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STUDY OF THE STRUCTURAL-PHASE STATE AND MECHANICAL-TRIBOLOGICAL PROPERTIES OF STRUCTURAL STEELS AFTER PLASMA ELECTROLYTIC CARBURIZING

Abstract: *The paper presents a study of the influence of plasma electrolytic carburizing (PEC) regimes on the structural, phase, microhardness, and tribological characteristics of structural steels. Plasma electrolytic carburizing was carried out in an aqueous solution containing 10% soda ash (Na_2CO_3) and 20% urea ($CO(NH_2)_2$), at a temperature of about 950°C and a voltage of 300V. Two cooling regimes were implemented after PEC for steel 20: natural cooling in the electrolyte and active nozzle cooling with electrolyte supply to the treatment zone, and for 30CrMnSiA steel only natural cooling in the electrolyte. The morphology of the structure and phase composition were studied using X-ray diffraction analysis, scanning electron microscopy with energy-dispersive X-ray spectroscopy, and optical microscopy. The results showed that the microstructure of steels after PEC morphologically has a zonal structure with a main martensitic phase with Fe_3C and Fe_7C_3 carbide inclusions. The microhardness profile was determined from the cross-section of the modified layer using a FISCHERSCOPE HM2000 device. Tribological tests were performed using the ball on disc method on a TRB³ machine under dry friction conditions at a normal load of 10 N and a sliding speed of 0.05 m/s. It was found that active cooling promotes the formation of a harder martensitic structure with maximum microhardness values of up to 430 HV for steel 20 and up to 720 HV for 30CrMnSiA steel, while their initial microhardness values were 170 HV and ~250 HV, respectively. It was also found that the coefficient of friction for these steels decreases by an average of 25–30% compared to the initial samples. The results confirm the effectiveness of PEC in forming hardened layers with increased microhardness and improved tribological parameters and demonstrate the potential of the method for use in the production of parts operating under high mechanical and frictional loads.*

Key words: *plasma electrolytic carburizing, chemical-thermal treatment, X-ray structural analysis, zonal structure, structural steel, carbides, microhardness, friction coefficient.*

Introduction

In the context of modern technological developments and increasing demands on the operational characteristics of machines and mechanisms, particular attention is paid to improving the properties of parts made from structural steels [1-2]. This is especially relevant for carbon and low-carbon steels, which are widely used in mechanical engineering due to their good mechanical properties, machinability, and availability. However, in their initial state, such steels do not always have sufficient hardness and wear resistance, which limits their service life when operating under conditions of intense friction and loads. Along with well-known technologies, one of the promising areas for improving the functional properties of steels is electrolytic plasma treatment (EPT), which is based on the action of a plasma-electrolyte environment on the metal surface. This technology is effective for various structural and non-ferrous materials, including carbon structural and stainless steels [3-5]. One of the key objectives of EPT is to saturate the surface layer of the product with light elements, such as carbon, nitrogen, boron, etc., depending on the regime and composition of the electrolyte. As a result of such treatment, the desired properties of the material are achieved: increased strength during carburizing, increased hardness and corrosion resistance during boriding, and improved wear resistance during nitriding [6-9].

This work focuses on plasma electrolytic carburizing as an effective method for hardening carbon and low-carbon structural steels. Plasma electrolytic carburizing has a number of technological advantages, including increased surface modification speed and relatively low process implementation costs [10]. This method was chosen because of its ability to significantly increase the wear resistance and durability of parts by saturating the surface layer with carbon at elevated temperatures (around 950 °C), followed by thermal hardening. This approach allows the formation of a hard and wear-resistant outer zone while maintaining a ductile and strong core, which is especially important for structural elements operating under cyclic loads and friction [11-13].

In traditional carburizing practices, medium-carbon steels were typically used as the base material. This is because they contain more carbon than low-carbon grades, which promotes more efficient carbon saturation of the surface layer and the formation of a strong, wear-resistant zone [14]. The high carbon content allows for significant hardness to be achieved after heat treatment, which is why such steels were considered the most suitable for this type of hardening.

Over the past decade, a significant amount of research has been conducted aimed at improving carburizing processes, including the use of electrolytic plasma technology. Thus, in [15], the influence of the electrolyte composition and temperature parameters of anodic plasma electrolytic carburizing on the formation of the structure, microhardness, phase composition, and corrosion resistance of the surface layer of steel 20 was studied. The results showed that the use of sucrose in the electrolyte composition provides deeper carbon saturation and the formation of a diffusion layer up to 56 μm thick, while glycerol electrolyte promotes more intensive anodic dissolution. The data obtained confirm the high sensitivity of the results of plasma electrolytic carburizing (PEC) to the composition of the electrolyte and the temperature parameters of the treatment. Nevertheless, questions remain open regarding the optimization of treatment regimes and the clarification of the mechanisms of formation of the phase components of the modified layer. Of particular interest is the study of the influence of various electrolyte compositions on the thermochemical processes occurring in the near-surface zone of steel during high-temperature PEC. Work [16] examines the features of the formation of the structure, phase composition, microhardness, and wear resistance of 20Kh steel during anodic plasma electrolytic carburizing in electrolytes of various compositions containing ammonium chloride in combination with sucrose or glycerin.

This work examines the influence of electrolyte composition and cooling regimes of electrolytic plasma carburizing on the peculiarities of the formation of the structure, microhardness, and tribological characteristics of steel 20 and 30CrMnSiA steel. The aim of the work is to study the structural-phase state and tribological properties of structural steels after plasma electrolytic carburizing under different cooling regimes.

Materials and methods of research

In this work, we consider the possibility of applying these technologies to less traditional materials – low-carbon steel 20 and alloy 30CrMnSiA steel. Their chemical composition: steel 20 (C – 0.2%, Si – 0.17-0.35%, Mn – 0.35-0.6%, Cr, Cu, Ni – up to 0.3%, P – up to 0.035%, S – up to 0.04%, Fe – 98%) according to GOST 1050-88; 30CrMnSiA (C – 0.28-0.34%, Si – 0.90-1.20%, Cu – 0.30%, Mn – 0.80-1.10%, Ni – 0.30%, P – 0.025%, Cr – 0.80-1.10%, S – 0.025%) according to GOST 4543-2016.

Samples measuring 20x20x20 mm were processed with sandpaper with a grain size of P120 on a Metapol-2000P surface grinding machine. PEC was carried out on an electrolytic plasma treatment unit at the Surface Engineering and Tribology Research Center of the Sarsen Amanzholov East Kazakhstan University (Fig. 1a-d). The technological parameters of the PEC with different cooling regimes are given in Table 1.

According to the schematic representation in Fig. 1b, the electrolyte-plasma unit intended for carrying out chemical-thermal treatment of metal samples includes a DC power source (1), a sealed working chamber (2), a bath with an electrolytic cell (5) with a plasmatron (3), a pump and circulation system (4), as well as a holder for fixing the workpiece (6), a connected pipeline for feeding the electrolyte (7). The power source serves to form the rectified voltage required for generating microplasma discharges in the electrolyte. The working bath is equipped with a built-in anode grid made of stainless steel, and the workpiece itself is connected as a cathode. When voltage is applied, local boiling of the electrolyte occurs and a vapor-gas shell is formed, within which intense microplasma discharges develop, providing chemical-thermal and micromechanical action on the surface of the sample. To maintain stable processing parameters, a pump-controlled electrolyte circulation and cooling system is provided, as well as pipelines regulating the supply and consumption of the working solution. In total, such a configuration of the installation ensures targeted modification of the surface layer of the metal due to the effect of high-energy discharges in the active processing zone.

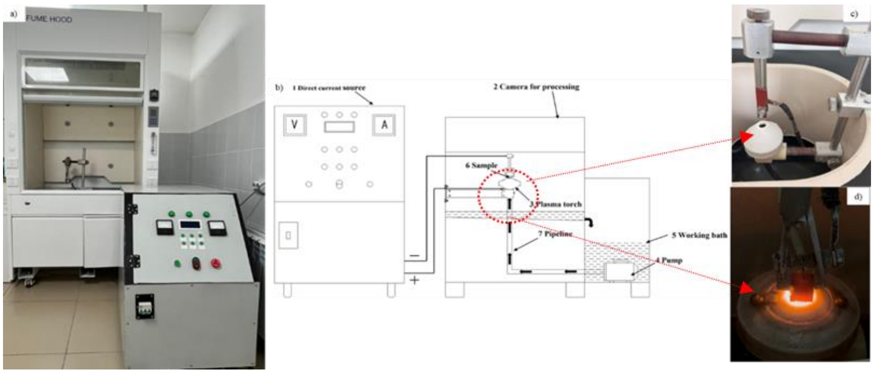

Figure 1 – Electrolytic-plasma treatment unit and diagram

a) General view of the electrolytic-plasma treatment unit; b) Electrical and hydraulic diagram of the unit; c) Working area with plasma torch and electrolyte; d) Plasma formation process during sample surface treatment

Table 1 – Technological parameters of the PEC with different cooling regimes

Samples	Processing regime	Electrolyte composition	Temperature, °C	Voltage, V	Time, minutes
steel 20 (1)	PEC + natural cooling in electrolyte	10% soda ash (Na_2CO_3) and 20% urea ($CO(NH_2)_2$)	950	300	5
steel 20 (2)	PEC + active nozzle cooling with electrolyte supply				
30 CrMnSiA steel	PEC + natural cooling in electrolyte				

During the study, steel 20 was subjected to carburization by electrolytic-plasma treatment at a temperature of about 950°C. The treatment was carried out in an aqueous solution containing 10% soda ash (Na_2CO_3) and 20% urea ($CO(NH_2)_2$). The process was carried out at a voltage of 300 V and an electrolyte temperature reaching 950°C. The treatment time was 5 minutes. Carbon structural steel 20 and 30CrMnSiA steel were used as study materials. Steel 20 was treated in two regimes: without cooling and with active cooling. In the first case, after heating, the part remained in the electrolyte and cooled naturally. This ensured a slow decrease in temperature, as a result of which a structure with a partial hardening effect and increased ductility was formed in the surface layer. In the second case, nozzle cooling or forced electrolyte feed to the processing zone was used, which ensured rapid cooling of the surface and contributed to the formation of a harder structure such as martensite. Thus, combining carburization with EPT in cooling regimes made it possible to obtain a hardened surface layer with different degrees of hardness and structural characteristics. In all experiments, steel 20 and 30KhGSA steel samples were processed in the same regimes, which ensured a correct comparison of the results.

X-ray diffraction analysis of the phase composition of the modified surface layers formed as a result of plasma electrolytic carburizing was carried out on an X'Pert PRO PANalytical setup (PANalytical BV, the Netherlands) equipped with a copper anode tube (Cu-Kα radiation, λ = 1.541 Å). The measurements were carried out at a voltage of 40 kV and a current of 30 mA in the 2θ angle range from 30° to 100°, with a step of 0.02° and an exposure time of 0.5 s per step. The diffraction patterns were processed and the obtained data were interpreted in the HighScore Plus software environment. Monitoring of microstructural changes caused by thermochemical treatment was carried out using an SEM3200 scanning electron microscope (China). Before visualization, the surface structure of the samples was activated by chemical etching in a 4% solution of nitric acid (HNO_3) in ethanol. Flat sections were prepared on a Metapol-2000P machine using diamond pastes of different dispersion. The morphological features of the formed layers were studied using an Olympus BX53M optical microscope. Microhardness control over the cross-section of the cemented layer was carried out on a FISCHERSCOPE HM2000 installation (Helmut Fischer GmbH, Germany), certified in accordance with the DIN EN ISO 14577-1 standard. The tests were carried out under loads of up to 2000 mN in automatic regime with step profiling by depth. Evaluation of the tribological characteristics was carried out by the ball on disk method on a TRB^3 universal installation (Anton Paar, Austria) in accordance with the ASTM G133 standard. The samples were tested under dry friction conditions at an ambient temperature of (25±1°C) and a sliding speed of 0.05 m/s. Contact was made with a 100Cr6 steel ball under a normal load of 10 N. The friction coefficient was measured continuously during the test over a period of 60 m, with automatic recording of the parameters over time.

Results and discussion

As a result of electrolytic plasma treatment of steel 20 and 30CrMnSiA steel, various microstructures were obtained, depending on the cooling regimes. The steel 20 sample, which underwent slow cooling, was characterized

by the formation of a ferrite-pearlite structure with cementite inclusions, which indicates a partial hardening effect. When using directed nozzle cooling, the formation of a martensitic structure was observed, and for 30CrMnSiA steel, the formation of a predominantly martensitic structure was observed, which is explained by the higher content of alloying elements.

The microstructure shown in Figure 2 indicates a significant influence of cooling conditions on the results of electrolytic plasma treatment of steel 20. The SEM image in Figure 2a shows the structure of steel 20 with subsequent cooling, while Figure 2b shows the structure of the sample without cooling. In the case of steel 20(1) with cooling (Fig. 2a), a pronounced modified surface layer with a fine-grained and dense structure is observed. The contrast of the image indicates the presence of a fragmented substructure characteristic of hardening zones with a high cooling rate. Such morphological features may be associated with the formation of carbon compounds (carbides) and zones with increased hardness. A gradient structure is observed: from the saturated zone to the transition zone and further to the initial ferrite-pearlite zone. In the steel 20(2) sample without cooling, Fig. 2b, the structure is more sparse.

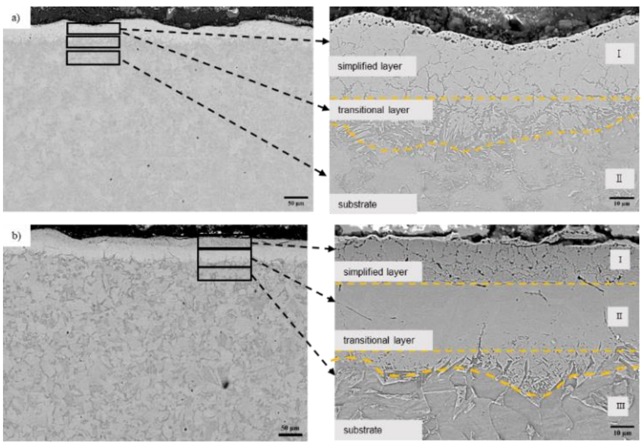

Figure 2 – Microstructure of steel 20 after PEC

The modified zone is less pronounced, the morphology is larger, and the dispersion is lower. This indicates partial decomposition of the solid solution and phase stabilization under slow cooling conditions, during which reverse diffusion processes occur. The boundary between the treated and untreated layers is less contrasting, which also indicates weaker thermal fixation of structural changes.

According to Figure 3, the microstructure of 30 CrMnSiA steel after electrolytic plasma treatment is characterized by good density and a pronounced fine-grained structure. Ordered substructural elements are observed, indicating the formation of carbides due to alloying elements (Cr, Mn, Si). This indicates the increased thermochemical activity of 30CrMnSiA steel and its high hardenability compared to carbon steel 20.

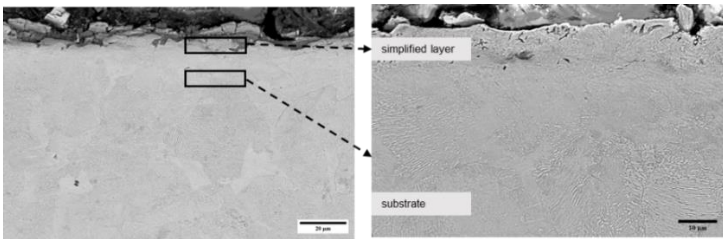

Figure 3 – Microstructure of 30CrMnSiA steel after PEC

Figure 4 shows the diffraction patterns of steel 20 and 30CrMnSiA steel in the initial state and after plasma electrolytic carburizing. In the initial state, only α-Fe peaks corresponding to the main ferrite-pearlite phase are recorded. After PEC, additional peaks identified as Fe_3C and Fe_7C_3 appear in steel 20 samples (both with and without cooling), indicating intense carbon saturation and the formation of carbide phases, as well as an iron oxide peak indicating surface oxidation as a result of decomposition of the active components of the electrolyte. In 30CrMnSiA steel, predominantly Fe_7C_3 and Fe_3C peaks are observed, which is explained by the influence of alloying elements (Cr, Mn), which contribute to the stabilization of carbides. This confirms that even under identical PEC conditions, the chemical composition of the steels has a decisive influence on the phase composition.

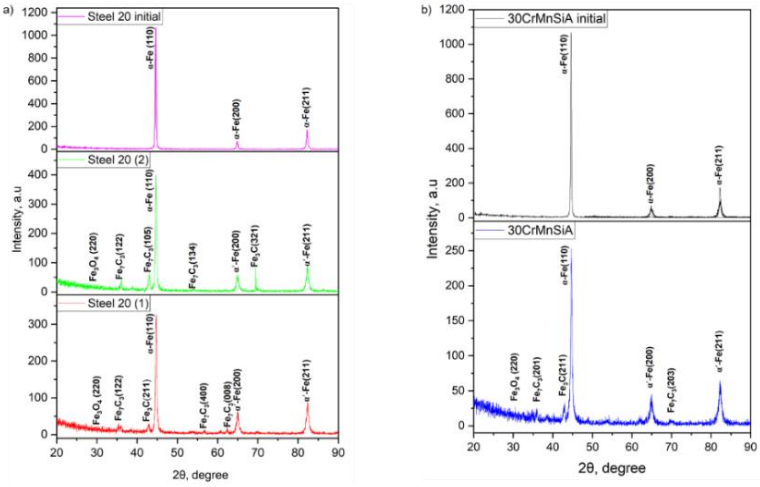

Figure 4 – X-ray diffraction (XRD) spectra of the surface layers of steels before and after plasma electrolytic carburizing (PEC)
a) steel 20: before PEC, after PEC with cooling and without cooling;
b) 30CrMnSiA steel: before and after PEC

Figure 5 shows the spectra and distribution of elements over the cross-section of steel 20 after plasma electrolytic carburizing (PEC). The treatment was carried out in a solution of 10% Na_2CO_3 + 20% $CO(NH_2)_2$ at 300 V, 950°C, 5 minutes. In the sample with cooling in Fig. 5a, an increased oxygen content is observed in the near-surface zone (spectrum 1), which indicates the formation of an oxide film. The inner zones (spectra 2 and 3) are characterized by an increase in carbon concentration, reaching maxima in these areas, and then a decrease towards the substrate (spectrum 4). Iron (Fe) remains the predominant element in the substrate material. Compared to the steel 20 (1) sample, the steel 20 (2) sample without cooling demonstrates a less contrasting distribution of carbon and oxygen, which may be due to a more stable diffusion during slow cooling. The surface is also covered with an oxide layer, but its thickness may be lower, which explains the decrease in oxygen concentration. In general, the sample with cooling forms a more pronounced carbonized zone, while the sample without cooling shows a tendency towards greater oxygen saturation with a smaller amount of carbon.

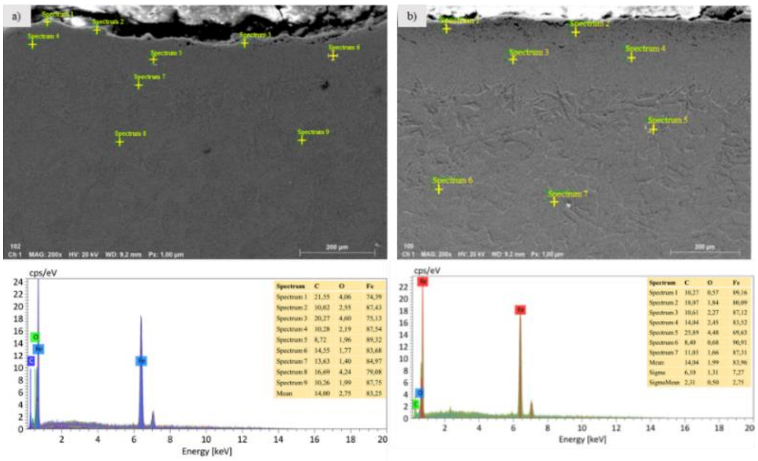

Figure 5 – Energy-dispersive X-ray spectroscopy (EDX) of steel 20 after PEC

Figure 6 shows the spectral analysis of a sample of 30CrMnSiA steel processed using the same PEC regime. The analysis shows a high carbon content in the near-surface zone, which indicates active saturation and formation of a hardened layer. Unlike carbon steel 20, 30CrMnSiA steel demonstrates better carbon saturation indicators in individual spectra, which is due to the presence of alloying elements that stabilize carbide phases (possibly Cr). The surface layer also contains an increased amount of oxygen, forming a strong oxide shell.

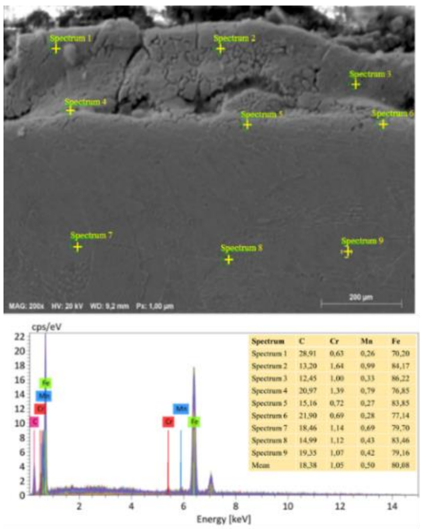

Figure 6 – Energy-dispersive X-ray spectroscopy (EDX) of 30CrMnSiA steel after PEC

The microhardness distribution shown in Figure 7 indicates differences in the nature of the hardened layers for steel 20 and 30CrMnSiA steel after plasma electrolytic carburizing. Steel 20 was processed under the same parameters, but with different cooling conditions. Comparison of microhardness shows that steel 20 (1) achieves higher hardness values in the near-surface zone (up to ~430 HV) compared to steel 20 (2) (maximum ~250-270 HV). In addition, the former has a sharp increase in hardness from the surface and stabilization at a depth of 60–180 μm, while the latter has more uniformly distributed values, but at a lower level. The differences can be explained by the cooling intensity, which determines the structural transformations after the PEC. Intensive cooling helps to fix the hardened structure by suppressing diffusion processes, which prevents the decomposition of the supersaturated solid solution and limits the growth of ferrite-pearlite areas. This, in turn, ensures the formation of a structure with increased hardness. On the contrary, with slow cooling, partial restoration of the original structure is possible due to the occurrence of diffusion transformations, which is accompanied by a decrease in the hardness of the material. For comparison, data on 30CrMnSiA steel processed by a similar method are also provided. This steel demonstrated the highest hardness in the near-surface zone (up to 720 HV) with a stable hardening profile to a depth of up to 100 μm, which is due to its alloy composition and a greater tendency to hardening phase formations during PEC.

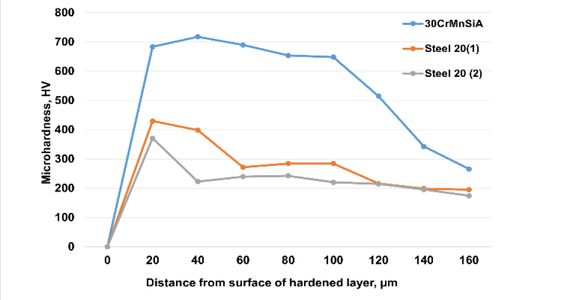

Figure 7 – Distribution of microhardness by depth from the surface modified after PEC

To assess the tribological properties of the surface layers of steel 20 and 30CrMnSiA steel (Fig. 8a-b), modified by cathodic plasma electrolytic carburizing (PEC), tests were carried out under dry friction conditions using the «ball on disk» scheme. The test results are presented as dependences of the friction coefficient on the path, where for steel 20 in Figure 8a, for 30CrMnSiA steel in Figure 8b, the friction coefficient after PEC decreased by 25-30% compared to the initial state, which indicates a significant improvement in the tribological characteristics of the treated surface. High hardness is traditionally considered as the main criterion for the wear resistance of steels. However, the structure of the surface layer, providing maximum wear resistance, does not always coincide with the structure with the highest hardness. Since wear resistance is one of the structure-sensitive characteristics, its improvement requires a comprehensive approach to managing the structure of the surface layer.

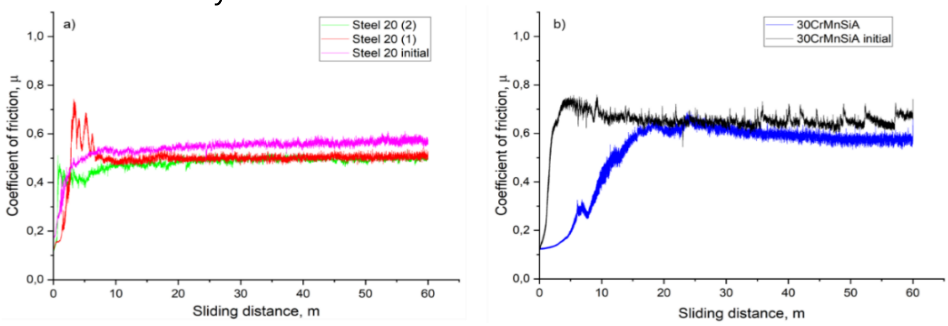

Figure 8 – Friction coefficient of steel 20 and 30CrMnSiA steel before and after PEC

During friction in the surface deformation zone, structural transformations and changes in the material properties occur, resulting in the formation of the so-called friction structure, which directly affects the nature and intensity of wear. In this regard, striving exclusively for maximum hardness is not always advisable when developing wear-resistant steels (Table 2).

Table 2 – Results of the study of steels before and after PEC with different cooling regimes

Samples	Electrolyte composition	Phase	Microhardness	Friction coefficient
steel 20 (initial)	10% (Na_2CO_3) and 20% ($CO(NH_2)_2$) Regime: 950°C, 300V, 5 min	Ferrite-pearlite	170–190 HV	—
steel 20 (1)		Martensite + carbides Fe_3C, Fe_7C_3	430–190 HV	Down 25%
steel 20 (2)		Ferrite-pearlite + carbides	370–170 HV	Down 25%
30CrMnSiA steel (initial)		Ferrite-pearlite	250–270 HV	—
30CrMnSiA steel		Martensite + Fe_3C, Fe_7C_3	720–260 HV	Down 25%

Conclusion

A comparative study was conducted on the influence of plasma electrolytic carburizing (PEC) parameters on the surface characteristics of structural steel 20 and 30CrMnSiA steel. It was found that PEC promotes the formation of a hardened layer with increased hardness (up to 430 HV for steel 20 and up to 720 HV for 30CrMnSiA steel), which is due to the formation of a martensitic structure and carbide phases.

X-ray phase analysis showed that in their initial state, both steels contain mainly the ferrite-pearlite phase α-Fe. After PEC, the formation of carbide compounds (Fe_3C, Fe_7C_3) is observed, with the chemical composition of the steel having a significant effect on their quantitative and qualitative ratio.

It has been established that the cooling regime plays a key role in the formation of the structure and properties of the hardened layer. Rapid nozzle cooling contributes to the fixation of the martensitic structure, while natural cooling forms a more plastic ferrite-pearlite zone with lower hardness.

Analysis of the morphology and elemental composition showed the presence of carbide and oxide phases, as well as the distribution of carbon and oxygen in the surface layer. In 30CrMnSiA steel, more effective carbon saturation was observed, which is associated with the presence of alloying elements.

Tribological tests showed a 25-30% reduction in the friction coefficient after PEC compared to the initial state, which, along with an increase in microhardness, indicates an improvement in the performance characteristics of the modified surfaces.

Thus, plasma electrolytic carburizing is an effective method for the comprehensive strengthening of structural steels, improving their mechanical and tribological properties for use under high loads and intense wear.

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ЭЛЕКТРОЛИТТІ-ПЛАЗМАЛЫҚ ЦЕМЕНТАЦИЯДАН КЕЙІН КОНСТРУКЦИЯЛЫҚ БОЛАТТАРДЫҢ ҚҰРЫЛЫМ-ФАЗАЛЫҚ ЖАҒДАЙЫ МЕН МЕХАНОТРИБОЛОГИЯЛЫҚ ҚАСИЕТТЕРІН ЗЕРТТЕУ

Бұл жұмыста электролитті-плазмалық цементация (ЭПЦ) режимдерінің конструкциялық болаттардың құрылым-фазалық күйіне, микроқаттылығына және трибологиялық сипаттамаларына әсері зерттелді. ЭПЦ процесі 10 % кальциленген сода (Na_2CO_3) және 20 % карбамид ($CO(NH_2)_2$) ерітіндісінде, шамамен 950 °C температурада және 300 В кернеуде жүргізілді. Болат 20 үшін екі түрлі салқындату режимі қолданылды: электролиттегі табиғи салқындату және өңдеу аймағына электролит ағынын бағыттау арқылы жүзеге асырылатын белсенді соплалық салқындату. Ал 30ХГСА болаты үшін тек табиғи салқындату қолданылды. Құрылым морфологиясы мен фазалық құрамы рентгендік дифракциялық талдау, сканерлейтін электрондық микроскопия және оптикалық микроскопия арқылы зерттелді. Зерттеу нәтижелері ЭПЦ-дан кейінгі болаттардың микроқұрылымы айқын зоналық сипатқа ие екенін және негізінен мартенсит фазасымен бірге Fe_3C және Fe_7C_3 карбидті қосындыларынан тұратынын көрсетті. Модификацияланған қабаттың қимасы бойынша микроқаттылық FISCHERSCOPE HM2000 құрылғысы арқылы өлшенді. Трибологиялық сынақтар TRB[3] құрылғысында «шар-диск» сызбасы бойынша, 10 Н қалыпты жүктемеде және 0,05 м/с сырғанау жылдамдығында, құрғақ үйкеліс жағдайында жүргізілді. Белсенді салқындату болат 20 үшін максималды микроқаттылықтың 430 HV дейін, ал болат 30ХГСА үшін 720 HV дейін артуына ықпал ететіні анықталды (бастапқы мәндері тиісінше 170 HV және шамамен 250 HV). Сондай-ақ, ЭПЦ-дан кейін үйкеліс коэффициентінің орта есеппен 25-30 % төмендегені байқалды. Алынған нәтижелер ЭПЦ-ның микроқаттылығы жоғары және трибологиялық қасиеттері жақсарған беріктендірілген қабаттарды қалыптастырудағы тиімділігін дәлелдейді және бұл әдістің ауыр механикалық және үйкеліс жүктемелері жағдайында жұмыс істейтін бөлшектерді өндіруде қолдануға әлеуеті бар екенін көрсетеді..

Түйін сөздер: *электролитті-плазмалық цементация, химиялық-термиялық өңдеу, рентгенқұрылымдық талдау, зоналық құрылым, конструкциялық болат, карбидтер, микроқаттылық, үйкеліс коэффициенті.*

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ИССЛЕДОВАНИЕ СТРУКТУРНО-ФАЗОВОГО СОСТОЯНИЯ И МЕХАНО ТРИБОЛОГИЧЕСКИХ СВОЙСТВ КОНСТРУКЦИОННЫХ СТАЛЕЙ ПОСЛЕ ЭЛЕКТРОЛИТНО-ПЛАЗМЕННОЙ ЦЕМЕНТАЦИИ

В работе представлено исследование влияния режимов электролитно-плазменной цементации (ЭПЦ) на структурные, фазовые, микротвердость и трибологические характеристики конструкционных сталей. Электролитно-плазменная цементация проводилась в водном растворе, содержащем 10 % кальцинированной соды (Na_2CO_3) и 20 % карбамида ($CO(NH_2)_2$), при температуре около 950 °C и напряжении 300 В. Были реализованы два режима охлаждения после ЭПЦ для стали 20:

естественное охлаждение в электролите и активное сопловое охлаждение с подачей электролита в зону обработки, а для стали 30ХГСА только естественное охлаждение в электролите. Исследование морфологии структуры и фазового состава проводилось с использованием рентгенодифракционного анализа, сканирующей электронной микроскопии с энергодисперсионной рентгеновской спектроскопии, оптической микроскопии. По результатам которых установлено, что микроструктура сталей после ЭПЦ морфологически имеет зональную структуру с основной мартенситной фазой с карбидными Fe_3C, Fe_7C_3 включениями. Профиль микротвёрдости определяли по сечению модифицированного слоя с использованием прибора FISCHERSCOPE HM2000. Трибологические испытания выполнялись по схеме «шар-диск» на установке TRB^3 в условиях сухого трения при нормальной нагрузке 10 Н и скорости скольжения 0,05 м/с. Установлено, что активное охлаждение способствует формированию более твёрдой мартенситной структуры с максимальными значениями микротвёрдости до 430 HV у стали 20 и до 720 HV у стали 30ХГСА, а их исходные микротвёрдости 170 HV и ~250 HV соответственно. Также было установлено, что коэффициент трения у этих сталей снижается в среднем на 2530 % по сравнению с исходными образцами. Полученные результаты подтверждают эффективность ЭПЦ в формировании упрочнённых слоёв с повышенной микротвёрдостью с улучшенным трибологическим параметром и демонстрируют потенциал метода для применения в производстве деталей, работающих в условиях высоких механических и фрикционных нагрузок.

Ключевые слова: *электролитно-плазменная цементация, химико-термическая обработка, рентгеноструктурный анализ, зональная структура, конструкционная сталь, карбиды, микротвёрдость, коэффициент трения.*

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ҰШҚЫН ПЛАЗМАЛЫҚ ПІСІРУ ӘДІСІМЕН $LANI_5$ НЕГІЗІНДЕГІ СУТЕГІ САҚТАУ МАТЕРИАЛЫН АЛУ

Аңдатпа: *Бұл мақалада ұшқын-плазмалық пісіру (ҰПП) әдісі арқылы $LaNi_5$ негізіндегі сутегі жинақтаушы қорытпаны алу технологиясы зерттелді. Алдын ала механикалық белсендіру және синтездеу процестері лантан (La) және никель (Ni) металл ұнтақтарының 20: 1 және 30: 1 массалық қатынастарында жүргізілді. Дайындалған ұнтақ қоспалары диаметрі 20 мм графиттік матрицаға салынып, алдын ала престеліп, вакуумдық ортада 1250°C температурада және тұрақты қысымда ISKRA қондырғысында 1250°C температурада және тұрақты қысымда пісіру.*

Синтезделген үлгілерге фазалық талдау жүргізу үшін рентгендік дифрактометрия әдісі қолданылды. Нәтижесінде $LaNi_5$ фазасының түзілуі байқалатыны анықталды. Негізгі фазадан басқа La_2O_3 оксиді де анықталды, бұл материалдың ішінара тотығуын көрсетеді. Қорытпа құрылымындағы фазалық өзгерістер мен кристаллдық ерекшеліктер анықталды. Сонымен қатар, материалдың морфологиясы мен микроструктурасын зерттеу үшін сканерлеуші электронды микроскоп қолданылып, алынған үлгілердің беткі құрылымы мен бөлшек өлшемдерінің таралуы сипатталды.Зерттеу нәтижелері $LaNi_5$ негізіндегі сутегі жинақтаушы материалды алу үшін ұшқын-плазмалық пісіру әдісінің тиімділігін көрсетті және синтез параметрлерінің материалдың фазалық құрамына және микроструктуралық сипаттамаларына әсерін айқындауға мүмкіндік берді.

Түйін сөздер: *механосинтез, механикалық белсендіру, ұнтақ қоспасы, сутегі, лантан,никел, ұшқын-плазмалық пісіру.*

Кіріспе

Дүниежүзілік экономиканың, халық санының және урбанизацияның қарқынды өсуі энергияға деген сұраныстың артуына және қазба отындарының белсенді пайдаланылуына алып келді. Алайда, жаңартылмайтын энергия көздерін қолданудың жағымсыз экологиялық салдары барған сайын айқын көрініс табуда. Бұл жағдай экологиялық қауіпсіз энергетикалық жүйелерді әзірлеу мен зерттеуді жеделдетуге түрткі болуда [1, 2]. Осы тұрғыда сутегі энергетикасы қоршаған ортаға зиянсыздығы, қолжетімділігі және жану тиімділігі жоғары балама ретінде үлкен қызығушылық тудырып отыр [3-5]. Сутегі энергетикасын енгізу үш негізгі кезеңнен тұрады: өндіру, сақтау және тасымалдау. Аталған технологиялардың кеңінен қолданылуында сутегіні тиімді әрі қауіпсіз сақтау жүйелері шешуші рөл атқарады [6, 7].

Сутегіні сақтау бойынша қазіргі қолданыстағы технологияларға газ тәрізді күйде қысыммен сақтау, сұйылту және қатты фазада сақтау жатады. Бұл әдістердің әрқайсысы өзіндік пайдалану және энергетикалық сипаттамаларға ие болғанымен, белгілі бір