ISSN 0208-7774 T R I B O L O G I A 4/2019 p. 105–111
DOI: 10.5604/01.3001.0013.5971

Erkezhan TABIEVA[*], **Bauyrzhan RAHADILOV**[**], **Zarina SATBAEVA**[***],
Aidar KENESBEKOV[****], **Gulzhaz UAZYRKHANOVA**[*****]

INFLUENCE OF ELECTROLYTIC-PLASMA SURFACE HARDENING ON THE SURFACE PROPERTIES OF BANDAGE STEEL

WPŁYW HARTOWANIA ELEKTROLITYCZNO-PLAZMOWEGO NA WŁASNOŚCI POWIERZCHNI STALI STOSOWANEJ NA OBRĘCZE KÓŁ KOLEJOWYCH

Key words: electrolytic-plasma surface hardening, bandage steel, wear resistance, microstructure, microhardness.

Abstract: This work is devoted to the research of the influence of the technological parameters of electrolytic-plasma surface hardening on the structure and tribological properties of the surface of samples of the retaining steel Mark 2. Electrolytic-plasma surface hardening was carried out in an electrolyte from an aqueous solution of 10% urea and 10% sodium carbonate. According to the result of metallographic and X-ray diffraction analysis, it was determined that the phase composition of steel Mark 2 after processing varies, and fine martensite with a small amount of troostite and iron oxide is formed on the surface of the samples. Tribological experiments of samples without lubrication were carried out. These experiments have shown that all the samples studied have an increased wear resistance, which may be associated with the formation of a fine-grained martensitic structure. It was shown that from the point of view of the complex of the properties obtained, and the most promising is electrolytic-plasma action with a treatment time of 4 s.

Słowa kluczowe: elektolityczno-plazmowe hartowanie powierzchniowe, stal bandażowa, odporność na zużycie, mikrostruktura, mikrotwardość.

Streszczenie: Praca opisuje wpływ parametrów technologicznych elektrolityczno-plazmowego hartowania powierzchniowego na strukturę i właściwości tribologiczne stali „Mark 2“ (GOST 398-96). Stal GOST 398-96 – „Mark 2” jest niestopową stalą średniowęglową i jest najczęściej stosowanym materiałem na obręcze kół kolejowych w Kazachstanie. Hartowanie elektrolityczno-plazmowe przeprowadzono w 10-proc. roztworze wodnym mocznika z dodatkiem 10% węglanu sodu. Na podstawie wyników analizy metalograficznej i badań z zastosowaniem dyfrakcji rentgenowskiej ustalono, że skład fazowy stali „Mark 2” po obróbce cieplnej jest zróżnicowany a na powierzchni próbek powstaje drobny martenzyt z niewielką ilością trostytu i tlenku żelaza. Przeprowadzone badania tribologiczne podczas tarcia suchego wykazały zwiększenie odporność na zużycie próbek poddanych hartowaniu elektrolityczno-plazmowemu w stosunku do próbek w stanie nieobrobionym cieplnie. Efekt ten może być związany z tworzeniem się na powierzchni drobnoziarnistej struktury martenzytycznej. Badania porównawcze próbek stalowych poddanych obróbce cieplnej z różnymi parametrami technologicznymi wykazały, że najbardziej korzystna jest obróbka elektrolityczno-plazmowa wykonana w czasie 4 s.

INTRODUCTION

The problem of wear of the crests of tires of locomotive wheelsets has been repeatedly highlighted by many scientists as the most significant reason for the inability to increase the overhaul run of locomotives, which significantly increases maintenance costs and simple

---

[*] ORCID: 0000-0002-9726-7187. D. Serikbayev East-Kazakhstan State Technical University, Ust-Kamenogorsk, Kazakhstan.

[**] ORCID: 0000-0001-5990-7123. S. Amanzholov East-Kazakhstan State University, Ust-Kamenogorsk, Kazakhstan.

[***] ORCID: 0000-0001-7161-2686. S. Amanzholov East-Kazakhstan State University, Ust-Kamenogorsk, Kazakhstan.

[****] ORCID: 0000-0002-5630-9467. D. Serikbayev East-Kazakhstan State Technical University, Ust-Kamenogorsk, Kazakhstan

[*****] ORCID: 0000-0002-9817-9752. D. Serikbayev East-Kazakhstan State Technical University, Ust-Kamenogorsk, Kazakhstan.

locomotives in repair depots **[L.1–4]**. It is known that, over the past 20 years, there has been a gradual increase in the wear rate of the wheelset of locomotives on Kazakhstan Railways. This is due to the increase in distillation speeds of trains and axial loads, as well as the transition to reinforced concrete sleepers. At the same time, steel for the manufacture of bandages has not changed. For the manufacture of bandages in Kazakhstan, mainly Mark 2 steel is used. The bandage is a replaceable element of a wheel pair. The bandage directly interacts with the rail and, due to the large static and dynamic loads, it is subjected to the greatest wear. The strength characteristics of the bandage Mark 2 steel according to Industry Standard 398-2010 is insufficient and does not correspond to the more stringent conditions of loading of the bandage in operation, which is associated with the increased power of the locomotive and the implementation of the increased coefficient of adhesion of the bandage with the rail **[L. 5, 6]**.

Currently, there are several methods for increasing the service life of wheelset bands. The most effective of these is plasma hardening of the crests of the tire trunking of wheel sets and the lateral surface of the rails. Currently in practice, various methods of plasma hardening (quenching) are used using a compressed arc of direct or indirect action generated by a special plasma torch **[L. 7, 8]**. However, many technologies have several disadvantages associated with the processes of decarburization, oxidation, and insufficient cooling rate. To eliminate these drawbacks, electrolytic-plasma technology can be used for surface heat treatment. Electrolyte-plasma surface hardening (EPSH) is one of the methods of high-speed heating in which the workpiece is a cathode or anode relative to an aqueous electrolyte **[L. 9–11]**. Depending on the heating mode, electrolyte composition, and the design parameters of the equipment, it is possible to produce hardening, and chemical-thermal and thermal-cyclic processing of materials. At the same time, EPSH is the most economical and productive method. It is characterized by less energy consumption, the simplicity of technological equipment, and the large size of the hardened zone. The advantages of the method are a sufficiently large process performance and the ability to strengthen the details of a large mass and a complex profile and the degree of hardening is comparable to plasma quenching **[L. 12]**.

In connection with the above, the aim of this work is to study the effect of EPSH on the structure and surface properties of specimens of the Mark 2 retaining steel.

MATERIAL AND METHODS

In this work, EPSH was subjected to samples of Mark 2 steel used for the manufacture of locomotive wheel sets in accordance with the requirements of Industry Standard 398-96. The chemical composition of the steel is shown in **Table 1**.

Table 1. Chemical composition in mass. % of Mark 2 steel, according to Industry Standard 398-96 [L. 13, 14]
Tabela 1. Skład chemiczny w masie. % stali Mark 2, zgodnie z normą branżową 398-96 **[L. 13, 14]**

Steel mark	Mass fraction of elements, %					
	C	Mn	Si	V	S	P
2	0.55–0.65	0.50–0.90	0.22–0.45	No more 0.10	No more 0.030	No more 0.035
The rest of Fe, also the permissible mass fraction (%): Ni ≤0.25, Cr=0.20, Cu=0.30						

Blanks of steel samples of Mark 2 for the study were cut out of a bandage in the form of a parallelepiped measuring 15×15×10 mm^3. The technology of preliminary heat treatment of steel wheels provides for their hardening and subsequent tempering. In this work, in its initial state, Mark 2 steel was heat-treated by quenching at 890–920ºC (exposure 2 hours) with subsequent tempering at 580–620ºC (exposure 2.5 h, cooling in warm water at 30–60ºC) **[L. 15]**. EPSH was carried out at the electrolyte-plasma treatment facility developed by the authors of work **[L. 16, 17]**. A schematic diagram of the installation for the EPSH is shown in **(Figure 1)**. The power source was a powerful rectifier, giving a maximum 360V/60A output in the form of direct current. Samples were processed by rapid heating for 2–4 s and then cooling in a flow-through electrolyte. A water solution of urea and sodium carbonate was chosen as the electrolyte. Processing parameters are presented in **Table 2**.

Table 2. Technological parameters of electrolyte-plasma treating
Tabela 2. Parametry technologiczne obróbki elektrolitowo-plazmowej

Electrolyte composition (% mass)	Processing time, [s]	T_{max}, [ºC]	U, [V]	I, [A]
10% carbamide $(NH_2)_2CO$ +10% sodium carbonate Na_2CO_3 +80% water	2, 3, 4	850–900	320	40

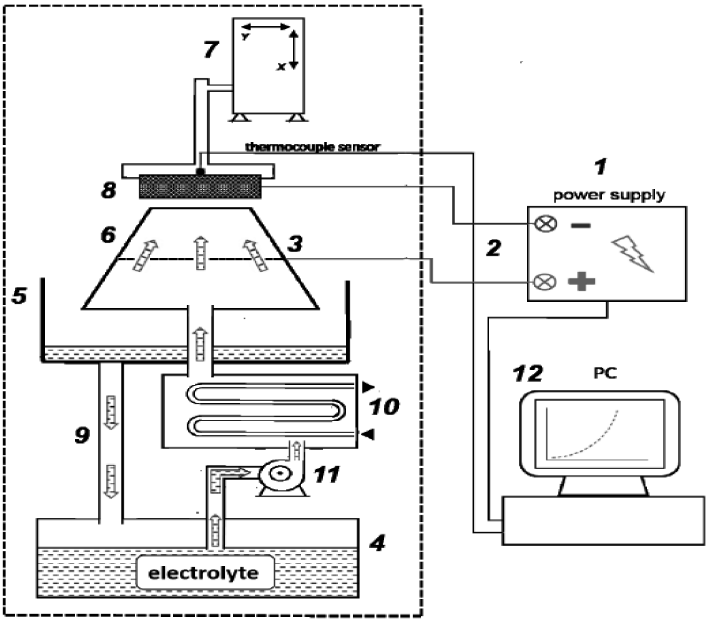

Fig. 1. Functional diagram of the installation for electrolyte – plasma processing of materials: 1 – power supply, 2 – current lead, 3 – anode (plate), 4 – main tank for electrolyte, 5 – intermediate capacity, 6 – electrolytic cell, 7 – coordinate device, 8 – workpiece, 9 – branch pipes, 10 – heat exchanger, 11 – pump, 12 – control computer

Rys. 1. Schemat funkcjonalny instalacji do obróbki materiałów elektrolitowo-plazmowych: 1 – zasilanie, 2 – bieżący przewód, 3 – anoda (płyta), 4 – główny zbiornik na elektrolit, 5 – pojemność pośrednia, 6 – ogniwo elektrolityczne, 7 – urządzenie współrzędnych, 8 – przedmiot, 9 – rury odgałęźne, 10 – wymiennik ciepła, 11 – pompa, 12 – komputer sterujący

The microstructure of the surface was studied on an optical microscope "ALTAMI-MET-1M". The microhardness of the surface layers of the samples before and after processing was measured by the method of pressing a diamond indenter using a PMT-3M instrument at a load of 1 N and a holding time at this load of 10 s. Tribological characteristics were studied on the THT-S-BE-0000 tribometer. The wear tracks were investigated using a MICROMEASURE 3D station contactless 3D profilometer. The phase composition of the samples was studied by X-ray diffraction analysis on an X'PertPro diffractometer using CuKα radiation. Test samples for abrasive wear were performed on an experimental setup for testing for abrasive wear according to the scheme "rotating roller – flat surface" in accordance with Industry Standard 23.208-79. The durability of the treated sample was evaluated by comparing its wear with the wear of the reference sample (not the treated sample). Wear was measured by the gravimetric method on an ADB-200 analytical balance with an accuracy of up to 0.0001 g. The wear resistance of the test material was estimated by the weight loss of the samples during the test according to Industry Standard -23.208- 79 which coincides with the American standard ASTM C 6568 **[L. 18–20]**.

RESULTS OF RESEARCH

The conducted metallographic studies have shown that the structure of the bandage Mark 2 steel in the initial state, i.e. after standard heat treatment, is a ferritic-pearlite structure **(Fig. 2)**. As can be seen from **Fig. 2a**, the pearlite (P) and ferrite (F) grains are randomly located relative to each other. Approximately 60% of the bulk of the investigated steel is occupied by ferrite grains. **Figure 2b** shows a fragment of the X-ray diffraction pattern, where the diffraction peaks correspond to the α-Fe phase.

Under the research of the microstructure of the surface layers of samples of Mark 2 steel subjected to EPSH, structural changes were found. **Figures 3a–d** show the microstructure of the surface layer of steel before and after treatment in the electrolyte containing an aqueous solution of 10% urea $(NH_2)_2CO$ and 10% sodium carbonate Na_2CO_3 with a treatment time of 2, 3, and 4 s.

After EPSH, the formation of a structure from fine martensite and troostite (highly dispersed perlite) is observed. According to the results of X-ray phase analysis, cementite and iron oxide FeO were found together with martensite (**Fig. 4**). The observed cementite lines on the diffractogram confirm the formation of troostite. Thus, the microstructure of the surface of a hardened sample of Mark 2 steel is a fine-grained martensitic structure with a small amount of troostite and iron oxide.

Considering the actual of the problem of increasing the performance characteristics of the retaining steel of Mark 2, one of the most important properties of the surface layer, which greatly affects wear resistance, is hardness. In this work, changes in the microhardness

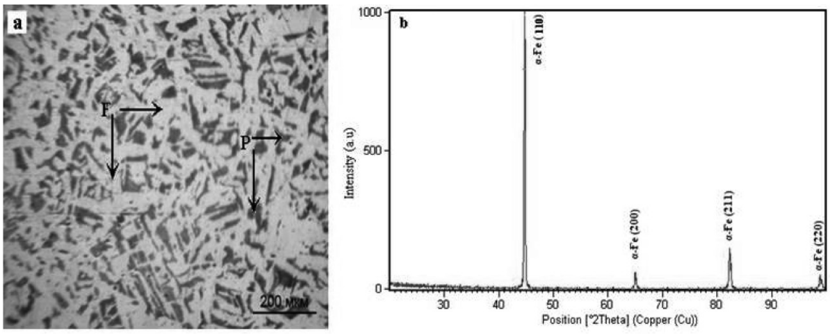

Fig. 2. Microstructure (a) and diffractogram (b) of Mark 2 steel in the initial state

Rys. 2. Mikrostruktura (a) i dyfraktogram (b) stalowego znaku 2 w stanie początkowym

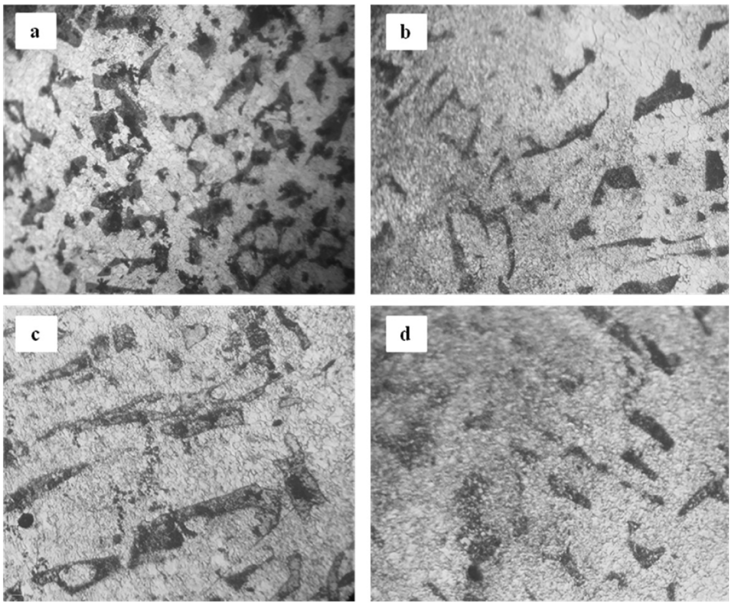

Fig. 3. Microstructure of the bandage Mark 2 steel before and after the EPSHL: a) In the initial state; after EPSH: b) 2 s, c) 3 s, d) 4 s

Rys. 3. Mikrostruktura znaku 2 bandażowej stali przed i po EPSH: a) w stanie początkowym; po EPSH: b) 2 s, c) 3 s, d) 4 s

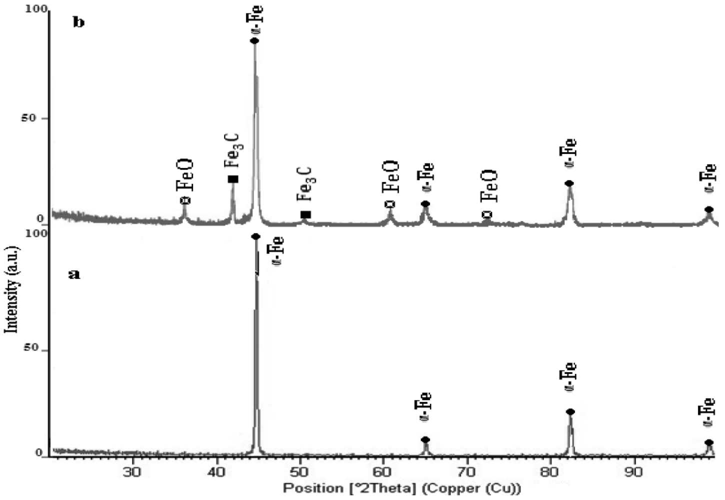

Fig. 4. X-ray phase analysis of Mark 2 steel before (a) and after the EPSH (b)

Rys. 4. Rentgenowska analiza fazowa stalowego znaku 2 przed (a) i po EPSH (b) of the surface layer of Mark 2 steel after EPSH are studied. Figure 5 shows a diagram of the dependence of the microhardness value of Mark 2 steel on the duration of exposure to electrolytic plasma. The microhardness of Mark 2 steel in the initial state is 1448 MPa, and after quenching with durations of 2, 3, and 4 s the hardnesses were 2489 MPa, 2911 MPa, and 3605 MPa, respectively, which is 2.4 times higher when compared to the microhardness in the initial state. According to the microhardness data obtained for the retaining Mark 2 steel, The following is considered the optimal mode for EPSH: treatment at a temperature of 860ºC with the electrolyte composition of an aqueous solution of 10% urea $(NH_2)_2CO$ and 10% sodium carbonate Na_2CO_3 with a processing time of 4 s.

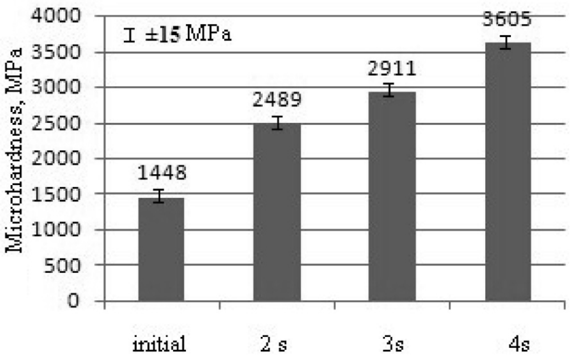

Fig. 5. Diagram of the value of the surface microhardness of Mark 2 steel

Rys. 5. Schemat wartości mikrotwardości powierzchni znaku stali 2

The tribological properties of the samples before and after the EPSH were also examined. Experimental curves of the friction coefficient versus the path length are shown in **Fig. 6**. The tests were carried out according to the ball-disk scheme, and the path length was 31 m, speed 2 cm/s, and load 5 N.

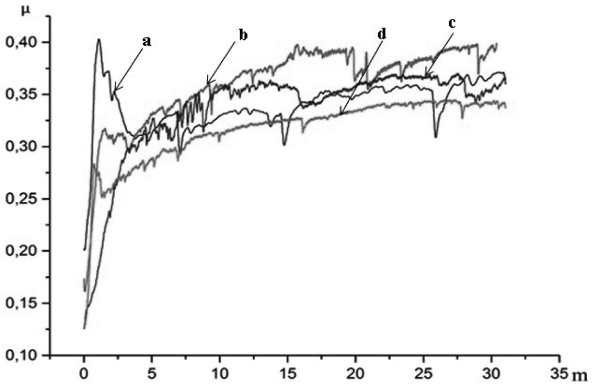

Fig. 6. Friction coefficient of Mark 2 steel before and after EPSH: (a) the initial; (b) 2 s; (c) 3 s; (d) 4 s

Rys. 6. Współczynnik tarcia znaku stali 2 przed i po EPSH: (a) początkowy; (b) 2 s; (c) 3 s; (d) 4 s

The results of experiments showed that there is a slight change in the coefficient of friction after the EPSH. At the same time, a relatively low coefficient of friction is observed in samples treated with EPSH for 4 s.

We took photographs of the sample wear track before and after the EPSH with different processing times using a 3D profilometer, **(Fig. 7)**. Assessing the

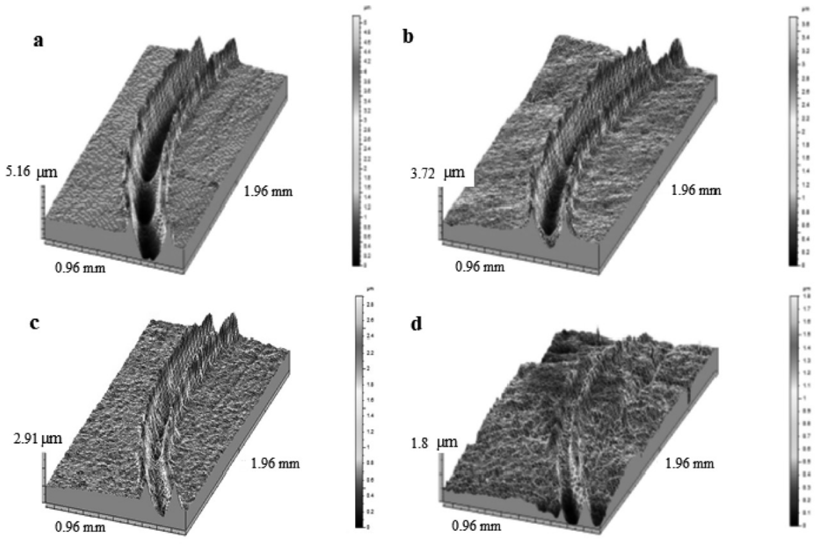

Fig. 7. Wear tracks after tribological testing of samples in the initial state (a) and after an EPSH with a treatment time of 2 s (b), 3 s (c), 4 s (d)

Rys. 7. Nośne ślady po testach tribologicznych próbek w stanie początkowym (a) i po EPSH z czasem leczenia 2 s (b), 3 s (c), 4 s (d) wear resistance of the samples based on the geometrical parameters of the wear tracks, it can be said that the depth of the sample track after the EPSH is significantly lower compared to the untreated sample.

The tribological characteristics of the samples before and after the EPSH were characterized by the wear rate **(Tab. 3)**. After processing the samples under different modes of EPSH, an increase in wear resistance under conditions of dry friction was established.

Table 3. The intensity of wear of steel samples of Mark 2 before and after the EPSH

Tabela 3. Intensywność zużycia próbek stali Mark 2 przed i po EPSH

Sample Name	Wear rate, $mm^3/(N*m)$
Initial	4.83×10^{-4}
After EPSH, 2 s	3.11×10^{-4}
After EPSH, 3 s	1.33×10^{-4}
After EPSH, 4 s	0.33×10^{-4}

The results of the abrasive wear test were characterized by the weight loss of the samples after the tests. **Figure 8** shows the mass loss values of samples of Mark 2 steel before and after the EPSH. A significant increase in wear resistance is observed on all samples subjected to EPSH.

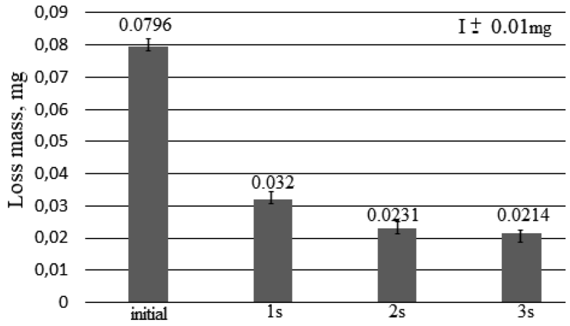

Fig. 8. Resistance to abrasive wear of samples of Mark 2 steel

Rys. 8. Odporność na zużycie ścierne próbek znaku stali 2

It is seen that the loss of mass after the EPSH is less than the original samples, which indicates an increase in the resistance to abrasive wear of Mark 2 steel after the EPSH. According to the mass loss data, the relative wear resistance of Mark 2 steel was determined. After the EPSH, the resistance to abrasive wear increased by 2.5–3 times.

Therefore, according to the result of metallographic and X-ray structural analysis, it was determined that the phase composition of Mark 2 steel after the EPSH changes, and fine-dispersed martensite with a small amount of troostite and iron oxide is formed on the surface of the samples. The tribological tests performed showed that the samples after the EPSH have an increased wear resistance, which may be associated with the formation of a fine-grained martensitic structure. It was determined that, from the point of view of the complex of the properties obtained, the electrolyte-plasma action with a treatment time of 4 s is the most optimal.

CONCLUSIONS

Analysing the results obtained in the work, we can draw the following main conclusions:

The use of EPSH allows one to obtain a fine-grained martensitic surface structure, which significantly affects the mechanical and tribological properties.

At the EPSH of steel Mark 2 with a processing time of 2 s, 3 s, 4 s at a temperature of 860°C in an electrolyte containing an aqueous solution of 10% urea $(NH_2)_2CO$ and 10% sodium carbonate Na_2CO_3 a surface layer is formed on the surface of the samples under study – α-Fe ferrite, cementite Fe_3C, and iron oxide.

Based on the results of micro-indentation and abrasive wear tests, it was shown that EPSH of Mark 2 steel with a heating time of 2–4 s leads to an increase in wear resistance 3.5–3.7 times, and microhardness 1.8–2.4 times.

This paper presents the results of an experimental study of the effect of the technological parameters of the EPSH on the microhardness and tribological properties of the retaining of Mark 2 steel. In further studies, the laws governing the improvement of the tribological properties of Mark 2 steel will be studied based on the results of the study of the structural phase state and the evolution of the fine structure of sample.

ACKNOWLEDGMENTS

The work was performed in the framework of program-targeted funding of the Committee of Science of the Ministry of Education and Science of the Republic of Kazakhstan for 2018–2020.

REFERENCES

1. Razumov A.S., Pasholok I.L., Zurenko V.N.: Wheels high operational stability for freight cars of new generation, Development of railway transport in the context of reforms, 2007, pp. 199–206 (in Russian).
2. Aksoy A., Altan A.: The integrated Locomotive Assigment and Crew Scheduling Problem, International Journal of Computational Engineering Research, 2013, pp. 18–24.
3. Babachenko A.I., Kononenko A.A., Dementieva G.A., Litvinenko P.L., Knush A.V.: Issledovanie prichin obrasovania defektov na poverhnosti katania vusokoprochnuh koles v prozesse ekspluatazii (Research the causes of defects on the surface of the high-rolling wheels during operation), Rail Ukraine, 5, 2010, pp. 35–38 (in Russian).
4. Babichenko A.S., Togobitsky D.N., Kozachok A.S., Golovko L.N., Kononenko A.A.: Knysh Conceptual framework for the selection of the chemical composition of steel for railway wheels, Metallography and heat treatment of metals, 4, 2014, pp. 34–48 (in Russian).
5. Klimenov V.A., Kovalevskaya Zh.G., Uvarkin P.V., Belyavskaya O.A., Tolmachev A.I.: Ultrasonic surface treatment – a method of increasing the service life of locomotive wheel bandages, Heavy engineering 12, 2009, pp. 24–28 (in Russian).
6. Yokoyama H., Mitao S., Yamamoto S., Kataoka Y., Sugiyama T.: High Strength Bainitic Steel Rails for Heavy Haul Railways with Superior Damage Resistance,NKK Technical Review No. 84, taken on Feb 8th 2011.
7. Meletis E.I., Nie X., Wang F.L., Jiang J.C.: Electrolytic plasma processing for cleaning and metal-coating of teel surface, Surfce and Coatings Nechnology 150 (2002), pp. 246–256.
8. Saltykov S.A.: Stereometric metallography, M: Metallography, 1970, p. 376.
9. Chernyavsky K.S.: Stereology in Metallurgy, Moscow:Metallurgy, 1977, p. 280.
10. Skakov M.K., Rahadilov B.K., Zarva D.B., Gulkin A.V.: Installation of electrolytic-plasma processing, Innovative patent for the invention of the Republic of Kazakhstan: IPC C255F 7/00 – No. 29978, Application. 03/02/2014; Publ. 15.06.2015, Bul. № 6.
11. Rakhadilov B., Zhurerova L., Pavlov A.: Method of Electrolyte-Plasma Surface Hardening of 65G and 20GL Low-Alloy Steels Samples, Materials Science and Engineering, 2016 (142), pp. 1–7.
12. Skakov M., Rakhadilov B., Scheffler M., Batyrbekov E.: Microstructure and tribological properties of electrolytic plasma nitrided high-speed steel, Materials Testing, 2015, 57(4), pp. 360–364.
13. Yi J., Li J., Lu J., Liu Z.: On the stability and agility of aggressive vehicle maneuvers: a pendulum-turn maneuver example, IEEE Transactions on Control Systems Technology, 3, 2012, pp. 663–676.
14. Babachenko A.I., Knish A.V., Kuzmitchov V.M., Litvinenko P.L., Polsky G.M., Bϵsϵdnov S.V., Roslik O.B.: Zamovnik i patentovlasnik Institut chornoї metalurgiї Natsionalnoї Academiy Nayk Ukrainu (Customer and patentee Iron and Steel Institute of the National Academy of Sciences of Ukraine), 2011, publ. 04.25.2013, Bull. No. 8.
15. Skakov M., Rakhadilov B., Batyrbekov E.: The formation of modified layers at high-speed steels after electrolytic-plasma nitriding, Applied Mechanics and Materials, 682, 2014, pp. 104–108.
16. Mazhyn S., Bauyrzhan R., Michael S.: Effects of electrolyte plasma carbonitriding on tribological properties of high speed steel, Advanced Materials Research, 2013, pp. 7–11.
17. Skakov M., Rakhadilov B., Scheffler M., Batyrbekov E.: Microstructure and tribological properties of electrolytic plasma nitrided high-speed steel, Materials Testing, 57(4), 2015, pp. 360–364.
18. Skakov M.K., Sapatayev E., Verigin A.: Abrasive wear test plant, Innovative patent for the invention of the Republic of Kazakhstan: G01N 3/56 – № 2328720, Application 09/07/2012; Publ. 15.05.2013, Bul. No 5.
19. Skakov M., Rakhadilov B., Scheffler M.: Modification of structure and properties of steel P6M5 at electrolyteplasma treatment, Advanced Materials Research, 601, 2013, pp. 64–68.
20. Tulenbergenov T., Skakov M., Kolodeshnikov A., Zuev V., Rakhadilov B., Sokolov I., Ganovichev D., Miniyazov A., Bukina O.: Interaction between nitrogen plasma and tungsten, Nuclear Materials and Energy, 13, 2017, pp. 63–67.