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Optimization of the technology for applying discrete coatings in restoration of bronze parts by electrospark alloying

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Abstract

In this work, a multicriteria optimization of the technology for applying discrete coatings by electrospark alloying in the restoration of bronze parts is carried out. As criteria for optimizing the process of electrospark alloying, tribotechnical characteristics were chosen – the wear intensity and friction coefficient of the coating. As adjustable parameters, those design, technological and operational factors that have the greatest influence on the value of optimization criteria are used: coating material; lubricant; operating current; amplitude of electrode oscillations; sliding speed; specific load. As a result of experimental studies, experimental dependences of wear intensity and friction coefficient for various coating materials, sliding speeds and lubrication conditions were obtained. The use of multicriteria optimization of the electrospark alloying technology made it possible to obtain various alternative coating options and technological parameters of their application for various operating conditions. Of the studied coatings, the most effective is a two-layer coating with the first layer SP-2 and an outer layer of the base material bronze BrAZhMts 10-3-1.5, which is explained by the formation of wear-resistant areas based on Mn and Ni. Multiparametric optimization of the electrospark alloying technology made it possible to reveal a combination of structural and technological factors that ensure the formation of discrete coatings with high operational properties in the restoration of bronze parts.

Key words: electrospark alloying, discrete coatings, bronze parts, multicriteria optimization, tribotechnical characteristics, design and technological factors.

Introduction

Parts made of bronze are one of the most common elements of plain bearings, which limit the resource of the entire unit. Taking into account the high cost of such material, its scarcity, rapid wear, as well as the fact that such parts are usually replaced with new ones during repairs, makes the problem of restoring bronze parts relevant [1-3].

The data of bronze parts fault detection results during the modern aircraft overhaul indicate that about 82% of the parts are rejected due to increased wear [4]. This is due to high specific loads at low sliding speeds, contamination of the contacting friction surfaces with abrasive, dust, condensate, as well as the non-additivity of the lubricant. Such units, in addition to plain bearings, include swivel-bolt joints, hinges with ball supports, etc.

The search for progressive coating application technologies for the restoration of worn parts operating under extreme friction and wear conditions showed that the coating application methods that are traditionally used in the aircraft repair industry do not allow effective restoration of triboconjugations parts "steel – bronze".

It was shown in [5-7] that one of the most effective and economical ways to eliminate wear of parts, including bronze ones, is the method of electrospark alloying (ESA).

Literature review

A number of works [8, 9, etc.] are devoted to the study of bronze parts restoration technology.

The work [8] presents a classification of existing methods applicable to the restoration of bronze plain bearings. According to this classification, all methods can be divided into two main groups:

- restoration of parts by applying coatings on worn surfaces;
- restoration of parts dimensions by plastic deformation.

At the same time, the author [8] concluded that the presented recovery methods require the final machining operation (boring, grinding, etc.) in order to obtain dimensional accuracy and surface roughness. Therefore, to restore the internal surfaces of bronze bushings, it is advisable to use combined processing methods.

In works [5, 6], the effectiveness of bronze parts restoration by ESA was declared. The predominant area of ESA application is the restoration and hardening of worn parts. This method is based on the use of a concentrated energy flow – a spark discharge. ESA differs from a number of other methods of applying wear-resistant coatings by the low energy intensity of the process, environmental friendliness, and simplicity of the technological operation. The use of ESA technology does not require highly qualified service personnel, as well as the previous preparation of the hardened surface. ESA is characterized by small equipment dimensions, the possibility of local coating application on any conductive materials, and is implemented both in a mechanized version (with process automation) and in a manual vibrator version [10]. A comparison of the ESA method with gas-thermal spraying and laser processing shows the advantages of ESA in power consumption, equipment dimensions, material utilization rate, equipment cost and the need for surface preparation. In contrast to such mass technologies as gas-thermal spraying and PVD, much less research has been devoted to the ESA method. This refers the ESA technology to developing and promising technologies.

The ESA method is increasingly used in industry to improve the wear resistance and hardness of machine parts surface, including those operating at elevated temperatures and aggressive environments, to increase heat and corrosion resistance, as well as to restore worn surfaces of machine parts during repairs. Despite the fact that ESA has a positive effect on the wear resistance of the surface layer, its disadvantages often limit the implementation of this method for a wide range of machine parts. Such disadvantages include a change in surface roughness after ESA, uneven surface hardening, a negative effect of an electric discharge on the fatigue properties of products, and the appearance in some cases of a sublayer with reduced hardness in hardened products [5].

The undoubted advantage of the ESA method is the possibility of applying coatings of a discrete structure, which were studied by the scientific school of Professor B.A. Lyashenko. They found that a feature of most worn parts is the local nature and uneven wear. Taking into account this feature, the authors [5-7] developed a technology for restoring parts by applying discrete coatings of variable thickness in accordance with the diagram of uneven wear.

The efficiency of applying discrete coatings is confirmed by a number of studies [6, 7, etc.]. In particular, it was shown in work [10] that the minimum wear of the coating is observed at continuity ψ = 55…65% (Fig. 1).

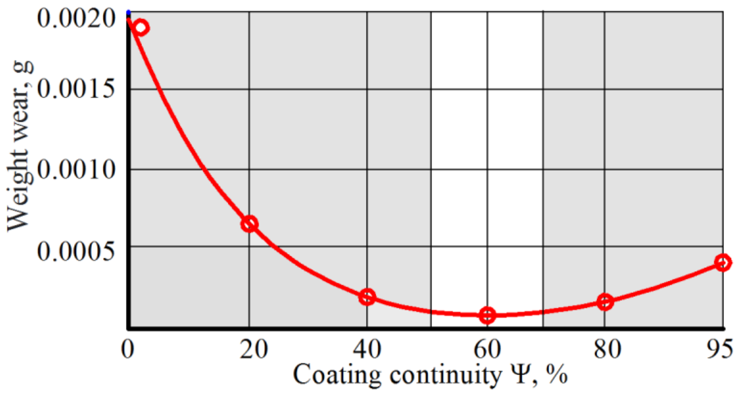


Fig. 1. Dependence of wear on coating continuity [10]

When applying discrete coatings, the ESA method has a number of advantages:

- a single electric discharge makes it possible to ensure the stability of the dimensions and properties of a separate discrete section of the coating;
- by changing the electrical parameters of each individual discharge, it is possible to apply discrete sections of various sizes and, above all, of various thicknesses;
- by changing the pulse frequency or the speed of the electrode and the part relative movement, it is possible to control the number of discrete sections on the working surface of the part, as well as the continuity of the coating;
- there is no need for additional heat treatment, since the discrete section is in a hardened state when the discharge heat is removed to the mass of the part;
- the ability to restore large parts.

In order to develop a technology for the restoration of bronze parts by ESA, it is very important to establish a connection between the tribotechnical characteristics of the studied surface and with design, technological, and operational factors. This will allow choosing coating options and technological parameters of their application for various conditions, providing the formation of coatings with high operational properties.

Purpose

The aim of the work is to find optimal solutions and establish connections between tribotechnical characteristics – wear rate and friction coefficient with design, technological and operational factors when applying discrete coatings by the ESA method.

Research Methodology

Bronze BrAZhMts 10-3-1.5, which works in triboconjugations of aviation equipment in contact with steel 30HGSN2A, was chosen as the base material for coating application. The chemical composition of the studied materials is presented in Tables 1-2.

Table 1

Chemical composition of bronze BrAZhMts 10-3-1.5, % [11]

Fe	Si	Mn	P	Al	Cu	Pb	Zn	Sn	Impurities
2 - 4	≥ 0.1	1 - 2	≥ 0.01	9 - 11	82.3 - 88	≥ 0.03	≥ 0.5	≥ 0.1	0.7

Table 2

Chemical composition of steel 30HGSN2A, % [11]

C	Si	Mn	Ni	S	P	Cr	Cu	Fe
0.27 - 0.34	0.9 - 1.2	1.0 - 1.3	1.4 - 1.8	≥ 0.025	≥ 0.025	0.9 - 1.2	≥ 0.3	~94

To apply coatings by the ESA method, a serial installation "Elitron-22" was used. The electrode materials were SP-1 and SP-2 alloys, the compositions of which are given in Table 3.

Table 3

Chemical composition of electrodes, % [6]

Name of electrode material	Composition of elements, %					
	Al	Si	Mn	Fe	Ni	Cu
SP-1	3 - 5	1	38 - 40	1 - 2	34 - 35	16 - 17
SP-2	-	8 - 9	36 - 37	1 - 2	33 - 34	1

When choosing an antifriction wear-resistant material for ESA electrodes, Mn and Ni were taken as the basis. Manganese increases strength, plasticity and corrosion resistance. Nickel improves mechanical properties, increases heat resistance and corrosion resistance. A further increase in the tribotechnical characteristics of the electrode material was carried out by introducing alloying additives Al, Si, Fe and Cu [6].

Studies on friction and wear of experimental coatings were carried out on a universal friction machine SMT-1 according to the “disk – block” scheme. In this case, the lubrication conditions were provided by a special hermetic chamber. CIATIM-201, AMG-10, and Svintsol-01 were used as a lubricating environment [6].

For a rational choice of the discrete coating structure parameters, preliminary experiments were carried out to establish the dependence of wear resistance on the continuity characteristic ψ. The coefficient ψ is determined by the ratio of discrete coatings area to the total area.

The size of the coating area was determined based on the results of metallographic analysis of the surface using digital image processing methods on a PC (Fig. 2). For this purpose, a program was written in C++ using the Qt framework and OpenCV image processing libraries [12].

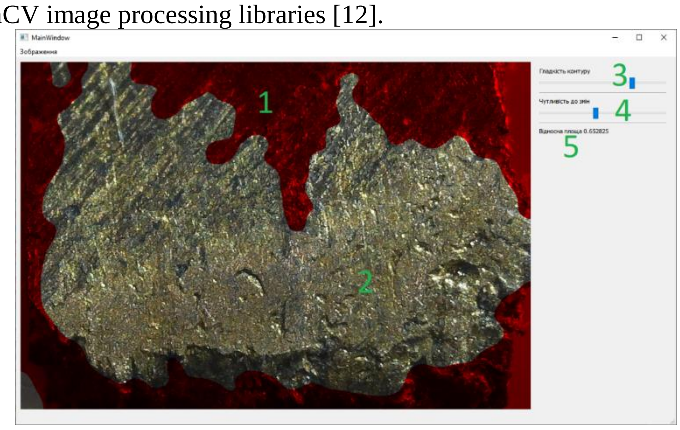


Fig. 2. The interface of the program for determining the coating area: 1 – a selected area without an applied coating; 2 – not selected area with an applied coating; 3, 4 – controls that allow you to adapt the selection algorithm to the capabilities of the chamber; 5 – the ratio of not selected area to the total area of the photograph [12]

Since the minimum wear of the coating is observed at continuity ψ = 55...65% (Fig. 1), in all further studies, continuity ψ = 0.6 was used.

Three types of coatings were tested:
1) coating by electrode SP-1;
2) coating by electrode SP-2;
3) two-layer coating SP-2 + AP with the first layer SP-2 and the outer layer of the base material – bronze BrAZhMts 10-3-1.5.

The composition of the coating SP-2 + AP is justified by the fact that for high anti-scratch resistance it is advisable to apply a thin layer of a softer material on a hard surface, which plays the role of a solid lubricant. In this case, defects in the form of scratches will not appear on the surface, which, in practice, always puts out of action the triboconjugation. The SPD method was used as the finishing treatment of the coatings. Hardening of the coating surface layers by the SPD method ensures the achievement of the required surface roughness and dimensions of parts without machining, as well as an increasing its hardness and wear resistance [13]. As criteria for optimizing the ESA process, the main tribotechnical characteristics are chosen – the wear rate and the friction coefficient of the coating.

Results

The use of expert evaluation methods and a series of screening experiments [14] made it possible to obtain an average a priori ranking of the input factors influencing the ESA process (Fig. 3).

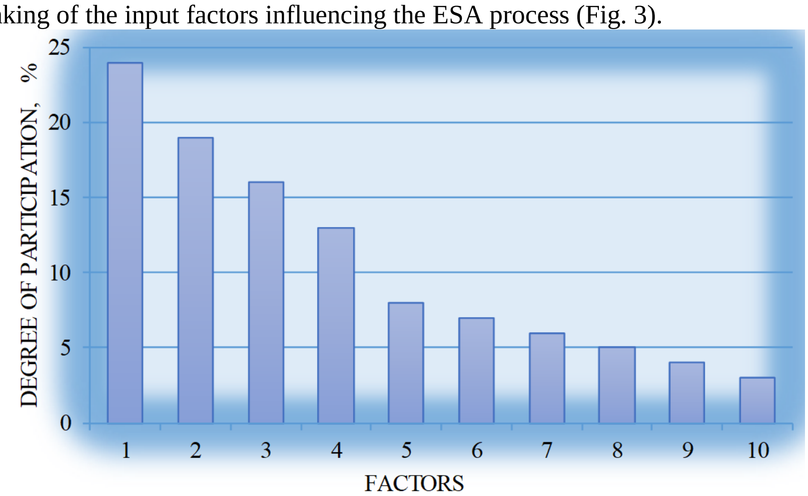


Fig. 3. Ranked number of factors: 1 – coating material; 2 – operating current of the ESA; 3 – amplitude of the ESA electrode oscillations; 4 – sliding speed; 5 – specific load; 6 – lubricant; 7 – coating thickness; 8 – electrode diameter; 9 – discreteness parameter ψ; 10 – application time

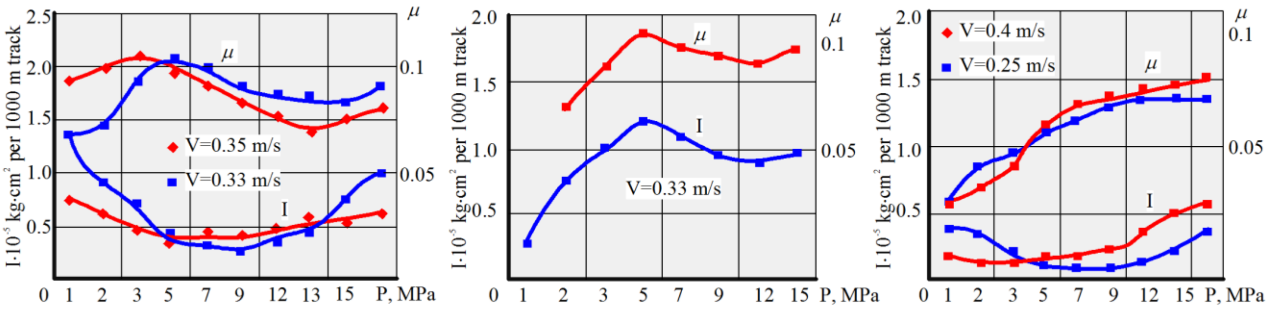
Modeling the coating application process based on the analysis of the conducted ranking made it possible to determine the group of parameters that have the greatest influence on the value of the optimization criteria, and therefore, the following factors were included in the planning matrix as adjustable factors: coating material; lubricant; operating current of the ESA; amplitude of electrode oscillations; sliding speed; specific load. Controlled factors and levels of their variation are presented in Table 4.

Table 4

Controlled factors and levels of their variation

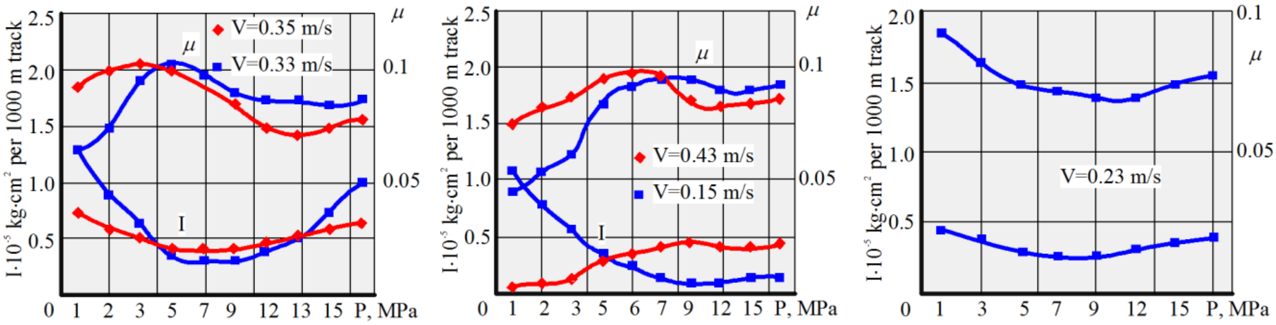
Factors	Levels of variation		
Coating material	SP-1	SP-2	SP-2 + AP
Lubricant	AMG-10	Svintsol-01	CIATIM-201
Operating current, A	1 - 4		
Electrode oscillation amplitude, mm	0,2 - 0,5		
Sliding speed, m/s	0,1 - 0,5		
Specific load, MPa	0 - 20		

Taking into account the data (Table 4), an experiment plan was generated. As a result of experimental studies, the tribotechnical characteristics of the studied coatings of a discrete structure were obtained when changing structural, technological and operational factors according to the plan of the experiment. Based on the results obtained, the dependences of the wear intensity and friction coefficient were constructed in accordance with the working matrix of experiment planning. Dependences of wear intensity and friction coefficient for various coating materials, sliding speeds and lubrication conditions are shown in Fig. 4-6.



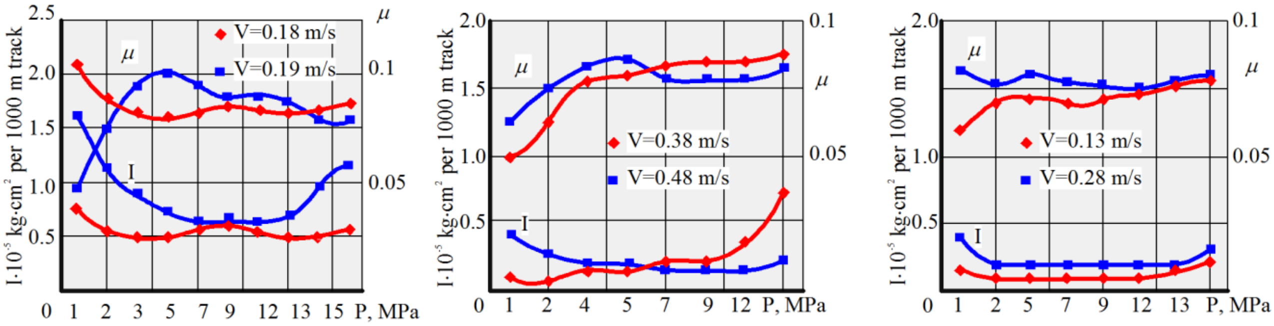
a) b) c)

Fig. 4. Tribotechnical characteristics (*I* and μ) for SP-1 coating under lubrication conditions: a – AMG-10 lubricant; b – CIATIM-201 lubricant; c – Svintsol-01 lubricant



a) b) c)

Fig. 5. Tribotechnical characteristics (*I* and μ) for SP-2 coating under lubrication conditions: a – AMG-10 lubricant; b – CIATIM-201 lubricant; c – Svintsol-01 lubricant

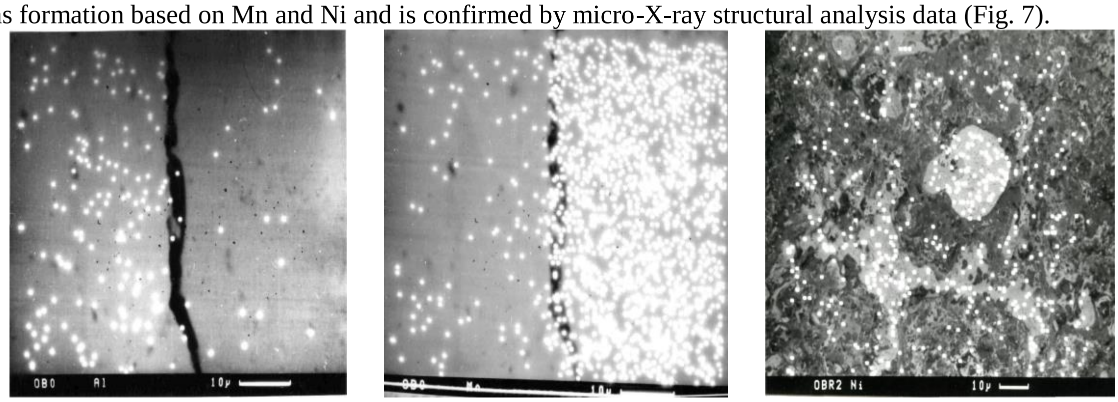


a) b) c)

Fig. 6. Tribotechnical characteristics (*I* and μ) for SP-2 + AP coating under lubrication conditions: a – AMG-10 lubricant; b – CIATIM-201 lubricant; c – Svintsol-01 lubricant

According to X-ray structural analysis, the surface structure during friction represents a stable secondary structure, the quantitative characteristics of which sharply change at $P_{cr} \geq 3.5\ MPa$. The results of the conducted experiment made it possible to reveal the tribotechnical characteristics of the coatings under the conditions of using various lubricants, at various sliding speeds and specific loads.

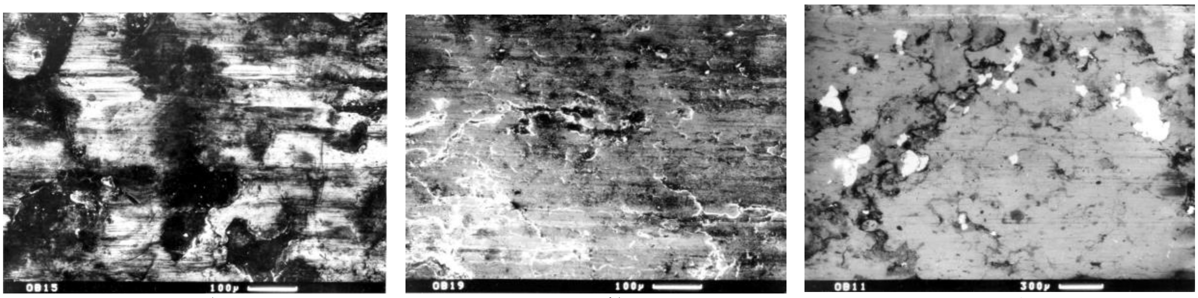
Of the studied coatings, the best results were shown by the SP-2 + AP coating. There are no scratches, cracks, or wear marks on the friction surface of this coating, which, in our opinion, is the result of wear-resistant areas formation based on Mn and Ni and is confirmed by micro-X-ray structural analysis data (Fig. 7).



a) b) c)

Fig. 7. Depth of penetration and distribution of alloying elements from the SP-2 coating into the base: a – aluminum distribution; b – manganese distribution; c – nickel distribution

The influence of the lubricant type on the friction surface is shown in Fig. 8.



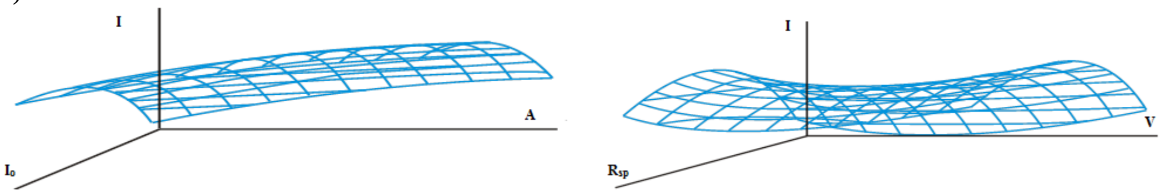
a) b) c)

Fig. 8. Microstructure of the friction surface of electrospark coatings in a lubricating environment: a – AMG-10; b – CIATIM-201; c – Svintsol-01

It should be noted that the CIATIM-201 anti-friction consistent lubricant is currently used to reduce friction and wear in the control units of aircraft and their engines, landing gear attachment points and mechanisms for closing it, wheel bearings and various electrical units, weapons mechanisms, special equipment and devices. When operating aviation equipment for hydraulic systems, in which sealing parts and hoses are made of oil-resistant rubber, AMG-10 oil is currently used as a working fluid. Svintsol-01 lubricant is characterized by a high antiwear effect and is a product of the combination of CIATIM-201 consistent lubricant and 10% lead powder, and is used in the operation of aviation equipment in units where the high specific pressure takes place, as it has a high stability of the boundary lubricating skin due to the presence of lead powder, which plays the role of a solid lubricant and protects the contact surfaces from scratching [15].

A more complete and accurate assessment of the connection between tribotechnical characteristics and design, technological and operational factors is provided by regression analysis of experimental results.

A graphical study of response surfaces shows a significant influence of factors on dependent variables (Fig. 9).



a) b)

Fig. 9. Wear intensity response function I from:
a – operating current I_o and amplitude of the electrode A oscillations; b – sliding speed V and specific load R_{sp}

The thickness of the coating plays a significant role in optimizing the ESA technology. Therefore, a separate experiment was carried out to establish the dependence of the wear intensity *I* on the coating thickness h_c while fixing the remaining ranked factors. The results are shown in Fig. 10.

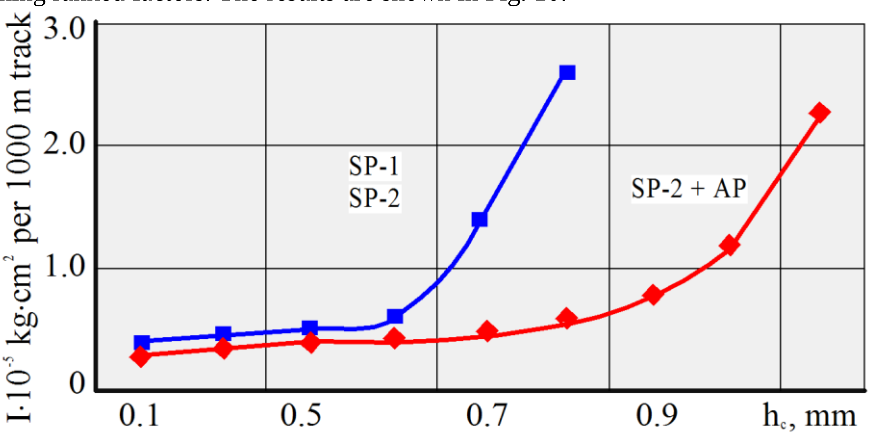


Fig. 10. Dependence of wear intensity I on coating thickness h_c
(V = 0.2 m/s, R_{sp} = 15 MPa, under conditions of Svintsol-01 lubrication)

For normal operation of coatings SP-1 and SP-2, their thickness should not exceed 0.6 mm. Coating SP-2 + AP has a high anti-scratch resistance due to the plastic outer layer. This makes it possible to apply SP-2 + AP coating up to 0.8 mm thick without decreasing of operational characteristics.

Thus, with the help of mathematical models, through multicriteria optimization, it is possible to obtain several alternative coating options and technological parameters of their application for various operating conditions.

Conclusions

Multicriteria optimization of applying discrete coatings technology in the restoration of bronze parts by electrospark alloying led to the following conclusions:

1. Alternative variants of coatings and technological parameters of their application for various operating conditions have been obtained.

2. Of the studied coatings, the most effective is the two-layer coating SP-2 + AP with the first layer SP-2 and the outer layer of the base material bronze BrAZhMts 10-3-1.5. This is explained by the formation of wear-resistant sections based on Mn and Ni.

3. Multiparametric optimization of the ESA technology made it possible to reveal a combination of structural and technological factors that ensure the formation of coatings with high operational properties.

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Солових Е.К., Шепеленко І.В., Черновол М.І., Магопець С.О., Солових А.Е., Катеринич С.Е.
Оптимізація технології нанесення дискретних покриттів при відновленні бронзових деталей електроіскровим легуванням

В роботі виконано багатокритеріальна оптимізація технології нанесення дискретних покриттів електроіскровим легуванням при відновленні бронзових деталей. В якості критеріїв оптимізації процесу обрано триботехнічні характеристики: інтенсивність зношування та коефіцієнт тертя покриття. Як регульовані параметри використано саме ті конструкційні, технологічні та експлуатаційні фактори, які найбільшою мірою впливають на вихідну величину: матеріал покриття; мастило; робочий струм; амплітуда коливань електроду; швидкість ковзання; питоме навантаження. В результаті проведення експериментальних досліджень отримано експериментальні залежності інтенсивності зношування та коефіцієнта тертя від питомого навантаження для різних матеріалів покриттів, швидкостей ковзання та умов змащення. Застосування багатокритеріальної оптимізації технології електроіскрового легування надало змогу отримати різні альтернативні варіанти покриттів та технологічних параметрів їх нанесення для різних умов експлуатації. Із досліджених покриттів найбільш ефективне – двошарове покриття з першим шаром СП-2 та зовнішнім шаром із матеріалу основи – бронзи БрАЖМц 10-3-1,5, що пояснюється утворенням зносостійких ділянок на основі Mn та Ni. Багатопараметрична оптимізація технології електроіскрового легування дозволила виявити поєднання конструкційних та технологічних факторів, які забезпечують формування дискретних покриттів з високими експлуатаційними властивостями при відновленні бронзових деталей.

Ключові слова: електроіскрове легування, дискретні покриття, бронзові деталі, багатокритеріальна оптимізація, триботехнічні характеристики, конструкційні та технологічні фактори