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STUDY OF THE INFLUENCE OF ELECTROLYTIC-PLASMA TREATMENT PARAMETERS ON THE SURFACE STRUCTURE AND MECHANICAL PROPERTIES OF THE STRAIGHT TOOTH OF AN EARTHMOVING BUCKET

Abstract: *This study examines how electrolytic plasma treatment can improve the wear resistance of 30CrMnSi bucket teeth used in loaders operating under severe abrasive conditions. Samples were subjected to various processing methods, including electrolytic plasma hardening, nitriding, carburizing, nitrocarburizing hardening, and quenching. Multiple analytical techniques, including scanning electron microscopy energy dispersive spectroscopy, X-ray diffraction, and microhardness testing, were used to comprehensively characterize the structure, phases, and mechanical properties of the samples. The tribological properties of the materials were evaluated using a TRB3 tribometer, and abrasive wear testing was conducted according to GOST 23.208–79. The results show that electrolytic plasma treatment results in the formation of diffusion layers with a thickness of 15 to 25 μm. This process is accompanied by the formation of carbide, nitride, and carbonitride phases (*Fe_4C*,* Fe_7C_3*,* Fe_4N*,* Fe_2N*, and* $Fe_3(CN)$*). This process significantly increases surface hardness (up to 810 HV) and improves wear resistance. The study also showed that electrolytic plasma nitriding provides an optimal balance between hardness and toughness, resulting in low friction and increased resistance to abrasive wear. The development of this technology can extend the service life of earthmoving and mining equipment components, reducing maintenance costs and downtime.*

Key words: *bucket teeth; chemical-thermal treatment; electric discharge surface chemical-thermal treatment; abrasive wear; microhardness.*

Introduction

For many years, buckets were equipped with teeth to help penetrate, excavate, and break up materials. Teeth also serve as wear parts and can be replaced when worn, extending the life of the bucket. Early teeth were manufactured as one-piece constructions, requiring both cutting and welding to replace them, a labor-intensive process. Modern teeth consist of an adapter welded to the bucket and a tooth with a locking system, making it easy to replace when needed. Teeth available on the market today are cast, meaning their hardness cannot be guaranteed throughout their entire length.

In their study, Florea V. A. and Toderaș M. M. conducted a three-year monitoring of quarry equipment operating in a quarry [1]. The wear evolution of quarry equipment teeth, which directly contact rock, was specifically monitored during the production process, along with wear indicators obtained by simulating wear phenomena under laboratory conditions, in order to verify the data collected during the machines' operation. As a solution, the authors proposed welding worn bucket teeth to reduce downtime and reduce the cost of replacing them.

In a study by Shivali S. and his co-authors, analyzing the problem of intense abrasive wear on the working parts of earthmoving equipment, they concluded that applying hard-alloy coatings is an effective way to extend the service life of excavator bucket teeth [2]. Experiments showed that the use of ferrocarbon carbide electrodes with varying chromium and carbon contents significantly reduces material loss due to sliding friction. All the deposited layers tested demonstrated higher wear resistance than the original low-alloy steel.

The most common approaches include design improvements, the use of new materials, and the use of thermochemical treatment and surface hardening technologies [3]. These methods allow for improving surface properties without changing the characteristics of the component's core, maintaining its toughness and impact strength [4].

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Classic methods of thermochemical treatment – carburizing, nitrocarburizing and nitriding – are based on diffusion saturation of the surface with active elements at elevated temperatures. They ensure the formation of a hard surface layer that retains the ductility of the core [5]. Carburizing provides high hardness (HRC 58-62), but requires significant energy consumption and a long processing time [6]. Nitrocarburizing is carried out at lower temperatures (570-750 °C) and provides high hardness with a smaller layer depth [7]. Nitriding (500-570 °C) makes it possible to obtain a layer with a hardness of 1000-1200 HV without subsequent hardening, but the process is lengthy - up to 60 hours [8]. Hardening forms a martensitic structure with high wear resistance, but requires precise selection of heating and cooling modes [9].

In [10], it was shown that traditional heat treatment of 30CrMnSi steel increases hardness but does not provide sufficient resistance to impact loads. In contrast, electrolytic plasma treatment forms a diffusion carbonitride layer with high hardness and wear resistance. Modern electric discharge surface chemical-thermal treatment combines the advantages of chemical-thermal treatment and high-energy impact, providing localized hardening, short process time, and cost effectiveness, making it a promising method for increasing the service life of loader bucket teeth [11-13].

The use of electric discharge plasma chemical-thermal treatment for hardening bucket teeth is particularly promising, as it allows for a significant increase in their service life under conditions of abrasive and impact-abrasive wear [14, 15]. This reduces operating costs, improves equipment reliability, and increases the efficiency of production processes.

Thus, improving the wear resistance of loader teeth has significant practical and economic implications. On the one hand, it extends maintenance intervals and reduces operating costs. On the other hand, it improves equipment efficiency and reduces the cost of mining and construction work.

Given the above circumstances, the primary objective of this study is to investigate the effect of electrolytic plasma treatment, including nitriding, carburizing, quenching, and carbonitriding, on the structure, phase composition, and wear resistance of 30CrMnSi steel used to manufacture earthmoving bucket teeth. This study aims to determine the optimal EPT regime for increasing hardness, reducing the friction coefficient, and extending the service life of loader bucket teeth operating under conditions of intense abrasive wear.

Materials and methods

For electrolytic plasma treatment, samples were cut from straight ladle teeth (30CrMnSi steel) (Fig. 2a) measuring 20x20x20 mm. The chemical composition of 30CrMnSi steel is given in Table 1 in accordance with GOST 4543-71.

Table 1 – Chemical composition of steel 30 CrMnSi according to GOST 4543-71

C	Mn	Si	Cr	Cu	S	P	Fe
0.28-0.34%	0.80-1.10%	0.9-1.2%	0.80–1.10%	no more than 0.30%	no more than 0.025%	no more than 0.025%	rest

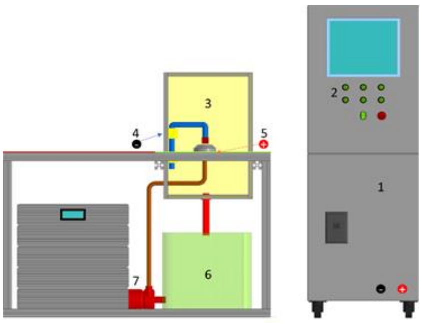


Figure 1 – Electrolytic-plasma treatment unit: 1) power source; 2) power source control panel; 3) electrolytic cell; 4) cathode; 5) anode; 6) container with electrolyte; 7) pump

The electrolytic-plasma unit operates as follows (Fig. 1): voltage is supplied from the power source (1) through the control panel (2) to the electrolytic cell (3), where the workpiece is connected as the cathode (4), and the opposite electrode serves as the anode (5); from the tank (6) the pump (7) circulates the electrolyte into the working area, where, when high voltage is applied, a vaporgas shell is formed on the surface of the cathode, which passes into a plasma state, which ensures local heating and modification of the material – removal of oxides, smoothing of microroughness and formation of a hardened or polished layer with improved performance properties.

Table 2 shows the parameters for nitrocarburizing, nitriding, carburizing and hardening, as well as the electrolyte composition, process temperature, voltage and processing time.

Table 2 – Processing parameters for each regime

Processing regime	Electrolyte	Temperature, °C	Voltage, V	Time, min
Nitrocarburization	10% Na_2CO_3, 20% CH_4N_2O, 5% $C_3H_8O_3$	800	170	6
Nitriding	10% Na_2CO_3, 20% CH_4N_2O	600	170	5
Cementation	10% $C_3H_8O_3$, 15% Na_2CO_3	950	170	10
Hardening	15% Na_2CO_3	600	200	2

To study the cross-sectional microstructure of the samples before and after electrolytic plasma treatment, an SEM3200 scanning electron microscope (Guangzhou, China) equipped with an energy-dispersive spectrometer was used. X-ray diffraction analysis was performed using an X'PertPRO diffractometer (Kyoto, Japan) with Cu-Kα radiation (λ = 1.54 Å) at 40 kV and 30 mA to identify the phases of the samples before and after EPT. Diffraction patterns were collected in the 2θ range from 20° to 90° with a step size of 0.02° and a counting time of 1 second per step. The data were analyzed using HighScore software.

A TRB3 tribometer (Austria) was used to study the tribological properties of samples before and after EPT. The load was 6 N, the distance was 100 m, the track radius was 3 mm, and a 100Cr6 steel ball with a diameter of 6 mm served as the counterweight. The tests were conducted at room temperature (24°C).

Abrasive wear tests were conducted in accordance with GOST 23.208-79. The abrasive material was electrocorundum with a grain size of 16P and a relative humidity in accordance with GOST 23.208-79. The test lasted 30 minutes (1800 roller revolutions).

The abrasive wear testing apparatus (Figure 2b) operates as follows: a rotating rubber roller (1), driven by an electric motor, interacts with a sample (2) secured in a sample holder (3). A lever (4) creates a constant force pressing the sample against the roller surface. A continuous flow of abrasive material is fed from the dosing hopper (5) through a guide chute (6) positioned at an angle of 45° into the contact zone. Abrasive particles, getting between the surface of the roller and the sample, cause gradual abrasion of the material. After a specified number of roller revolutions has been completed, the test is stopped, and wear is assessed based on the loss of sample mass. The formula for abrasive wear (1):

$$K_w = \frac{g_R \rho_S N_S}{g_S \rho_R N_R} \quad (1)$$

Where: K_w is the coefficient of abrasive wear;

g_R, g_S – mass of the reference and test samples, respectively (g);

ρ_R, ρ_S – densities of the reference and test materials (g/cm³);

N_R, N_S – the number of roller revolutions (or friction cycles) for the test and reference samples, respectively.

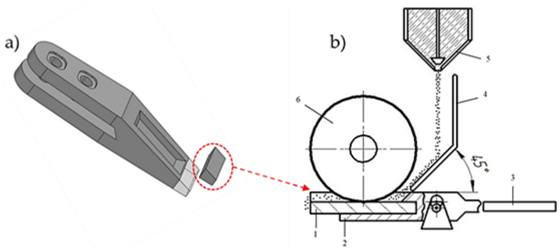


Figure 2 – 3D model of an excavator bucket tooth (a) and a setup diagram (b) for abrasive wear testing

Results and discussion

As shown in Figure 3, diffraction patterns of the original steel and samples after different types of electrolytic plasma treatment. In the initial state (initial), intense peaks of α-Fe (cubic body-centered lattice) are recorded, which confirms the ferrite structure of the material without any pronounced secondary phases.

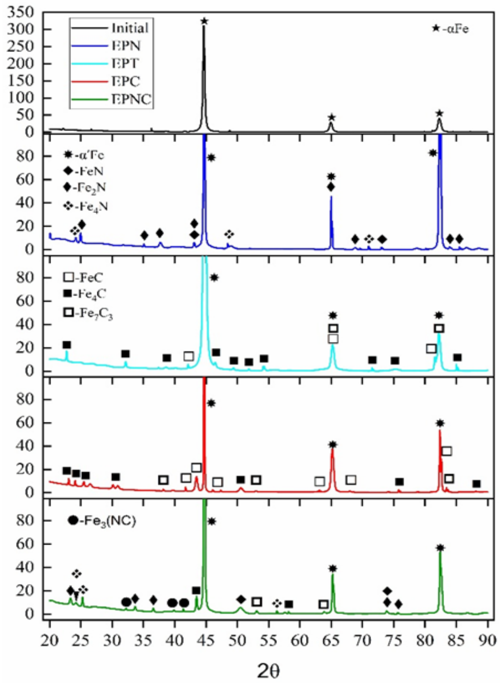


Figure 3 – X-ray diffraction patterns of the original steel and samples after different regimes of electrolytic-plasma treatment:
EPN – nitriding; EPT – hardening; EPC – carburizing; EPNC – nitrocarburizing

After electrolytic plasma nitriding, additional peaks corresponding to FeN, Fe_2N, and Fe_4N phases appear in the diffraction pattern at 2θ ≈ 37-43° and 55-75°, indicating effective nitrogen saturation and nitride layer formation.

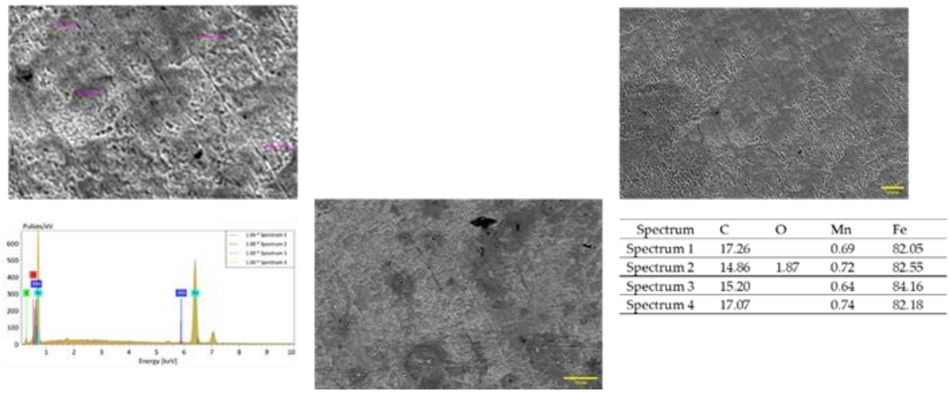
Carbon-enriched heat treatment results in the formation of iron carbides (FeC, Fe_4C, Fe_7C_3), while strong α-Fe reflections confirm their dispersed distribution within the ferrite matrix. Electrolytic plasma carburizing also produces these carbides, but with higher peak intensities due to enhanced carbon diffusion and a more saturated carbide layer.

After electrolytic plasma nitriding, a complex phase composition is observed, including nitrides (Fe_2N, Fe_4N), carbides (Fe_4C, Fe_7C_3), and $Fe_3(CN)$, confirming simultaneous nitrogen and carbon enrichment and the formation of a wear-resistant multicomponent structure. XRD analysis shows that each processing method forms a distinct phase set, with electrolytic plasma nitriding providing the highest structural diversity and performance.

In the initial state, 30CrMnSi steel exhibits a heterogeneous ferrite-pearlite microstructure with uniformly distributed carbides and minor surface defects, as confirmed by SEM and EDS analyses. This structure is typical of alloyed structural steels used for bucket teeth and serves as the basis for subsequent electrolytic plasma hardening (Fig. 4).

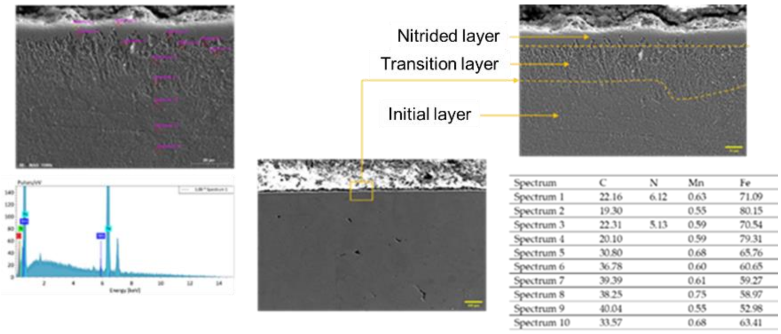
Figure 5 shows scanning electron micrographs of a cross-section of a 30CrMnSi steel sample after electrolytic plasma nitriding, along with energy-dispersive analysis results. The structure clearly reveals a modified surface layer approximately 15-20 μm thick, which has a lighter contrast than the substrate. The surface is characterized by the formation of a nitrided layer with a heterogeneous morphology.

Point EDS analysis (Table) shows a significant increase in carbon (19-40 at.%) and nitrogen (5-6 at.%) in the near-surface zone, while iron content decreases from 79.3 to 52.9 at.%, indicating effective surface saturation and diffusion layer formation. The maximum nitrogen content (6.12 at.%) recorded in the upper layer correlates with XRD results confirming FeN, Fe_2N, and Fe_4N phases. High carbon content (up to 40 at.%) suggests the formation of iron carbides and carbonitrides.



Spectrum	C	O	Mn	Fe
Spectrum 1	17.26		0.69	82.05
Spectrum 2	14.86	1.87	0.72	82.55
Spectrum 3	15.20		0.64	84.16
Spectrum 4	17.07		0.74	82.18

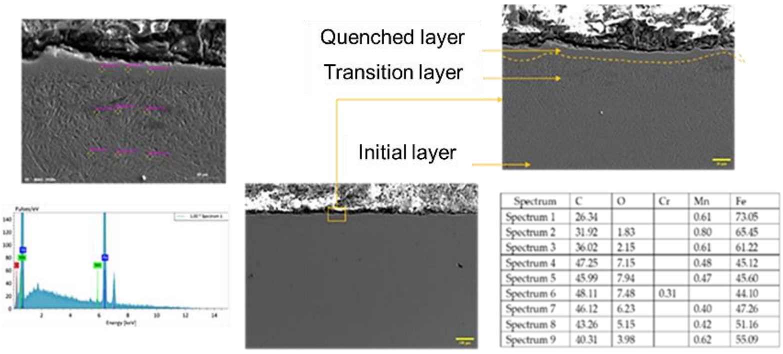
Figure 4 – Scanning electron micrographs and energy-dispersive analysis spectra of the surface of the original sample of a bucket tooth made of 30CrMnSi steel



Spectrum	C	N	Mn	Fe
Spectrum 1	22.16	6.12	0.63	71.09
Spectrum 2	19.30		0.55	80.15
Spectrum 3	22.31	5.13	0.59	70.54
Spectrum 4	20.10		0.59	79.31
Spectrum 5	30.80		0.68	65.76
Spectrum 6	36.78		0.60	60.65
Spectrum 7	39.39		0.61	59.27
Spectrum 8	38.25		0.75	58.97
Spectrum 9	40.04		0.55	52.98
Spectrum 10	33.57		0.68	63.41

Figure 5 – Microstructure of the cross-section of 30CrMnSi steel after electrolytic-plasma nitriding in a scanning electron microscope using energy-dispersive analysis

These results confirm that electrolytic plasma nitriding forms a diffusion layer enriched with carbon and nitrogen, promoting surface hardening through nitride and carbonitride formation. SEM cross-sections (Fig. 6) reveal a distinct modified layer 15-25 μm thick, featuring acicular and lamellar structures typical of martensitic transformation.



Spectrum	C	O	Cr	Mn	Fe
Spectrum 1	26.34			0.61	73.05
Spectrum 2	31.92	1.83		0.80	65.45
Spectrum 3	36.02	2.15		0.61	61.22
Spectrum 4	47.25	7.15		0.48	45.12
Spectrum 5	45.99	7.94		0.47	45.60
Spectrum 6	48.11	7.48	0.31		44.10
Spectrum 7	46.12	6.23		0.40	47.26
Spectrum 8	43.26	5.15		0.42	51.16
Spectrum 9	40.31	3.98		0.62	55.09

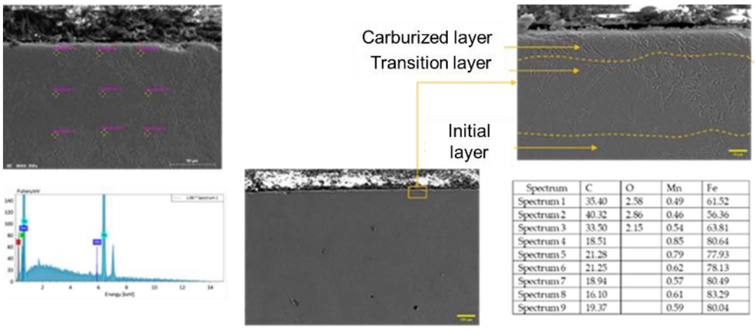
Figure 6 – Microstructure of the cross-section after electrolytic plasma hardening (EPH) in a scanning electron microscope using energy-dispersive analysis

Energy dispersive X-ray diffraction analysis revealed a significant increase in the carbon content in the upper layers, reaching 47-48 at.% (spectra 4-6), while in the substrate the carbon content decreased to 26-31 at.%. The oxygen concentration near the surface reached 7-8 at.%, which is possibly due to the formation of thin oxide films under the influence of intense thermal action in the electrolyte.

In contrast, the iron content in the surface layers decreases significantly from 73 at.% (spectrum 1) to 44 at.% (spectrum 6) due to the displacement of iron by carbon and oxygen during the formation of carbide and oxide compounds. Minor amounts of Cr (0.3-0.8 at.%) and Mn (0.3-0.8 at.%) are uniformly distributed and do not significantly affect phase formation.

Electrolytic plasma hardening produces a surface layer with a martensitic structure and high carbon content. The presence of oxygen indicates the formation of a thin oxide coating, which increases the hardness and wear resistance of the material.

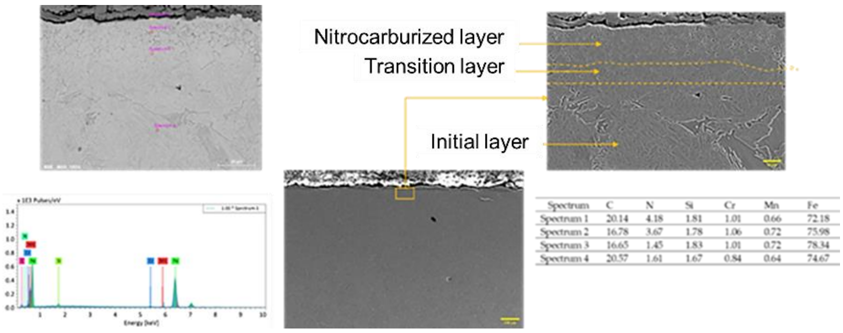
Figure 7 presents SEM images of a steel cross-section after electrolytic plasma carburizing. A modified surface layer 20-25 μm thick with a pronounced carbon-enriched zone is observed. At higher magnification, acicular and lamellar precipitates typical of carbide structures are clearly visible. EDS spectra confirm a significant increase in carbon content and a corresponding decrease in iron concentration, indicating the formation of iron carbides (FeC, Fe_4C, Fe_7C_3), in agreement with XRD results. Trace elements (Mn, Cr) are uniformly distributed and contribute to cementite stabilization. These results confirm the formation of a carbon rich diffusion layer, demonstrating the effectiveness of electrolytic plasma carburizing in improving hardness and wear resistance.



Spectrum	C	O	Mn	Fe
Spectrum 1	35.40	2.58	0.49	61.52
Spectrum 2	40.32	2.86	0.46	56.36
Spectrum 3	33.50	2.15	0.54	63.81
Spectrum 4	18.51		0.85	80.64
Spectrum 5	21.28		0.79	77.93
Spectrum 6	21.25		0.62	78.13
Spectrum 7	18.94		0.57	80.49
Spectrum 8	16.10		0.61	83.29
Spectrum 9	19.37		0.59	80.04

Figure 7 – Microstructure of the cross-section after electrolytic plasma carburizing in a scanning electron microscope using energy dispersive analysis

Figure 8 shows SEM cross-sections after electrolytic plasma nitriding, revealing a pronounced diffusion layer with an acicular-lamellar structure. Enlarged images display elongated precipitates characteristic of a hardened carbonitride layer formed by combined carbon and nitrogen saturation.



Spectrum	C	N	Si	Cr	Mn	Fe
Spectrum 1	20.14	4.18	1.81	1.01	0.66	72.18
Spectrum 2	16.78	3.67	1.78	1.06	0.72	75.98
Spectrum 3	16.65	1.45	1.83	1.01	0.72	78.34
Spectrum 4	20.57	1.61	1.67	0.84	0.64	74.67

Figure 8 – Microstructure of the cross-section after electrolytic plasma nitrocarburizing (EPNC) in a scanning electron microscope using energy-dispersive analysis

Energy-dispersive X-ray spectra demonstrate elevated carbon and nitrogen contents in the surface region compared to the substrate, accompanied by a decrease in iron concentration. The presence of carbon and nitrogen elements indicates the probable formation of iron carbonitride compounds ($Fe_3(CN)$, $Fe_{2-4}N$, Fe_4C), which is consistent with the X-ray diffraction analysis results.

The analysis revealed that electrolytic plasma nitriding promotes the formation of a multicomponent hardened layer enriched with nitrogen and carbon. The formation of carbonitride compounds, combined with the characteristic surface morphology, provides an optimal combination of increased hardness and wear resistance.

A comparison of microstructural studies, phase composition, element distribution, and microhardness shows that each type of electrolytic plasma treatment forms a specific hardened layer. During nitriding, nitride phases are formed, leading to an increase in hardness to 699 ± 57 HV. During the quenching process, the maximum hardness is recorded (810 ± 83 HV) due to the formation of a martensitic structure and a high carbon concentration. In the case of carburizing, the hardness is 586 ± 47 HV, which is associated with the formation of carbide phases, but their influence is weaker. Nitrocarburizing provides a combined effect due to the formation of carbonitrides, providing a hardness of 545 ± 52 HV and a more balanced combination of wear resistance. The microhardness of the base steel was 178 ± 14 (Fig. 9).

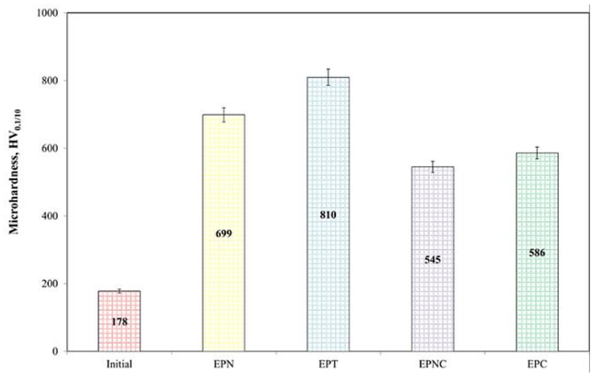


Figure 9 – Distribution of microhardness (HV) by surface depth of 30CrMnSi steel after different regimes of electrolytic-plasma treatment

As shown in Figure 10, tribological tests revealed that the electrolytic plasma treatment method has a significant impact on the frictional behavior of the steel. The initial sample demonstrated a high and unstable friction coefficient (0.55-0.60), indicating reduced wear resistance. Subsequent nitriding and carburizing processes reduced the friction coefficient to 0.45-0.50 and 0.45-0.48, respectively, resulting in more stable curves due to the formation of nitride and carbide phases. Despite achieving maximum hardness (812 HV), hardening was accompanied by the highest friction coefficient (0.55-0.60) and instability due to the formation of brittle martensite. Nitriding demonstrated optimal performance with a friction coefficient of only 0.25-0.35, maintaining stability. Throughout the experiment, the formation of a multicomponent carbonitride layer was observed, which provided an optimal balance of hardness and wear resistance.

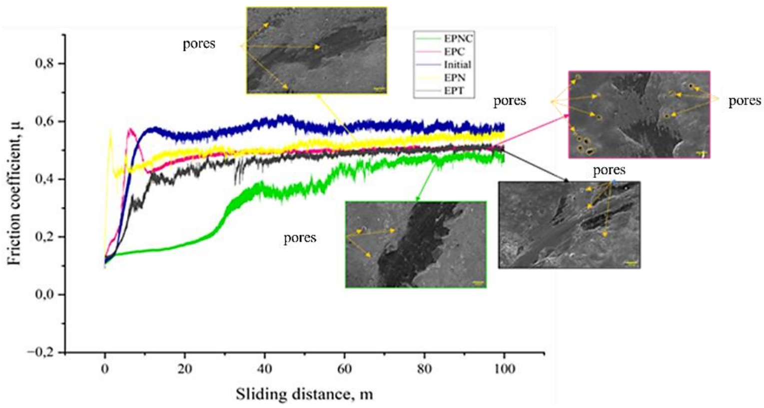


Figure 10 – Results of tribological tests of 30CrMnSi steel before and after and wear track morphology on scanning electron microscope:
change in friction coefficient depending on the processing mode

Abrasive wear tests were performed to determine the relative wear resistance of the initial sample (Table 3). The initial sample demonstrated a relative wear resistance of 0.2349, accompanied by a weight loss of 0.2046 g. The highest weight loss was observed after quenching (0.2539 g, K_W = 0.1893), which is explained by the brittleness of martensite. Nitriding gave K_W = 0.2102 with a weight loss of 0.2286 g, nitriding gave K_W = 0.2018 with 0.2382 g, and nitrocarburizing gave the best result with a weight loss of only 0.2021 g and a relative wear resistance of 0.2378, which exceeds the initial condition and is associated with the formation of. The presence of hard carbide phases is indicated.

Table 3 – Results of abrasive wear

Electrolytic plasma Processing regimes	Abrasive wear	
	Weight loss (g)	Relative wear resistance (K_w)
Standard steel 45	0.048	1
Initial	0.2046	0.234904
quenching	0.2539	0.18929287
nitriding	0.2286	0.21024261
carburizing	0,2021	0.23781029
nitrocarburizing	0.2382	0.20176935

Thus, the research results demonstrate that different processing regimes have a significant impact on the properties and structure of steels. The results of the studies and their analysis are summarized in Table 4.

Table 4 – Correlation table of results before and after electrolytic plasma treatment

Electrolytic plasma processing regimes	Phase composition	Microhardness, HV	Wear resistance assessment	
			μ	Abrasive wear
initial	α-Fe	178	0.55-0.60	0.2349
quenching	Fe_3C, FeO	810	0.55-0.60	0.1893
nitriding	FeN, Fe_2N, Fe_4N	699	0.45-0.50	0.2102
carburizing	FeC, Fe_4C, Fe_7C_3	586	0.45-0.48	0.2378
nitrocarburizing	$Fe_3(CN)$, $Fe_{2-4}N$, Fe_4C	545	0.25-0.35	0.2018

Conclusion

Comprehensive structural, phase, and tribological studies revealed that electrolytic plasma treatment of 30CrMnSi steel results in the formation of hardened diffusion layers. These layers were shown to significantly alter the physical and mechanical properties of the surface. A comparative analysis revealed that electrolytic plasma nitrocarburizing results in the formation of the most complex multicomponent layer, consisting of iron compounds and carbonitride ($Fe_3(CN)$, $Fe_{2-4}N$, Fe_4C), characterized by increased hardness and chemical stability. The presence of these phases ensures an optimal balance of surface hardness and sublayer ductility, preventing the formation of microcracks and fatigue failure under cyclic loading.

Clearly, the nitrocarburizing process reduces the friction coefficient and increases abrasion resistance. This is due to the uniform distribution of diffusion elements and the formation of a dense, fine-grained structure. Unlike traditional carburizing, which predominantly forms carbides, nitrocarburizing promotes the simultaneous saturation of the surface with carbon and nitrogen. This process creates favorable conditions for the formation of hard carbonitride phases and stabilization of the surface layer.

Therefore, electrolytic plasma nitrocarburizing is the most optimal method for treating loader bucket teeth, providing increased hardness, reduced friction, and improved wear resistance. This method has been proven to significantly increase the service life and operational reliability of earthmoving equipment components subject to intense abrasive wear.

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ЭЛЕКТРОЛИТТІК-ПЛАЗМАЛЫҚ ӨҢДЕУ ПАРАМЕТРЛЕРІНІҢ ЖЕР ҚАЗАТЫН ШӨМІШТІҢ ТҮЗУ ТІСІНІҢ БЕТКІ ҚҰРЫЛЫМЫ МЕН МЕХАНИКАЛЫҚ ҚАСИЕТТЕРІНЕ ӘСЕРІН ЗЕРТТЕУ

Бұл зерттеу қатты абразивті жағдайларда жұмыс істейтін тиегіштерде қолданылатын 30CrMnSi маркалы шөміш тістерінің тозуға төзімділігін арттырудағы электролиттік-плазмалық өңдеудің тиімділігін қарастырады. Үлгілер әртүрлі өңдеу әдістеріне ұшыратылды, соның ішінде электролиттік-плазмалық шынықтыру, азоттау, цементациялау, азот-көміртекпен қанықтыру және шынықтыру процестері жүргізілді. Үлгілердің құрылымын, фазалық құрамын және механикалық қасиеттерін жан-жақты сипаттау үшін бірнеше талдау әдістері қолданылды: сканерлеуші электрондық микроскопия, энергия-дисперсиялық спектроскопия, рентгенқұрылымдық талдау және микротвердостық өлшеулер. Материалдардың трибологиялық қасиеттері TRB3 трибометрі көмегімен бағаланды, ал абразивтік тозу сынақтары ГОСТ 23.208-79 стандартына сәйкес жүргізілді. Нәтижелер электролиттік-плазмалық өңдеу кезінде қалыңдығы 15-25 мкм болатын *диффузиялық қабаттардың түзілетінін көрсетті. Бұл процесс карбид, нитрид және карбонитрид фазаларының (Fe_4C, Fe_7C_3, Fe_4N, Fe_2N және $Fe_3(CN)$) түзілуімен қатар жүреді. Аталған өңдеу беткі қаттылықты айтарлықтай арттырып (810 HV-қа дейін) және тозуға төзімділікті жақсартады. Зерттеу нәтижелері электролиттік-плазмалық азоттаудың қаттылық пен тұтқырлықтың оңтайлы тепе-теңдігін қамтамасыз ететінін, соның нәтижесінде үйкеліс коэффициенті төмендеп, абразивтік тозуға төзімділіктің артатынын көрсетті. Бұл технологияны дамыту жер қазу және тау-кен жабдықтары бөлшектерінің қызмет ету мерзімін ұзартуға, техникалық қызмет көрсету шығындары мен жабдықтың тоқтап қалу уақытын азайтуға мүмкіндік береді.*

Түйін сөздер: *шөміш тістері; химиялық-термиялық өңдеу; электрразрядты беттік химиялық-термиялық өңдеу; абразивтік тозу;микроқаттылық.*

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ИССЛЕДОВАНИЕ ВЛИЯНИЯ ПАРАМЕТРОВ ЭЛЕКТРОЛИТНО-ПЛАЗМЕННОЙ ОБРАБОТКИ НА СТРУКТУРУ ПОВЕРХНОСТИ И МЕХАНИЧЕСКИЕ СВОЙСТВА ПРЯМОГО ЗУБА ЗЕМЛЕРОЙНОГО КОВША

В данном исследовании рассматривается эффективность электролитно-плазменной обработки в повышении износостойкости зубьев ковша марки 30CrMnSi, используемых в погрузчиках, работающих в условиях сильного абразива. Образцы подвергались различным методам обработки, включая электролитически-плазменную закалку, азотирование, цементацию, азотно-углеродное насыщение и процессы закалки. Для всестороннего описания структуры, фазового состава и механических свойств образцов было использовано несколько методов анализа: сканирующая электронная микроскопия, спектроскопия энергодисперсии, рентгеноструктурный анализ и микротвердостные измерения. Трибологические свойства материалов оценивали с помощью трибометра TRB3, а испытания на абразивный износ проводились в соответствии со стандартом ГОСТ 23.208-79. Результаты показали, что при электролитически-плазменной обработке образуются диффузионные слои толщиной 15-25 мкм. Этот процесс сопровождается образованием карбидной, нитридной и карбонитридной фаз (Fe_4C, Fe_7C_3, Fe_4N, Fe_2N и $Fe_3(CN)$). Указанная обработка значительно увеличивает твердость поверхности (до 810 HV) и улучшает износостойкость. Результаты исследования показали, что электролитически-плазменное азотирование обеспечивает оптимальный баланс твердости и вязкости, в результате чего снижается коэффициент трения и повышается износостойкость абразива. Разработка этой технологии позволит продлить срок службы деталей землеройного и горнодобывающего оборудования, снизить затраты на техническое обслуживание и время простоя оборудования.

Ключевые слова: *ковшовые зубья; химико-термическая обработка; электроразрядная поверхностная химико-термическая обработка; абразивный износ; микротвердость.*

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ВЛИЯНИЕ ТОНКОГО HVOF-ПОКРЫТИЯ CR_3C_2-NICR НА ТЕРМИЧЕСКОЕ СОПРОТИВЛЕНИЕ И ТЕМПЕРАТУРНОЕ СОСТОЯНИЕ ТРУБ ПАРОПЕРЕГРЕВАТЕЛЯ КОТЛА БКЗ-320-140

Аннотация: *В работе проведён анализ влияния газотермических покрытий на основе Cr_3C_2-NiCr, полученных методом высокоскоростного газопламенного напыления (HVOF), на теплофизические характеристики труб ширмовых пароперегревателей котлоагрегата БКЗ-320-140. Рассмотрено влияние защитного покрытия на процессы теплопередачи, включая конвективный и радиационный теплообмен, а также на температурное состояние металла в условиях высокотемпературного воздействия дымовых газов. Расчёт температурного поля выполнен методом конечных элементов в программном комплексе ELCUT 6.6 с учётом нестационарного режима теплопередачи. В ходе моделирования учтены реальные эксплуатационные параметры, включая давление и температуру пара, скорость потоков и теплофизические свойства материалов. Установлено, что наличие покрытия приводит к незначительному увеличению суммарного термического сопротивления системы «стенка трубы – покрытие». При этом влияние покрытия на температурный режим труб и плотность теплового потока остаётся минимальным. Показано, что применение покрытий Cr_3C_2-NiCr позволяет повысить коррозионно-эрозионную стойкость поверхностей нагрева без существенного снижения теплотехнической эффективности котлоагрегата в реальных условиях эксплуатации. Полученные результаты могут быть использованы при проектировании, модернизации и оптимизации энергетического оборудования тепловых электростанций в промышленной энергетике Казахстана.*

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