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IMPROVEMENT OF SURFACE LAYER QUALITY PARAMETERS OF STEEL PARTS AFTER NITROCARBURUZING BY ELECTROSPARK ALLOYING METHOD.
Part 1. FEATURES OF THE STRUCTURAL STATE AND TOPOGRAPHY OF STEEL SURFACES AFTER NITROCARBURIZING

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The paper analyses modern methods for improving the surface quality of steel parts of nuclear power plant pumps. The aim of the work was to improve the technology of nitrocarburisation by the method of electrospark alloying (ESA) by studying the effect of the ESA process performance on the quality parameters of the formed surfaces. As a result of the studies, the dependence of the quality parameters of the surfaces of steel parts during nitrocarburizing by the ESA method on the energy parameters of the equipment (discharge energy Wp) and the technological parameters of the process (productivity Q) was established. Experimental studies have shown that as Wp increases, the thickness of the hardened layer, its microhardness and continuity, and surface roughness grow. As Q decreases, the thickness, microhardness and continuity of the hardened layer rise, while the roughness remains practically unchanged. The proposed technology can be recommended for implementation in manufacturing.

INTRODUCTION

The continuous development of nuclear power requires the production of modern power equipment. Most of this equipment consists of powerful rotating machines (turbines, pumps, compressors, centrifuges, etc.). The largest part of this equipment consists of pumps for various purposes. The machines used in nuclear power plants (NPPs) are constantly being improved, resulting in the need for more reliable and durable parts and components. They are manufactured using high-strength and tend to costly materials [1–3].

It is well known that the destruction of parts during operation usually begins with the appearance of surface damage that is incompatible with further operation. Therefore, in most cases, it is sufficient to modify only the surface layer and use cheaper materials with mechanical strength to manufacture the part in order to ensure the required performance characteristics [4–6]. The development of new composite materials with a hard, wear-resistant surface and a substrate with high fatigue strength is an important task [7–10].

STATEMENT OF THE PROBLEM

Traditional technologies that provide the required functional properties to the surfaces of parts include: metal-ceramic coatings [11–13], welding of coatings with composite materials [14, 15], vapor deposition [16–18], laser surfacing [19], laser melt injection [20], composite electroplating [21], chemical deposition [22], etc.

In recent years, much attention has been paid to technologies using concentrated energy flows (CEF): ion treatment [23], laser treatment [24], ion nitriding [25], etc.

One of the most promising modern technologies using CEF is electrospark alloying (ESA), which creates surface structures with unique physical, mechanical and tribological properties at the nanoscale in the surface layers [26–28].

The characteristics of ESA, the influence of machining energy parameters and the electrode materials used are presented in the literature [29–36]. It should be noted that tool electrodes (TEs) made of compact (cast) or sintered materials by powder metallurgy (PM) are usually used for deposition. For a long time, the main TEs were hard alloys. However, these no longer meet the ever-increasing surface quality requirements. PM technologies have proven to be a promising direction in the development of TEs [12, 37]. New methods have made it possible to form composite coatings, including nanostructured ones, with improved properties. However, the use of PM for the production of TEs for industrial use is not cost-effective, as PM requires the use of expensive raw materials, the development of production technology, special equipment, including controlled atmosphere furnaces, etc.

The authors of [27, 30, 34, 36] proposed new energy and cost efficient ESA technologies using special technological saturation media (STSM) applied to the treated surface prior to ESA. In this way, alitisation [29–31], cementation [32–34], nitriding [35], synthesis of boron-containing coatings [36] and multi-component coatings have been carried out and introduced into production.

The analysis of ESA operations with both compact TE and STSM showed that the quality parameters of the surface layers were studied as a function of the discharge energy (W_p). At the same time, the value of the machining productivity (Q), i.e. the amount of 100% machined area per unit time (cm^2/min), was taken according to the recommendations of the companies that manufacture ESA equipment (Table 1). It is also known that for most materials the thickness of the layer formed on the cathode (part) is limited [32].

Table 1

Parameters of electrospark alloying [29, 38]

Discharge energy W_p, J	0.52	1.3	2.6	4.6	6.8
Productivity Q, cm^2/min	1.0…1.3	1.3…1.5	1.5…2.0	2.0…2.5	2.5…3.0

It should be noted that the traditional productivity parameters given in Table 1 are more acceptable when using hard alloys or alloys based on V, Ti, W, etc. as TE, so it is advisable to study the effect of ESA productivity in a wider range of alloying times on the surface layer parameters.

The authors of [38] proposed to perform nitrocarburisation by ESA using a paste (STSM) containing nitrogen-carbon components. Traditional processing parameters (see W_p and Q according to Table 1) were used for processing. It is shown that the proposed technology is effective and allows to obtain a coating of high continuity and hardness 9731…9930 MPa.

Thus, the aim of the work is to improve the technology of nitrocarburizing by the method of electrospark alloying by studying the effect of the productivity of the ESA process on the quality parameters of the formed surfaces.

RESEARCH METHODOLOGY

The ESA nitrocarburisation process was carried out as follows. First, the surface of samples of 20 and 40 steels, 15x15x8 mm in size, was alloyed with aluminum on an Elitron-52A model ESA apparatus at Wp = 3.40 J using TE made of 3.0 mm diameter AD grade aluminum wire (DSTU ISO 209-2:2002) [38]. Then, STSM in the form of a paste composition (urea 45%; yellow blood salt 45% and vaseline 10%) was applied to the aluminum coated surface without waiting for it to dry and further ESA by TE in the form of a graphite rod of EG-4 grade 3×3×25 mm in size at W_p = 0.13, 0.52, and 3.40 J and productivity according to Table 2.

Table 2

ESA parameters for nitrocarburization with graphite TE

Discharge energy W_p, J		0.13	0.52	3.4
Productivity Q, cm^2/min	The 1st variant	0.3	0.6	1.0
	The 2nd variant	0.2	0.3	0.5
	The 3rd variant	0.1	0.2	0.3

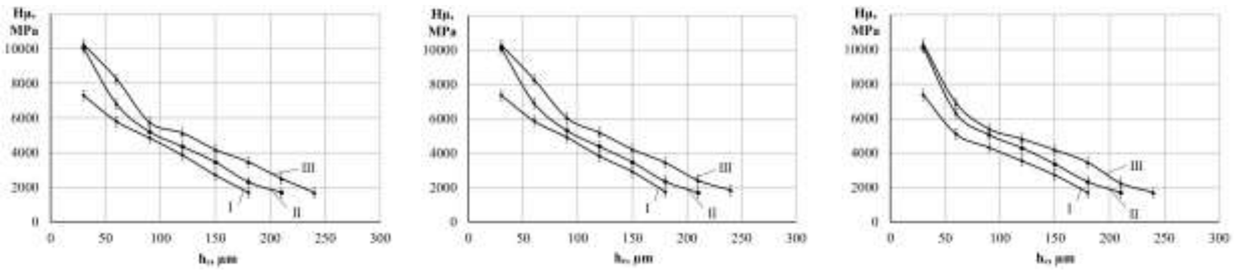
In order to evaluate the effect of productivity on the quality parameters of the coatings obtained, further studies were carried out with productivity ~ two, three and four times lower, i.e. the treatment time (τ) per unit area (labour intensity of the ESA) was increased by two, three and four times (see Table 2).

Metallographic studies of the prepared specimens were carried out using a MIM-7 optical microscope. Durometric analysis was carried out on a PMT-3 microhardness tester by pressing a diamond pyramid under a load of 0.05 N, according to GOST 9450-76. At all stages of the treatment, the surface roughness was measured using a profilograph mod. 201 from Kalibr.

RESEARCH RESULTS

The microstructure of the surface layer of steel 20 samples after nitrocarburizing by ESA using STSM at different productivity values of the treatment process was investigated. The results of the metallographic analysis show that the coating at all productivity levels (see Table 2) is formed by three regions: the 'white layer', the diffusion zone and the substrate metal. Discharge energy and ESA productivity affect the parameters of the structural regions.

Fig. 1 shows the microhardness distribution over the depth of the nitrocarburized layer on steel 20. It should be noted that the maximum hardness is fixed at the surface and gradually decreases towards the substrate, which has a microhardness of 1700…1800 MPa. The gradual change in the microhardness of the coating-substrate indicates a good adhesive-diffusion bond between the coating and the substrate. The microhardness of the coating zones is determined by the energy parameters of the ESA: the higher the discharge energy, the greater the hardness of the 'white' layer and hence the transition zone. Such a change in micro-hardness is probably related to the diffusion of nitrogen and carbon into the substrate and is also caused by a change in the phase composition of the coating [38].



a *b* *c*

Fig. 1. Distribution of microhardness along the depth of the surface layer of the Steel 20 sample after nitrocarburizing process thereof by the ESA method, where a, b, c are the 1st, 2nd, and 3rd variants, respectively. On the graph: I, II, and III, respectively, are W_p = 0.13; 0.52, and 3.4 J

Table 3

Surface layer quality parameters for Steel 20 specimens after nitrocarburisation by the ESA method using STSM

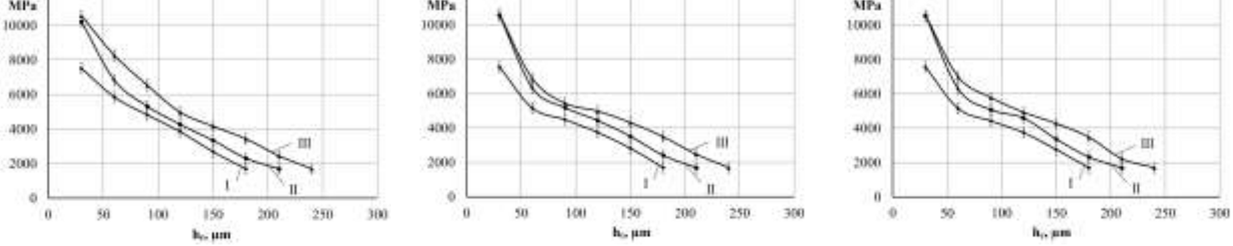
Discharge energy, J	Productivity Q, cm^2/min	Labor intensity τ, min/cm^2	The thickness of the strengthened layer, µm	Microhardness, MPa		Roughness Ra, µm	Continuity of the "white" layer, %
				"white" layer	transition zone		
Existing technology – productivity according to Table 1							
0.13	0.4…0.6	1.7	145…165	7150	4450	1.1	90
0.52	1.0…1.3	0.8	155…190	9921	4650	1.6	100
3.40	1.6…2.2	0.5	210…260	10050	4970	5.9	100
The first variant – ESA performance is reduced by 2 times (see Table 2)							
0.13	0.3	3.3	165…180	7310	4550	1.0	100
0.52	0.6	1.7	175…210	10030	4750	1.5	100
3.40	1.0	1.0	225…275	10250	5130	6.5	100
The second variant – ESA performance is reduced by 3 times (see Table 2)							
0.13	0.2	5.0	170…185	7360	4590	1.0	100
0.52	0.3	3.3	180…215	10090	4780	1.6	100
3.40	0.5	2.0	230…280	10290	5190	6.4	100
The third variant – ESA performance is reduced by 4 times (see Table 2)							
0.13	0.1	10.0	170…185	7360	4530	1.1	100
0.52	0.2	5.0	180…215	10100	4580	1.5	100
3.40	0.3	3.3	230…280	10300	4910	6.3	100

The productivity of the ESA process does not have a significant effect on the microhardness of the hardened layer, but it does have a positive effect on the thickness and continuity of the surface layer (Table 3). If at traditional productivity values (Q = 0.4…0.6 cm^2/min and W_p = 0.13 J) it is not possible to obtain a continuous layer, then by reducing Q it is possible to obtain 100% continuity with an increase in layer thickness. However, this will increase the surface roughness.

Analysis of the microstructure of the surface layer of samples of steel 40 after nitrocarburisation by ESA using STSM with nitrogen-carbon components. ESA of a steel surface results in the destruction of TE (anode); transfer of TE erosion products to the treated surface (cathode); micrometallurgical processes take place on the treated surface; TE and STSM material elements diffuse into the surface layer of the product; the surface of the product acquires a new specific topography; an altered layer is formed which contains a "white" layer and a diffusion zone. In this way, a new layer is formed on the surface with different properties from the initial state ('treated material'), which are determined by the spark discharge parameters (discharge energy W_p) and process productivity (Q).

Similar to steel 20, the thickness of the 'white' layer and the diffusion (transition) zone increases with rising discharge energy. As the discharge energy increases, the diffusion processes during ESA are accelerated and obviously the diffusion zone between the coating and the substrate grows. At the classical productivity values (Table 4), the thickness of the hardened layer at W_p = = 0.13 J is 150…170 µm, while at W_p = 3.4 J it is about 215…265 µm. In this case, the continuity of the coating is up to 100%.

Fig. 2 shows the microhardness distribution in the surface layer of steel 40. The 'white' layer has a maximum microhardness of 7150…10580 MPa, depending on the treatment parameters, and gradually decreases to the substrate hardness.



a　*b*　*c*

Fig. 2. Distribution of microhardness along the depth of the surface layer of the Steel 40 sample after nitrocarburizing process thereof by the ESA method, where a, b, c are the 1st, 2nd, and 3rd variants, respectively. On the graph: I, II, and III, respectively, are Wp = 0.13; 0.52, and 3.4 J

Table 4

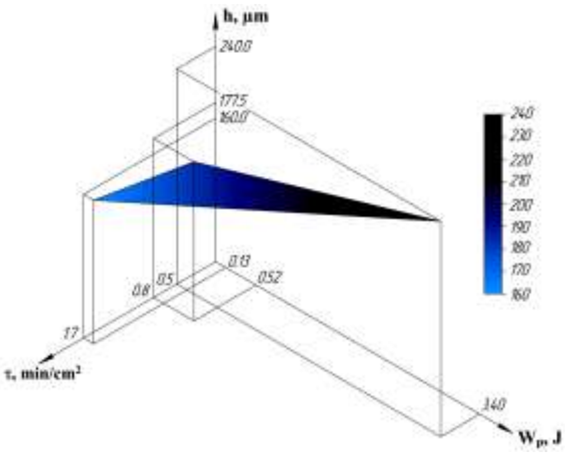
Surface layer quality parameters for steel 40 specimens after nitrocarburisation by the ESA method using STSM

Discharge energy, J	Productivity Q, cm^2/min	Labor intensity τ, min/cm^2	The thickness of the strengthened layer, μm	Microhardness, MPa		Roughness Ra, μm	Continuity of the "white" layer, %
				"white" layer	transition zone		
Existing technology							
0.13	0.4…0.6	1.7	150…170	7150	4450	1.1	90
0.52	1.0…1.3	0.8	160…195	9921	4650	1.6	100
3.40	1.6…2.2	0.5	215…265	10050	4970	5.9	100
The first variant							
0.13	0.3	3.3	170…185	7510	4550	1.0	100
0.52	0.6	1.7	180…215	10520	4750	1.5	100
3.40	1.0	1.0	230…280	10550	5130	6.5	100
The second variant							
0.13	0.2	5.0	175…190	7550	4590	1.0	100
0.52	0.3	3.3	185…220	10560	4780	1.6	100
3.40	0.5	2.0	235…285	10580	5190	6.4	100
The third variant							
0.13	0.1	10.0	175…190	7560	4530	1.1	100
0.52	0.2	5.0	185…220	10560	4580	1.5	100
3.40	0.3	3.3	235…285	10550	4910	6.3	100

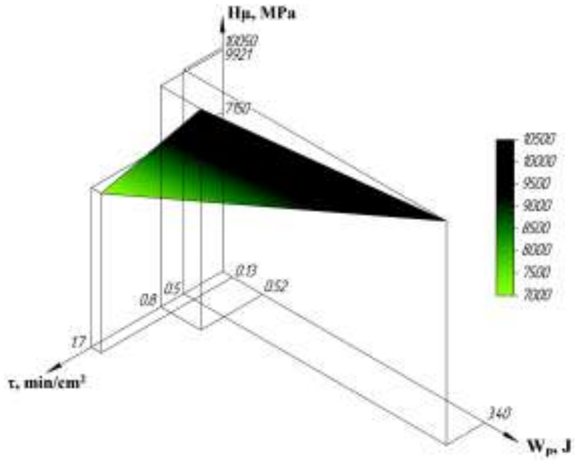
The increase in hardness in the transition zone can be caused by phase transformations that occur when the steel is heated above critical temperatures and accelerated cooling in air. The accelerated cooling after ESA results in some hardening of the steel surface layer and an increase in hardness. Similar to steel 20, the formation of intermetallics, nitrides, carbonitrides and oxides in the surface layer of steel 40 is possible due to the fact that the ESA process was carried out in air in a STSM environment. In addition, the formation of these phases contributes to an increase in the microhardness of the coating and the diffusion zone.

Figs. 3–6 show the summary data on the dependence of the thickness of the hardened layer (a) and the microhardness (b) of the "white" layer on Wp and the value of the reverse productivity – τ in nitrocarburizing by the ESA method of steel 40, respectively for the existing technology and the reduced productivity – the first, second and third treatment variants. Reducing the productivity of ESA has a positive effect on the quality of nitrocarburized layers, forming layers with a thickness of 170…285 μm and an increased hardness of 7510…10580 MPa. The highest hardness was achieved by the coatings produced by the second variant with a 3-fold reduction in ESA productivity (see Fig. 5).

The formation of strong and continuous nitrocarburised layers on the surface allows us to recommend them as protective and wear resistant.

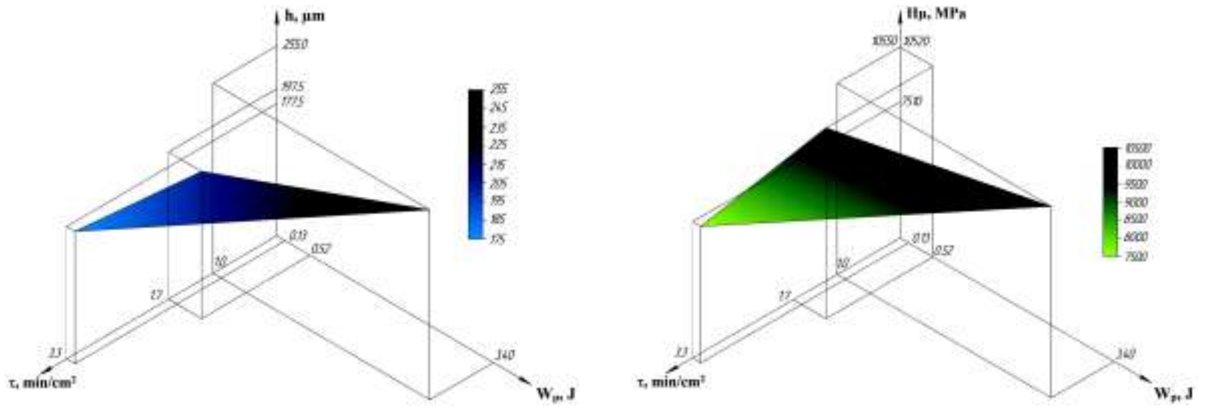


a



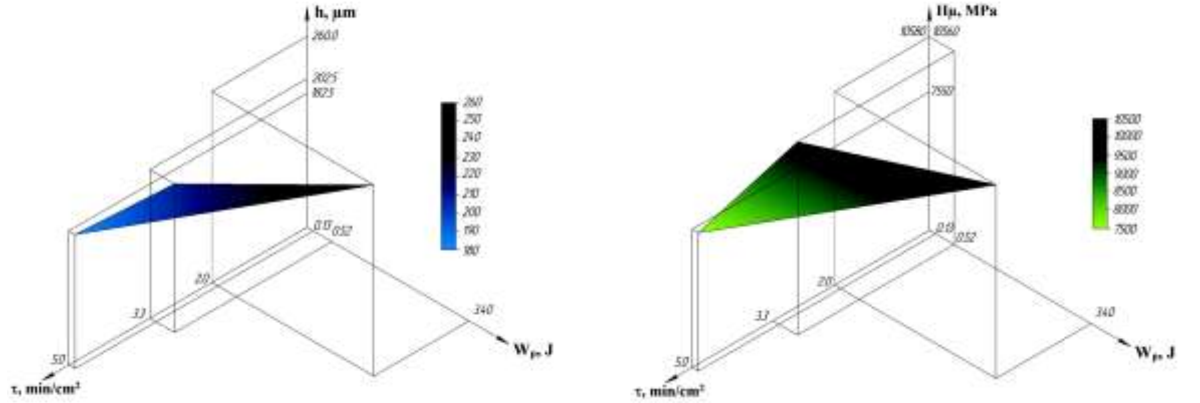
b

Fig. 3. Dependencies of the thickness of the strengthened layer (a) and the microhardness (b) of the "white" layer on W_p and τ values for the existing technology (steel 40)



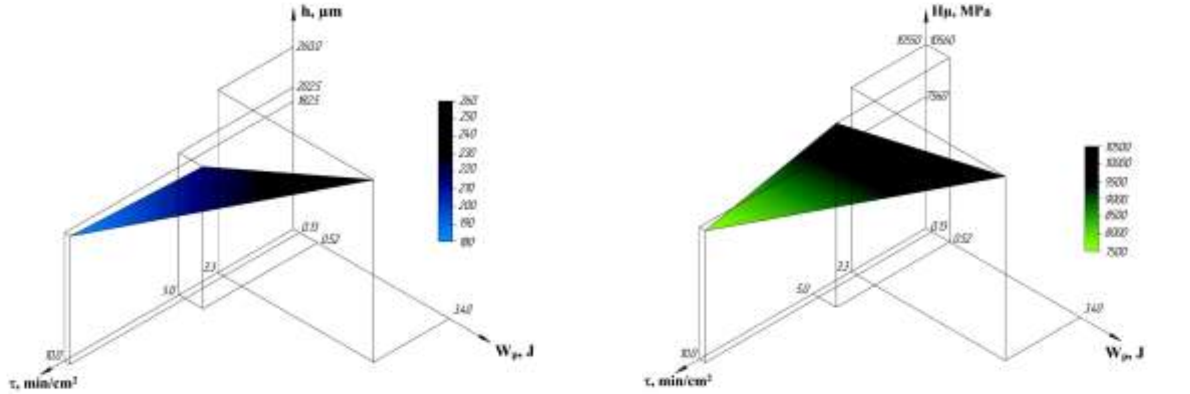
a *b*

Fig. 4. Dependencies of the thickness of the strengthened layer (a) and the microhardness (b) of the "white" layer on W_p and τ values for the first variant of processing (steel 40)



a *b*

Fig. 5. Dependencies of the thickness of the strengthened layer (a) and the microhardness (b) of the "white" layer on W_p and τ values during for the second variant of processing (steel 40)



a *b*

Fig. 6. Dependencies of the thickness of the strengthened layer (a) and the microhardness (b) of the "white" layer on Wp and τ values for the third variant of processing (steel 40)

CONCLUSIONS

Thus, as a result of the studies of nitrocarburized coatings synthesised according to the proposed technology, the following conclusions were obtained:

1. Correlations have been established between the quality parameters of the surfaces of steel parts during nitrocarburizing by the ESA method and the energy parameters of the equipment (discharge energy W_p) and the technological parameters of the process (productivity Q).

2. Experimental studies have shown that as the discharge energy increases, the thickness of the "white" layer and the diffusion (transition) zone, as well as microhardness, roughness and surface continuity grow; as the ESA productivity decreases, the thickness of the hardened surface layer and its microhardness increase, in addition, 100% surface continuity is achieved and the roughness almost does not change.

3. The carbon content of the substrate material (steel 20 and 40) has a negligible effect on the hardened surface layer thickness, surface roughness and continuity. However, the microhardness of the coating zones is slightly higher on steel 40 due to phase transformations that occur when the steel is heated above critical temperatures and accelerated cooling in air after treatment.

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УДОСКОНАЛЕННЯ ПАРАМЕТРІВ ЯКОСТІ ПОВЕРХНЕВИХ ШАРІВ ДЕТАЛЕЙ ЗІ СТАЛІ ПІСЛЯ НІТРОЦЕМЕНТАЦІЇ МЕТОДОМ ЕЛЕКТРОІСКРОВОГО ЛЕҐУВАННЯ

Частина 1. ОСОБЛИВОСТІ СТРУКТУРНОГО СТАНУ І ТОПОГРАФІЇ СТАЛЬНИХ ПОВЕРХОНЬ ПІСЛЯ НІТРОЦЕМЕНТАЦІЇ

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Проведений аналіз сучасних методів підвищення якості поверхонь стальних деталей насосів АЕС. Метою роботи було удосконалення технології нітроцементації методом електроіскрового легування (ЕІЛ) у результаті дослідження впливу продуктивності процесу ЕІЛ на параметри якості сформованих поверхонь. Внаслідок проведених досліджень встановлені залежності параметрів якості поверхонь стальних деталей при нітроцементації методом ЕІЛ від енергетичних параметрів обладнання (енергії розряду Wр) і технологічних параметрів процесу (продуктивності Q). Експериментальними дослідженнями встановлено, що зі збільшенням Wр зростають значення товщини зміцненого шару, його мікротвердість і суцільність, а також шорсткість поверхні. При зменшенні Q збільшуються величини товщини зміцненого шару, мікротвердість і суцільність, а шорсткість практично не змінюється. Пропоновану технологію можна рекомендувати для впровадження у виробництво.