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IMPROVEMENT OF WEAR RESISTANCE OF BEARING STEEL SHKH15 BY PLASMA HARDENING UNDER DIFFERENT PROCESSING CONDITIONS

Abstract: *This study investigates the effect of plasma hardening under different processing conditions on the microstructure and tribological properties of bearing steel ShKh15. It is shown that plasma treatment, based on localized high-speed heating followed by self-quenching, enables the formation of a hardened surface layer without the use of liquid cooling media. Experimental studies were carried out by varying the plasma arc current (120-140 A) and the flow rate of the plasma-forming gas (0.2-0.25 L/min).The results demonstrate that plasma hardening leads to the formation of a gradient microstructure consisting of martensite, retained austenite, and pearlite, with a smooth transition to the initial pearlitic structure. The maximum microhardness of the hardened layer reaches up to 700 HV with a depth of up to 250 µm. Tribological tests using a ball-on-disk configuration showed that after plasma treatment, the coefficient of friction increases, while the wear rate decreases by 3-3.5 times compared to the initial state. The obtained results indicate a significant improvement in the wear resistance of ShKh15 steel and confirm the effectiveness of plasma hardening as a surface strengthening method.*

Key words: *plasma hardening; ShKh15 steel; surface hardening; wear resistance; tribological properties.*

Introduction

The improvement of the performance characteristics of modern machines is largely determined by the condition of the surface layer of components, since it is in this layer that the main wear processes originate and develop. The problem of increasing the service life of components has both economic and resource-saving significance, as it is associated with the consumption of raw materials and energy resources. For practical application in industrial production, one of the most effective methods is plasma hardening, which is characterized by versatility, accessibility, and high economic efficiency. Plasma hardening is aimed at strengthening the surface layer of iron-carbon alloy components while preserving the initial properties of their internal structure. This process is based on localized high-speed heating of the surface by a plasma arc to temperatures above the critical point, followed by intensive cooling due to heat dissipation into the bulk of the material [1]. Plasma hardening is an effective method of surface strengthening that ensures an increase in wear resistance of components. According to literature data, plasma hardening leads to the formation of a martensitic structure and an increase in microhardness, which positively affects the wear resistance of the material [2]. The main technological parameters of the process are the arc current, the speed of the plasma torch movement, and the characteristics of the heat spot formed by the plasma flow [3]. In this regard, the selection of materials capable of operating effectively under high loads and friction conditions is of particular importance.

Modern mechanical engineering widely uses specialized structural materials, including bearing steels such as ShKh15, which exhibit high hardness and wear resistance [4]. A significant influence on the rolling contact fatigue of bearing steels is exerted by carbide heterogeneity, manifested in the form of carbide networks and stringer-type inclusions. According to studies, the elimination of this defect is achieved through a rational combination of plastic deformation and heat treatment. It has been shown in several works that the improvement of the performance characteristics of ShKh15 steel (analogous to 100Cr6) can be achieved not only through conventional heat treatment but also by modifying the surface layer [5-7]. In particular, the formation of a regular surface microgeometry (in the form of micro-dimples) reduces the coefficient of friction and increases wear resistance. Other studies [8] have shown that cold rolling of 100Cr6 steel rings leads to the formation of a gradient structure and texture, with the maximum degree of deformation observed near the inner diameter. According to literature data, during plasma treatment a dendritic-cellular structure is formed in the remelted zone, and the microhardness may reach up to 840 $HV_{0.1}$ depending on the treatment conditions. Optimization of processing parameters makes it possible to increase the microhardness up to 1400 HV. In a number of studies devoted to plasma nitrocarburizing of DIN 100Cr6 steel, it has been shown that the diffusion of nitrogen and carbon contributes to the formation of a hardened surface layer consisting of γ'-Fe_4N and ε-$Fe_{2-3}N$ phases, which leads to improved wear resistance. It has been established that the treatment temperature and the composition of the gas medium (in particular, CH_4 content) have a significant influence on the morphology of the compound layer and its properties. However, these studies are mainly focused on thermochemical saturation processes and do not consider the features of structure and property formation during plasma hardening based on localized high-speed heating and self-quenching. In particular, the influence of plasma hardening parameters on the formation of a gradient structure and its effect on the tribological properties of ShKh15 steel remains insufficiently studied [8]. Thus, the aim of this work is to investigate the effect of plasma hardening under different processing conditions on the structure, wear resistance, and properties of the surface layer of ShKh15 bearing steel.

Materials and methods

The object of the study was bearing steel ShKh15 (analogous to 100Cr6), the chemical composition of which is presented in Table 1. The preparation of metallographic specimens included sequential grinding with abrasive papers of various grit sizes followed by polishing to a mirror finish.

Table 1 – Chemical composition of ShKh15 steel according to GOST 801-2022 [9]

Steel Name	C	Cr	Mn	Si
Content (wt.%)	0.95-1.05	1.30-1.65	0.20-0.40	0.17-0.37

Plasma hardening was carried out using the UDGZ-200 installation, which provides local heating of the surface without the use of liquid cooling media. For each plasma hardening mode, three samples were studied to ensure the reliability and reproducibility of the experimental results. The samples were made from a 40 mm diameter ShKh15 steel rod, with the thickness of the test samples being 20 mm. Plasma hardening was carried out using a conical electrode and a ceramic nozzle with a diameter of 9 mm. The treatment was performed at a plasma arc current of 120-140 A, an argon plasma-forming gas flow rate of 0.2-0.25 L/min, an arc length of 18 mm, and a linear plasma torch travel speed of 35-45 mm/s. The movement of the plasma torch during processing was performed manually. The main plasma hardening parameters are presented in Table 2. Plasma hardening was carried out under the following conditions: arc current of 120-140 A and argon plasma gas flow rate of 0.2-0.25 l / min. It should be noted that in processing modes R1 and R2, the plasma arc current and argon flow rate were simultaneously varied to ensure stable plasma torch operation and process stability under increased energy conditions. Therefore, the obtained results reflect the combined influence of the processing parameters on the microstructure, microhardness, and wear resistance of the treated surface layer.

Table 2 – Plasma hardening parameters for ShKh15 steel processing modes

Processing mode	Plasma arc current, A	Argon flow rate, L/min	Arc length, mm	Plasma torch travel speed, mm/s	Nozzle diameter, mm	Depth of the hardened layer, μm
R1	120	0.20	15-20	35-45	9	370
R2	140	0.25	15-20	35-45	9	250

Metallographic examination of the ShKh15 bearing steel samples was carried out using a scanning electron microscope (SEM) SM3200 in backscattered electron (BSE) mode, which made it possible to obtain detailed information on the distribution of structural constituents before and after plasma treatment. The preparation of metallographic specimens included etching in a 4% nitric acid (HNO_3) solution in ethanol.

The phase composition of the investigated ShKh15 steel was determined by X-ray diffraction (XRD) using an X'Pert PRO diffractometer with CuKα radiation. The diffraction patterns were recorded under the following conditions: accelerating voltage – 40 kV, tube current – 30 mA, exposure time – 0.25 s, and scanning step – 0.02°. The diffraction data were processed using HighScore software and the PDF-2 database, ensuring reliable phase identification. Additionally, quantitative phase analysis was performed using PowderCell software.

Microhardness measurements were performed using the Vickers method under a load of 0.98 N (100 g) with a Metolab 502 microhardness tester. Measurements were carried out on the cross-section of the samples to determine the hardness distribution over the depth of the hardened layer.

Tribological tests were conducted using a ball-on-disk configuration in accordance with ASTM G99, employing a TRB3 tribometer under dry friction conditions. The test parameters were as follows: normal load – 6 N, sliding speed – 3 cm/s, sliding distance – 100 m, and wear track radius – 2 mm. During the experiments, the dependence of the coefficient of friction on the sliding distance was recorded, and the wear resistance of the material was evaluated. To ensure the reliability of the obtained experimental data, all measurements were performed at least three times, after which the average values of the results were calculated.

After the tribological tests, the wear track area was determined by contact profilometry in accordance with ISO 13565 using a TAYLOR HOBSON SURTRONIC S-100 SERIES profilometer. Based on the obtained experimental data, the wear rate of the investigated ShKh15 steel samples was calculated using the TRB3 tribometer software.

Results and discussion

The high microhardness values in the surface layer are associated with the formation of a martensitic structure after plasma hardening. The presence of retained austenite and pearlitic constituents in the transition zone leads to a gradual decrease in microhardness with increasing distance from the treated surface. Thus, the microhardness distribution is in good agreement with the nature of the structural transformations in the hardened layer. Figure 1 shows the microstructure of the cross-section of bearing steel ShKh15 (GOST 801-2022), formed under different plasma hardening conditions corresponding to regimes R1 and R2, which differ in plasma arc current (120 and 140 A) and plasma-forming gas flow rate (0.2 and 0.25 L/min). The initial microstructure of the steel (Fig. 1c) is represented by granular pearlite consisting of a ferritic matrix and globular cementite. It should be noted that such a pearlitic morphology provides higher strength characteristics compared to pearlite with a network distribution of cementite at the same chemical composition.

After plasma hardening under both processing conditions (R1 and R2), no clearly defined boundary between structural zones is observed. A gradient structure is formed, characterized by a gradual transition from the hardened surface layer, represented by martensite, to the initial pearlitic structure in the bulk of the material (Fig. 1a, b).

For regime R1 (I = 120 A; VAr = 0.2 L/min), the formation of a medium-acicular martensitic structure is typical. The transition zone is represented by a complex phase mixture including martensite, retained austenite, and pearlite, which is attributed to the incomplete phase transformations under conditions of high-speed heating and cooling. It is known that surface hardening processes are accompanied by a self-tempering effect, resulting in the formation of fine-grained tempered martensite. This effect is associated with high temperature gradients and specific heat dissipation conditions in the hardened layer.

With an increase in processing energy parameters (regime R2: I = 140 A; VAr = 0.25 L/min), an increase in the thickness of the so-called "white etching zones" is observed. Their formation is associated with local near-surface re-austenitization caused by high heating rates, which leads to the formation of fine-dispersed tempered martensite not revealed by conventional etching. The microstructure of the transition zone under regime R2 is characterized by a combination of martensite, pearlite, and retained austenite, indicating the complex nature of phase transformations and the formation of a gradient structure of the hardened layer.

Figure 2 shows the distribution of microhardness over the depth of the hardened layer of bearing steel ShKh15 after plasma hardening under different processing conditions (R1 and R2). The measurement error for the obtained microhardness and wear rate values did not exceed 5% of the average value, confirming the reliability and reproducibility of the experimental results.

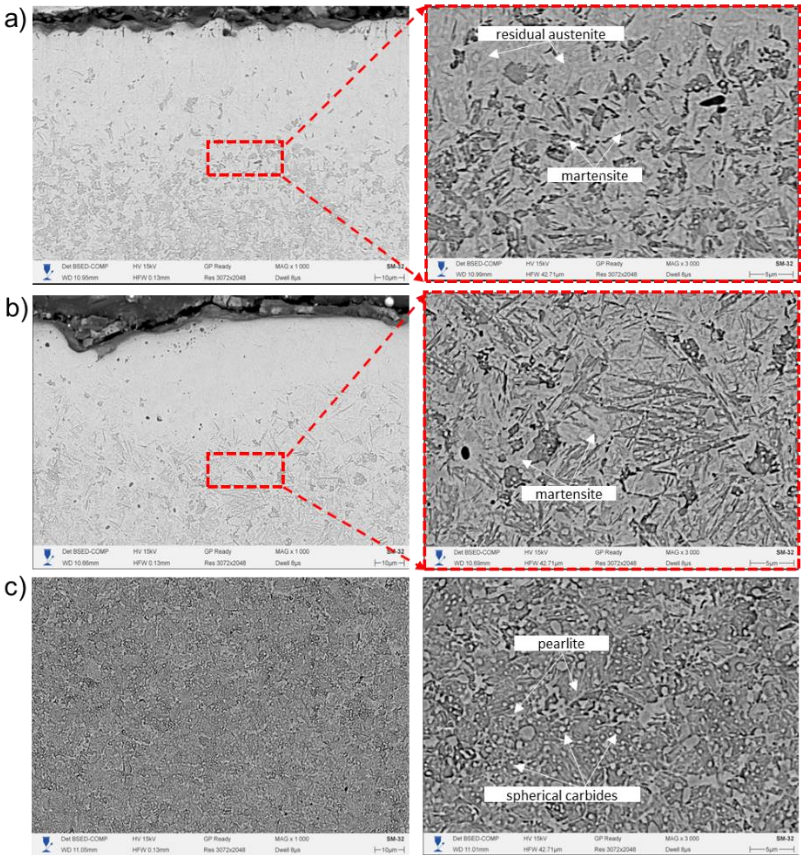

Figure 1 – Microstructure of the cross-section of ShKh15 steel in the initial state and after plasma hardening under different processing conditions:
a – regime R1 (I = 120 A; VAr = 0.2 L/min); b – regime R2 (I = 140 A; VAr = 0.25 L/min); c – initial microstructure

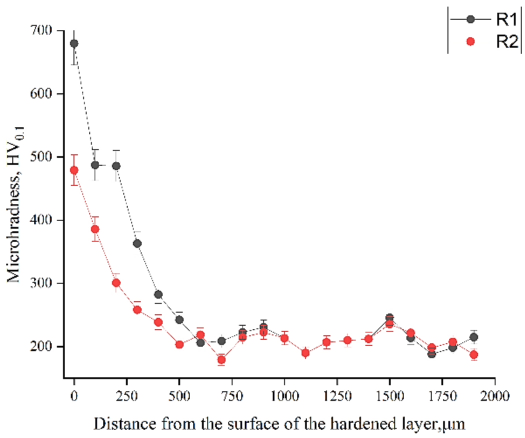

Figure 2 – Microhardness distribution over the depth of the hardened layer of ShKh15 steel after plasma hardening under different processing conditions (R1 and R2)

The obtained results demonstrate a good correlation between the variation of microhardness and the structural transformations occurring in the surface layer of the material. According to the data, for regime R1 (I = 120 A; VAr = 0.2 L/min), increased microhardness values reaching about 500 HV0.1 are maintained up to a depth of ~250 μm, indicating the formation of a hardened martensitic structure in the near-surface region. In the transition zone, located between the hardened layer and the heat-affected zone, a gradual decrease in microhardness from ~500 HV0.1 to values of about 200 HV0.1 corresponding to the initial state of ShKh15 steel is observed. This distribution indicates a gradient structural transformation and a gradual decrease in the martensite fraction with increasing depth. Relatively lower microhardness values in certain areas of the hardened layer may be attributed to insufficient heating temperature or low cooling intensity. Under underheating conditions (insufficient hardening temperature or short holding time), incomplete dissolution of carbon in austenite occurs, leading to reduced hardness of the formed martensite. In addition, at insufficient cooling rates, pearlitic transformation products and retained austenite may form in the structure, both having lower hardness compared to martensite, which negatively affects the microhardness level of the hardened layer [10]. According to the results reported in [11], ShKh15 steel after conventional heat treatment can achieve high hardness, especially at cooling rates above 30°C/s. At a cooling rate of about 100 °C/s, the hardness reaches approximately 700 HV, which is associated with the formation of martensite and retained austenite.

The high microhardness values in the surface layer are associated with the formation of a martensitic structure after plasma hardening. In the transition zone, the presence of retained austenite and pearlitic constituents leads to a gradual decrease in microhardness with increasing distance from the treated surface. Figure 3 shows the diffraction patterns of ShKh15 steel in the initial state and after plasma hardening under different processing conditions (R1 and R2). Analysis of the diffraction spectra indicates that after hardening, the steel structure exhibits pronounced peaks corresponding to retained austenite (γ-Fe), as well as reflections of the martensitic phase (α′-Fe) [12]. This confirms the formation of a hardened layer consisting of martensite with a noticeable fraction of retained austenite. In the initial state, ShKh15 steel is characterized by a ferrite–pearlite structure. The obtained phase analysis results are in good agreement with the microstructural data, confirming the nature of structural transformations during plasma treatment.

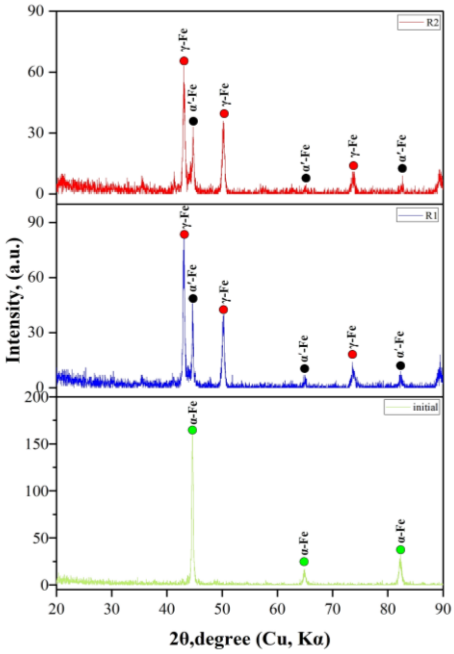

Figure 3 – Diffraction patterns of ShKh15 steel in the initial state and after plasma hardening under processing conditions R1 and R2

Quantitative XRD analysis results are presented in Table 3. The treated surface layers predominantly consist of γ-Fe (retained austenite) with a smaller fraction of α-Fe (martensitic/ferritic phase). For sample R1, the phase fractions were 92.4 wt.% γ-Fe and 7.6 wt.% α-Fe, whereas sample R2 contained 86.1 wt.% γ-Fe and 13.9 wt.% α-Fe. The refined lattice parameters were 3.5980-3.6046 Å for γ-Fe and 2.8612-2.8653 Å for α-Fe.

Table 3 – Quantitative phase composition and lattice parameters of the treated surface layers based on X-ray diffraction analysis

Sample	Detected phases	Phase content, wt.%	Lattice parameters, Å
R1	α-Fe (martensitic/ferritic phase)	7.6	a = 2.8653
	γ-Fe (retained austenite)	92.4	a = 3.5980
R2	α-Fe (martensitic/ferritic phase)	13.9	a = 2.8612
	γ-Fe (retained austenite)	86.1	a = 3.6046

Figure 4a shows the dependences of the coefficient of friction on the sliding distance, as well as the wear rate values of ShKh15 steel in the initial state and after plasma hardening under regimes R1 and R2. As can be seen from the graph, the coefficient of friction for the initial sample is characterized by pronounced instability at the initial stage of testing, followed by stabilization at a level of ~0.5-0.55. This behavior is associated with the formation of a contact layer and the gradual smoothing of the friction surfaces [13]. After plasma hardening, an increase in the coefficient of friction is observed: for regime R1, it stabilizes at ~0.70-0.75, while for regime R2 it is in the range of ~0.65-0.70. It should also be noted that the treated samples exhibit higher stability of the coefficient of friction compared to the initial state, indicating the formation of a more uniform and wear-resistant surface layer [14].

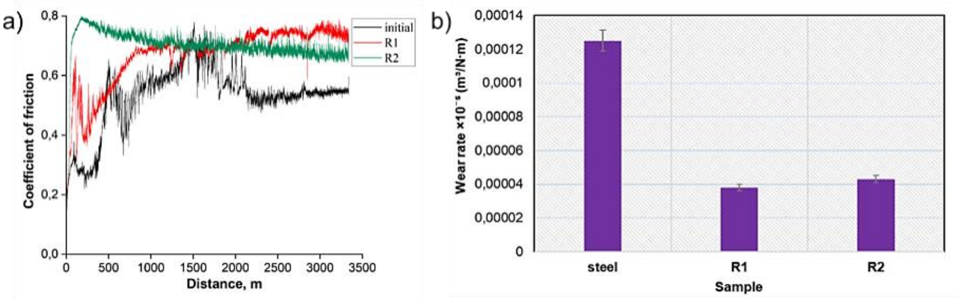

Figure 4 – Dependence of the coefficient of friction and wear rate of ShKh15 steel in the initial state and after plasma hardening: a) coefficient of friction vs. sliding distance; b) wear rate

As shown in Figure 4, the wear rate of the initial steel is about (1.25 ± 0.06) × 10^{-4} mm³/(N·m). After plasma hardening, this value significantly decreases to (3.7 ± 0.2) × 10^{-5} mm³/(N·m) for regime R1 and (4.2 ± 0.2) × 10^{-5} mm³/(N·m) for regime R2. Thus, the wear rate is reduced by approximately 3.4 times for regime R1 and 3 times for regime R2 (Fig. 4b). The improvement in wear resistance is attributed to the formation of a hardened martensitic layer with high hardness and resistance to plastic deformation, which reduces the rate of material removal during friction. At the same time, according to literature data, the development of residual stresses and stress concentration near inclusions may promote microcrack formation and influence the wear mechanism [15]. The main results of plasma hardening of ShKh15 steel under different processing regimes are summarized in Table 4.

Table 4 – Summary of the main results of plasma hardening of ShKh15 steel

Processing mode	Hardened layer depth, μm	Maximum microhardness, HV0.1	Surface microhardness, HV0.1	Coefficient of friction	Wear rate, mm³/(N·m)
Initial state	-	~200	~200	0.50-0.55	(1.25 ± 0.06) × 10^{-4}
R1 (120 A; 0.20 L/min)	200-250	679.4 ± 34.0	281.4 ± 14.1	0.70-0.75	(3.7 ± 0.2) × 10^{-5}
R2 (140 A; 0.25 L/min)	200-250	479.1 ± 24.0	240.3 ± 12.0	0.65-0.70	(4.2 ± 0.2) × 10^{-5}

Conclusion

As a result of the conducted studies, it was established that plasma hardening has a significant effect on the microstructure, microhardness, and tribological properties of ShKh15 steel. The maximum microhardness of the hardened layer, reaching approximately 679.4 ± 34.0 HV, was observed under the R1 mode (I = 120 A, VAr = 0.20 L/min), which is associated with the formation of a martensitic structure in the hardened surface layer. At the same time, the minimum wear rate was recorded under the R1 mode (I = 120 A, VAr = 0.20 L/min), where the wear intensity decreased by approximately 3–3.5 times compared to the initial state. The obtained results confirm the effectiveness of plasma hardening as a method for improving the wear resistance and operational properties of ShKh15 steel.

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References

1. Safonov E.N. Plasma hardening of machine parts / E.N. Safonov. – Moscow; Berlin: Direct-Media, 2014. – 165 p.
2. Modification of the surface of 40Kh steel by electrolytic plasma hardening / Z. Sagdoldina et al // Metals. – 2022. – Vol. 12, № 12. – P. 2071.
3. Kuznetsov V.P. Friction surface hardening of steels using a rotating tool / V.P. Kuznetsov, V.V. Voropaev, A.S. Skorobogatov. – Ekaterinburg: Ural University Press, 2022. – 110 p.
4. Estimation of the influence of heat treatment modes using negative temperatures on the mechanical properties of ShKh15 steel / S.A. Zemlyakov et al // Part I: The influence of heat treatment modes on hardness, strength and toughness // Fundamental'nye problemy sovremennogo materialovedenia. – 2024. – Vol. 21, № 1. – P. 82-90.
5. Brover G.I. Surface hardening by concentrated energy flows / G.I. Brover, A.V. Brover. – Rostov-on-Don: Don State Technical University, 2014.
6. Special steels / E.V. Bratkovsky et al. – Novotroitsk: NF NITU MISIS, 2013. – 87 p.
7. Bochnowski W. The influence of arc plasma treatment on the structure and microhardness of 100Cr6 bearing steel // Archives of Foundry Engineering. – 2010. – Vol. 10. – P. 19-22.
8. Tribological behaviour of microindented 100Cr6 steel surfaces in dry contact conditions / P. Guglielmi et al // The International Journal of Advanced Manufacturing Technology. – 2024. – Vol. 133. – № 5. – P. 2381-2400.
9. ГОСТ 801-2022. Rolled products of bearing steel. Technical specifications. – Moscow: Russian Institute of Standardization, 2023. – 23 p.
10. Plasma immersion ion implantation of 100Cr6 ball bearing steel / C. Blawert et al // Surface and Coatings Technology. – 1996. – Vol. 83, № 1-3. – P. 228-234.
11. Barrow A.T.W. The ε→η→θ transition in 100Cr6 and its effect on mechanical properties / A.T.W. Barrow, J.-H. Kang, P.E.J. Rivera-Díaz-del-Castillo // Acta Materialia. – 2012. – Vol. 60, № 6-7. – P. 2805-2815.
12. Kang J.-H. Rolling contact fatigue in martensitic 100Cr6: Subsurface hardening and crack formation / J.-H. Kang, R.H. Vegter, P.E.J. Rivera-Díaz-del-Castillo // Materials Science and Engineering A. – 2014. – Vol. 607. – P. 328-333.
13. Rapidly quenched materials and coatings: Proceedings of the 20th International Scientific and Technical Conference, October 17-18, 2023, MAI. – Moscow: Probel-2000, 2023. – 372 p.
14. The analysis of structure change and tribomechanical properties of alloyed steel surfaces modified by diffusion electrolyte-plasma boriding method / L.G. Sulyubayeva et al // Bulletin of the Karaganda University. Physics Series. – 2025. – Vol. 1, № 117. – P. 68-76.
15. Application of electrolyte based on sodium carbonate for electrolyte-plasma surface hardening of Steel 45 / B. Rakhadilov et al // Bulletin of Shakarim University. Technical Sciences Series. – 2024. – Vol. 3, № 15. – P. 414-424.

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ӘРТҮРЛІ ӨҢДЕУ РЕЖИМДЕРІНДЕ ПЛАЗМАЛЫҚ ШЫНЫҚТЫРУ ӘДІСІ АРҚЫЛЫ ШХ15 МОЙЫНТІРЕКТІК БОЛАТЫНЫҢ ТОЗУҒА ТӨЗІМДІЛІГІН АРТТЫРУ

Бұл жұмыста әртүрлі өңдеу шарттарындағы плазмалық шынықтырудың ШХ15 мойынтіректік болатының микроқұрылымы мен трибологиялық қасиеттеріне әсері зерттелді. Жергілікті жоғары жылдамдықты қыздыруға және кейінгі өздігінен шынығуға негізделген плазмалық өңдеу сұйық салқындатқыш орталарды қолданбай-ақ беріктендірілген беткі қабаттың қалыптасуын қамтамасыз ететіні көрсетілді. Эксперименттік зерттеулер плазмалық доға тогын (120-140 А) және плазма түзуші газ шығынын (0,2-0,25 л/мин) өзгерту арқылы жүргізілді. Алынған нәтижелер плазмалық шынықтырудың мартенситтен, қалдық аустениттен және перлиттен тұратын градиентті микроқұрылымның қалыптасуына алып келетінін, сонымен қатар оның бастапқы перлиттік құрылымға біртіндеп ауысатынын көрсетті. Беріктендірілген қабаттың максималды микрокаттылығы 250 мкм тереңдікке дейін 700 HV мәніне жетеді. «Шар-диск» сұлбасы бойынша жүргізілген трибологиялық сынақтар плазмалық өңдеуден кейін үйкеліс коэффициентінің артатынын, ал тозу жылдамдығының бастапқы күймен салыстырғанда 3-3,5 есе төмендейтінін көрсетті. Алынған нәтижелер ШХ15 болатының тозуға төзімділігінің едәуір артқанын дәлелдейді және плазмалық шынықтырудың бетті беріктендіру әдісі ретінде тиімділігін растайды.

Түйін сөздер: *плазмалық шынықтыру; ШХ15 болаты; беттік беріктендіру; тозуға төзімділік; трибологиялық қасиеттер.*

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ПОВЫШЕНИЕ ИЗНОСОСТОЙКОСТИ ПОДШИПНИКОВОЙ СТАЛИ ШХ15 МЕТОДОМ ПЛАЗМЕННОЙ ЗАКАЛКИ ПРИ РАЗЛИЧНЫХ РЕЖИМАХ ОБРАБОТКИ

В данной работе исследовано влияние плазменного упрочнения при различных условиях обработки на микроструктуру и трибологические свойства подшипниковой стали ШХ15. Показано, что плазменная обработка, основанная на локализованном высокоскоростном нагреве с последующей самозакалкой, обеспечивает формирование упрочнённого поверхностного слоя без применения жидких охлаждающих сред. Экспериментальные исследования проводились при варьировании тока плазменной дуги (120-140 А) и расхода плазмообразующего газа (0,2-0,25 л/мин). Полученные результаты показывают, что плазменная закалка приводит к формированию градиентной микроструктуры, состоящей из мартенсита, остаточного аустенита и перлита, с плавным переходом к исходной перлитной структуре. Максимальная микротвёрдость упрочнённого слоя достигает 700 HV при глубине до 250 мкм. Трибологические испытания по схеме «шарик-диск» показали, что после плазменной обработки коэффициент трения увеличивается, тогда как скорость износа снижается в 3-3,5 раза по сравнению с исходным состоянием. Полученные результаты свидетельствуют о значительном повышении износостойкости стали ШХ15 и подтверждают эффективность плазменного упрочнения как метода поверхностного упрочнения.

Ключевые слова: *плазменная закалка; сталь ШХ15; поверхностное упрочнение; износостойкость; трибологические свойства.*

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