria of "Functional Properties of Coating" group depends on the purpose of coating, which is subjected to the coating application.

It is important that the paper under consideration reviews two types of items: heat-resistant and abrasion-resistant coatings; the efficiency of technologies of applying the coatings is assessed (see below). Taking into account the above discussed points, there is done the assessment of the efficiency of criteria groups "Physical Properties of Coating", "The process of applying the coating", "Resources", and "Equipment" (see the Tables 2-5). Then the significance of criteria of the "Functional Properties of Coating" group for every type of coating is evaluated separately (see Sections 4.2 and 4.3). The obtained results will be employed for the process of estimating the technologies of applying the nano-coatings on heat-resistant and abrasion-resistant items.

Table 2. Matrix of evaluations of the vector of the criteria priorities of the "Physical Properties of Coating" group

Physical properties of coating	Adhesive strength	Depth	Homogeneity	Priority vector
Adhesive strength	1	9	7	**0,7720**
Depth	1/9	1	1/3	**0,0545**
Homogeneity	1/7	3	1	**0,1734**

Table 3. Matrix of evaluations of the vector of the criteria priorities of the "Process of Coating" group

Process of coating	Start time	Duration	Labour intensiveness	Ecological impact	Level of automation	Priority vector
Start time	1	1/3	1/2	1/7	1	**0,0673**
Duration	3	1	1/2	1/5	3	**0,1391**
Labour intensiveness	2	2	1	1/4	2	**0,1632**
Ecological impact	7	5	4	1	7	**0,5632**
Level of automation	1	1/3	1/2	1/7	1	**0,0673**

Table 4. Matrix of evaluations of the vector of the criteria priorities of the "Resources" group

Resources	Materials consumption	Power intensity	Personnel	Financial expenses	Priority vector
Materials consumption	1	2	7	3	**0,4863**
Power-intensity	1/2	1	5	2	**0,2856**
Personnel	1/7	1/5	1	1/4	**0,0555**
Financial expenses	1/3	1/2	4	1	**0,1726**

Table 5. Matrix of evaluations of the vector of the criteria priorities of the "Equipment" group

Equipment	Total dimensions	Weight	Cost	Supporting equipment	Personnel qualification	Velocity of reconfiguration	Safety	Maintainability	Priority vector
Total dimensions	1	1	1/3	1/5	1/5	3	1/7	1/4	**0,0378**
Weight	1	1	1/3	1/5	1/5	3	1/7	1/4	**0,0378**
Cost	3	3	1	1/3	1/3	5	1/5	1/2	**0,0787**
Supporting equipment	5	5	3	1	1	7	1/3	2	**0,1785**
Personnel qualification	5	5	3	1	1	7	1/3	2	**0,1785**
Velocity of reconfiguration	1/3	1/3	1/5	1/7	1/7	1	1/9	1/6	**0,0199**
Safety	7	7	5	3	3	9	1	4	**0,3516**
Maintainability	4	4	2	1/2	1/2	6	1/4	1	**0,1171**

3.3. Comparative assessment of nano-technologies for heat-resistant coatings

Additionally for every type of coating separately matrices of evaluations of the vector of the criteria priorities of the "Functional Properties of Coating" group were calculated. Let us consider heat-resistant coatings, the example of this coating application is hot tract of a gas turbine engine. The results of evaluations of the vector of the criteria priorities of the "Functional Properties of Coating" group are presented in Table 6.

Table 6. Matrix of evaluations of the vector of the criteria priorities of the "Functional Properties of Coating" group: heat-resistant coatings

Functional properties of coating	**Micro-hardness**	**Durability**	**Resistance to corrosion**	**Wear resistance**	**Heat resistance**	**Priority vector**
Micro-hardness	1	1/5	1/4	1/3	1/7	**0,0415**
Durability	5	1	3	4	1/3	**0,2527**
Resistance to corrosion	4	1/3	1	2	1/5	**0,1224**
Wear resistance	3	1/4	1/2	1	1/6	**0,0797**
Heat resistance	7	3	5	6	1	**0,5038**

The next stage of research is devoted to the comparison of the pairs of technologies under consideration according to every criterion inside the groups. Preceding the evaluations of the criteria priority vectors of two levels of the hierarchy, we receive the final result of the evaluations of the global priority vector shown in Table 7 and on Figures 3 and 4.

Table 7. Evaluations of the vector of the global criteria priorities: heat-resistant coatings

Heat-resistant coatings	**Groups of Criteria**					**Global Priority vector**
	Physical properties of coating	**Functional properties of coating**	**Process of coating**	**Resources**	**Equipment**	
Technologies\Weighs of groups	0,2534	0,5052	0,1257	0,0478	0,0680	
Method of ionic (gas-filled) condensation and bombing	0,6741	0,6420	0,3234	0,1996	0,4370	**0,5750**
Method of magnetron dispersion	0,3259	0,3580	0,6766	0,8004	0,5630	**0,4250**

It is easy to see that method of ion condensation and bombardment is substantially advantageous for heat-resistant coatings according to the groups of criteria "Physical Properties of Coating" and "Functional Properties of Coating"; this method has the twice higher values of corresponding priorities (0.6741 against 0.3259, and 0.6420 against 0.3580). Since these groups of criteria have higher weight compared to the other groups of criteria, method of ion condensation and bombardment is also more efficient than method of magnetron dispersion (0.5750 against 0.4250**).**

3.4. Comparative assessment of nano-technologies for abrasion-resistant coatings

For abrasion-resistant coatings (used for rubbing surfaces) the results of evaluations of the vector of the criteria priorities of the "Functional Properties of Coating" group is presented in Table 8.

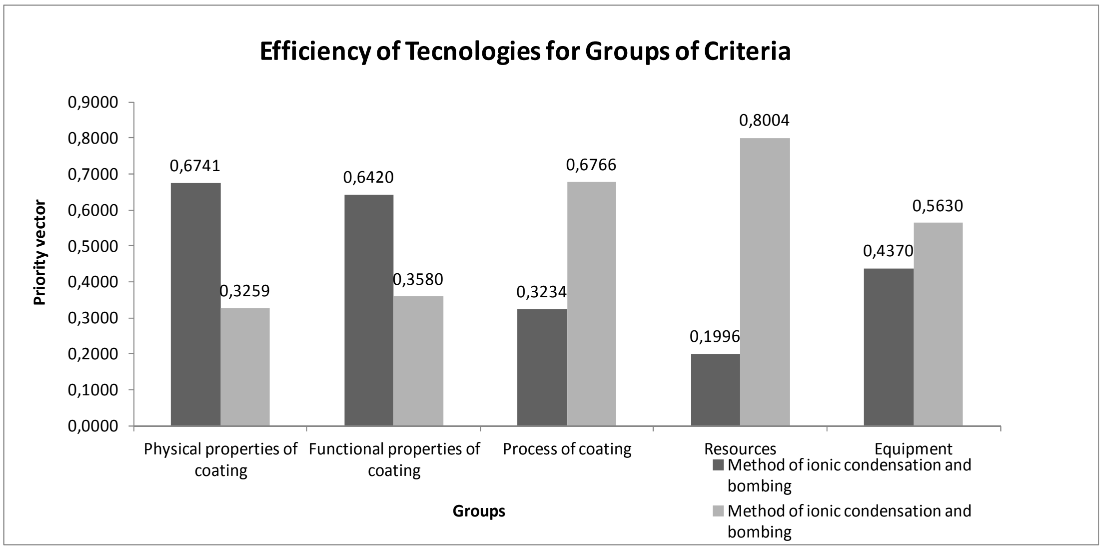


Figure 3. Efficiency of nano-coating methods for groups of criteria: heat-resistant coatings

Table 8. Matrix of evaluations of the vector of the criteria priorities of the "Functional Properties of Coating" group: abrasion-resistant coatings (for rubbing surfaces)

Functional properties of coating	Micro-hardness	Durability	Resistance to corrosion	Wear resistance	Heat resistance	Priority vector
Micro-hardness	**1**	5	1	1/3	3	**0,2064**
Durability	**1/5**	1	1/3	1/7	1/3	**0,0474**
Resistance to corrosion	**1**	5	1	1/3	3	**0,1864**
Wear resistance	**3**	7	3	1	5	**0,4728**
Heat resistance	**1/3**	3	1/3	1/5	1	**0,0871**

Preceding the evaluations of the criteria priority vectors of two levels of the hierarchy, we receive the final result of the evaluations of the global priority vector shown in Table 9 and on Figures 3 and 5a.

Table 9. Matrix of evaluations of the vector of the criteria priorities of the "Functional Properties of Coating" group: abrasion-resistant coatings (for rubbing surfaces)

Abrasion-resistant coatings	Groups of Criteria					Global Priority vector
	Physical properties of coating	Functional properties of coating	Process of coating	Resources	Equipment	
Technologies \ Weighs of groups	0.2534	0.5052	0.1257	0.0478	0.0680	
Method of ionic (gas-filled) condensation and bombing	0.6841	0.4261	0.3234	0.1996	0.4370	**0.4685**
Method of magnetron dispersion	0.3159	0.5739	0.6766	0.8004	0.5630	**0.5315**

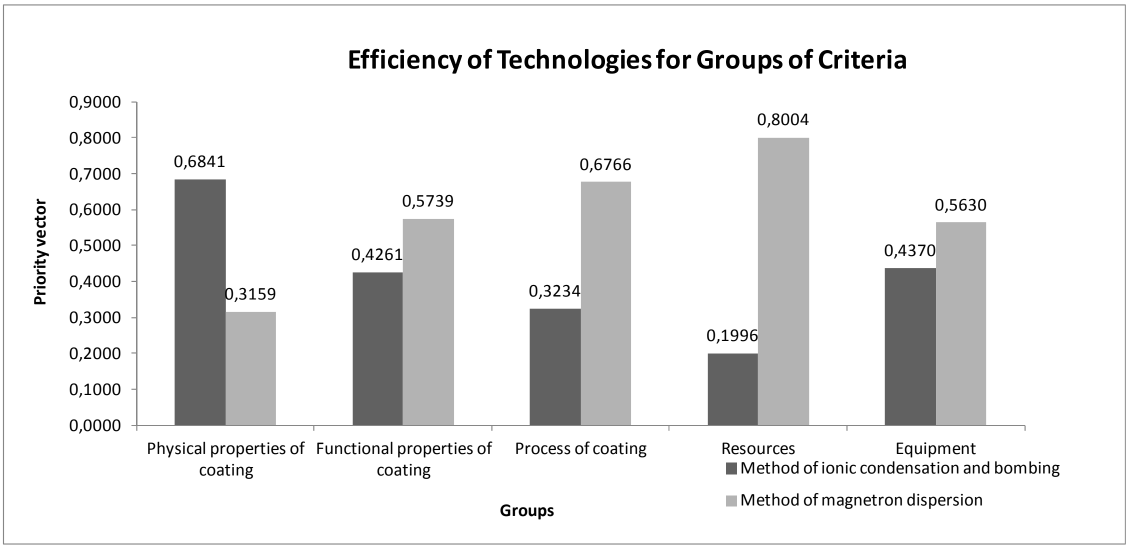
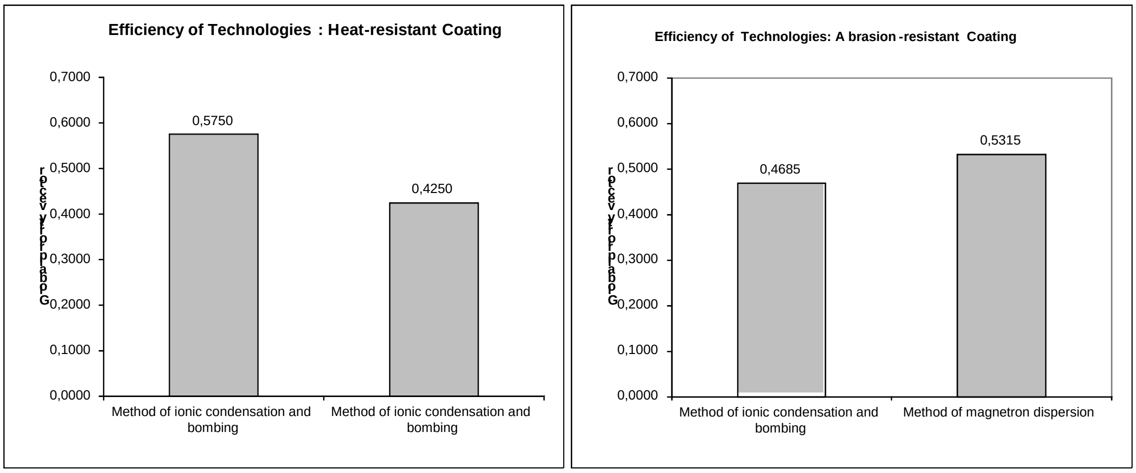


Figure 4. Efficiency of nano-coating methods for groups of criteria: abrasion-resistant coatings

It is easy to see that method of magnetron dispersion has higher priorities for abrasion-resistant coatings according to four groups of criteria; as a result the method of magnetron dispersion is more efficient than method of ion condensation and bombardment (the values of global priority are respectively 0.5315 and 0.4685).



a) b)

Figure 5. The global vectors of the priorities of nano-covering technologies: a - heat-resistant coating; b - abrasion-resistant coating.

4. Conclusions

The presented study has demonstrated that the AHP method can be used to solve the problem of assessment and choosing the better nano-coating technology for different types of coating taking in account system of criteria. The results of comparative assessment of nano-covering technologies considered in previous are summarized on Figure 5. The obtained results will be employed for the process of estimating the technologies of applying the nano-coatings on heat-resistant and abrasion-resistant items. Figures show that the technology of applying the nano-structural coatings with magnetron sputtering method is more efficient for heat-resistant coating, while the technology employing the method of ion condensation and bombardment is more suitable for abrasion-resistant coating.

Further development of current research is assessment of efficiency of other technologies of applying the nano-coatings, including the composite methods of application.

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