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## APPLYING SURFACE PLASMA HARDENING FOR IMPROVING THE TRIBOLOGICAL CHARACTERISTICS OF STEEL PARTS

### ZASTOSOWANIE UTWARDZANIA PLAZMOWEGO POWIERZCHNI W CELU POPRAWY WŁAŚCIWOŚCI TRIBOLOGICZNYCH CZĘŚCI STALOWYCH

<b>Key words:</b>	plasma hardening, microhardness, wear resistance, modified surface layer, martensite, residual austenite, friction coefficient, amount of wear.
<b>Abstract</b>	This work presents the results of experimental studies on the application of surface plasma hardening to improve the tribological characteristics of steel marks of 40CrNi, 20Cr2Ni4A, and 34CrNi1Mn. According to the obtained results, it was established that, after plasma treatment, a modified layer with a thickness of 1–1.2 mm with high hardness and wear resistance is formed, consisting of a hardened layer of fine-grained martensite and, an intermediate layer of perlite and martensite. It was determined that, after treatment with a heating time of 3 min, the microhardness of steels 40CrNi and 20Cr2Ni4A doubles, and the steel 34CrNi1Mn increases 1.6 times, depending on the initial state, and the wear resistance of all steel samples increases, on average, 30 times.
<b>Słowa kluczowe:</b>	utwardzanie plazmowe, mikrotwardość, odporność na zużycie, modyfikowana warstwa powierzchniowa, martenzyt, austenit szczątkowy, współczynnik tarcia, zużycie.
<b>Streszczenie</b>	W niniejszej pracy przedstawiono wyniki eksperymentalnych badań nad stosowaniem utwardzania plazmy powierzchniowej w celu poprawy charakterystyki tribologicznej próbek stalowych 40CrNi, 20Cr2Ni4A i 34CrNi1Mn. Zgodnie z uzyskanymi wynikami ustalono, że po obróbce plazmowej powstaje zmodyfikowana warstwa o grubości 1–1,2 mm o dużej twardości i odporności na ścieranie, składająca się z utwardzonej warstwy drobnoziarnistego martenzytu i warstwy pośredniej z perlitu i martenzytu. Stwierdzono, że po obróbce z czasem ogrzewania 3 min mikrotwardość stali 40CrNi i 20Cr2Ni4A podwaja się, a stal 34CrNi1Mn wzrasta 1,6 razy, w zależności od stanu początkowego, i odporność na zużycie wszystkich próbek stali wzrasta średnio 30 razy.

## INTRODUCTION

For increasing the service life of loaded steel parts (for example, gear wheels, etc.) operating under the action of cyclic loads and subjected to heavy wear in operation, it is necessary to radically change the approach to creating the required set of properties [L. 1–3]. The implementation of such a set of properties is possible when applying the method of surface heat treatment. At the present time, along with metallurgical methods and heat treatment under the conditions of manufacturers, local surface hardening of wear surfaces with the use of various technologies is also being considered to increase the service life of gear wheels. Surface thermal hardening

of steel parts is one of the most effective and efficient ways to increase the service life of loaded elements of machines and mechanisms. In this case, only the most loaded working surface of the part is strengthened, leaving the core intact [L. 4]. At the same time, the progress in improving the quality of heat treatment (hardening) of the working surfaces of parts is associated with the use of concentrated energy sources: electron and laser beams, plasma jets. Such methods allow achieving higher performance properties and quality of hardening. At present, high-frequency, gas-flame, plasma, electron-beam, and laser processing are widely used for surface thermal hardening of gear wheels [L. 5–8]. At the same time, of all the existing methods of hardening in terms of

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their technical and economic indicators and the results of a comparative analysis, plasma surface hardening is recommended. The main distinguishing feature of the plasma surface hardening method is the possibility of obtaining heating and cooling rates of materials that are several orders of magnitude higher than the values typical of traditional hardening methods (furnace hardening, high-frequency hardening, flame hardening, etc.), which contributes to obtaining hardened layers with previously unattainable levels operational properties [L. 9, 10]. The resulting quench-type structures have high hardness, wear resistance, and fracture resistance.

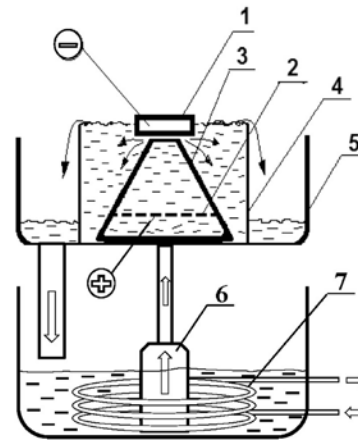
In connection what was mentioned above, the purpose of this work is the use of surface plasma quenching technology, providing a given structure of the surface layer to increase the hardness, wear resistance, and strength characteristics of steel parts.

## MATERIAL AND METHODS

In accordance with the goal, 40CrNi, 20Cr2Ni4A, and 34CrNi1Mn steel samples were chosen as the objects of study. The choice of materials research is justified by the fact that these steels are widely used for the manufacture of hard-loaded gears. The chemical compositions of steels 40CrNi, 20Cr2Ni4A, and 34CrNi1Mn are presented in **Table 1**.

Plasma surface hardening of steel samples was carried out at the facility, which constructively consists of a power source, an electrolyte-plasma material processing chamber, and a personal computer. Figure 1 shows a setup diagram for plasma surface hardening (PSH) materials. PSH steel samples were treated as follows. Before starting work, the working bath is filled with electrolyte. Then the electrolyte, through a pump installed at the bottom of the working bath, enters the electrolytic cell. In this case, the electrolyte exits through the opening of the cone-shaped partition in the form of a jet and fills the electrolytic cell. Then the electrolyte is drained over the edge of the electrolytic cell into a pan, and then back into the working bath. Thus, the electrolyte is in a circulation mode [L. 10, 11].

To study the general nature of the structure, an optical microscope was used –NEOPHOT-21 of the National Research Laboratory for Collective Use of S. Amanzholov EKSU. The preparation of metallographic sections of steel samples was carried



**Fig. 1. Installation diagram for electrolytic-plasma surface hardening: 1 – processed sample (cathode), 2 – anode from stainless steel with holes, 3 – conical partition, 4 – working chamber – bath with electrolyte, 5 – tray, 6 – pump, 7 – heat exchanger**

Rys. 1. Schemat instalacji do hartowania powierzchni elektrolitycznie plazmy: 1 – próbka (katoda), 2 – anoda ze stali nierdzewnej z otworami, 3 – stożkowa przegroda, 4 – komora robocza – wanna z elektrolitem, 5 – taca, 6 – pompa, 7 – wymiennik ciepła

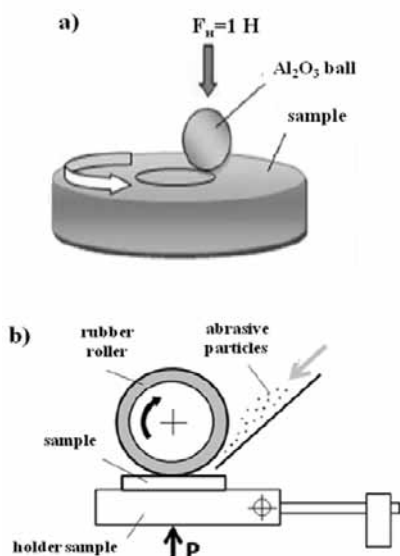
out according to the methods described in [L. 12]. The morphology and elemental composition of the sample treated in plasma were investigated in the engineering laboratory of D. Serikbayev EKSTU on a JSM-6390LV raster electron microscope – made by JEOL (Japan), with an INCAEnergy energy dispersive microanalyser from "OXFORD Instruments." The microhardnesses of steel samples were measured at the National Research Laboratory for Collective Use of S. Amanzholov EKSU on the device MTC-3 in accordance with Industry Standard 9450-76, with the load on the indenter  $P = 1$  N and the dwell time at this load of 10 s. Tribological sliding friction tests were carried out on a THT-S-BE-0000 high-temperature tribometer in the laboratory of Tomsk polytechnic university (Tomsk, Russia) using the standard "ball-disk" technique (**Figure 2a**) (international standards ASTM G 133-95 and ASTM G 99). The tribological characteristics of the modified layer were characterized by wear intensity and friction coefficient [L. 13, 14]. Abrasive wear samples were tested at the National Research Laboratory for Collective Use of S. Amanzholov EKSU, on the experimental setup for

**Table 1. The chemical composition of the investigated steels**

Tabela 1. Skład chemiczny badanych stali

Steel marks	C	Si	Mn	Ni	S	P	Cr	Cu	Mo
40CrNi	0.36–0.44	0.17–0.37	0.5–0.8	1.0–1.4	<0.04	<0.04	0.45–0.75	<0.3	-
20Cr2Ni4A	0.16–0.22	0.17–0.37	0.3–0.6	3.25–3.65	<0.02	<0.02	1.25–1.65	<0.3	-
34CrNi1Mn	0.3–0.4	0.17–0.37	0.5–0.8	1.3–1.7	<0.04	<0.03	1.3–1.7	-	0.2–0.3

testing abrasive wear when rubbing with not rigidly fixed abrasive particles according to the “rotating roller – flat surface” scheme in accordance with Industry Standard 23.208-79, which coincides with the American ASTM C 6568 standard (**Figure 2 b**). 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.



**Fig.2. Diagram of instruments for tribological testing of samples: a) according to the scheme "ball-disk," b) according to the scheme "rotating roller-flat surface"**

**Rys. 2. Schemat przyrządów do badania tribologicznego próbek: a) zgodnie ze schematem „kulka-dysk”, b) zgodnie ze schematem "obracający się wałek-płaska powierzchnia"**

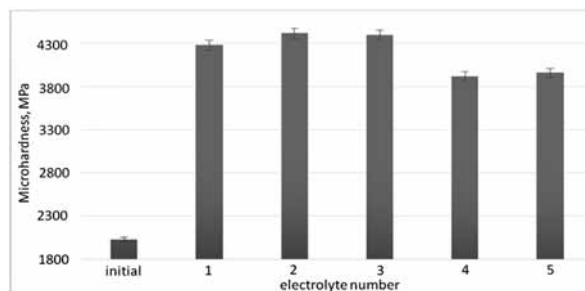
**RESULTS AND ANALYSIS**

For studying the effect of the electrolyte composition on the processes of erosion and oxidation, surface plasma quenching of 40CrNi samples in the considered electrolytes was carried out as indicated in **Table 2**.

**Table 2. The chemical composition of the investigated steels**  
Tabela 2. Skład chemiczny badanych stali

Electrolyte number	Electrolyte composition, %		
	Sodium carbonate	Carbamide	Water
No. 1	10	15	75
No. 2	10	20	70
No. 3	15	15	70
No. 4	15	10	75
No. 5	20	10	70

**Figure 3** shows the dependences of the microhardness of steel 40CrNi on the electrolyte composition. PSH is carried out by exposure to electrolytic plasma for 3 s, followed by cooling in a flow-through electrolyte. It can be seen that the microhardness of the samples increases with an increase in the concentration of carbamide in the electrolyte and reaches 4420 MPa. High hardness is observed in samples treated in electrolytes containing 15% and 20% carbamide. The samples treated in electrolytes containing 10% carbamide and 15–20% sodium carbonate showed the lowest hardness. This is probably due to the decarburization of the surface layer. Thus, carbamide contains carbon and nitrogen in larger quantities than does sodium carbonate, which allows modifying the surface and prevents surface decarburization [L. 15]. The change in the concentration of sodium carbonate does not lead to a significant change in the hardness of the surface.



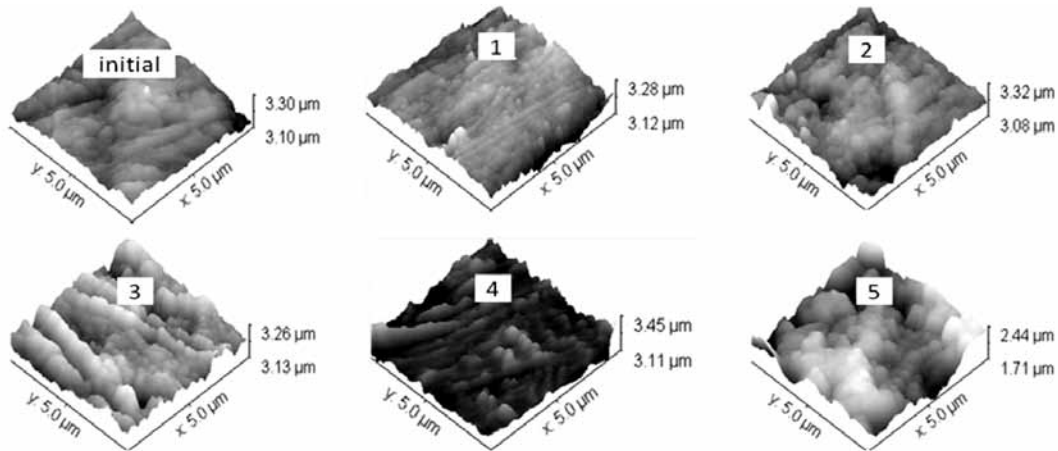
**Fig. 3. The dependence of the microhardness of steel 40CrNi from the electrolyte composition**

**Rys. 3. Zależność mikrotwardości stali 40CrNi od składu elektrolitu**

Studies of the surface morphology carried out on an atomic force spectrometer showed that microscopic irregularities were observed on the surface during surface plasma quenching (**Figure 4**). For a qualitative assessment of asperities, surface roughness was determined.

As is known, roughness refers to the microgeometry of a solid body and determines the most important operational properties of the surface [L. 16–18], primary, wear resistance from abrasion, strength, the density (tightness) of compounds, chemical resistance, and appearance. **Figure 5** shows the dependence of the parameter of the surface roughness of steel samples 40CrNi on the composition of the electrolyte. It can be seen that, after the PSH, the roughness parameter increases. An increase in the concentration of sodium carbonate leads to an increase in the roughness parameter. This may be due to more intense heating with a high concentration of sodium carbonate in the electrolyte.

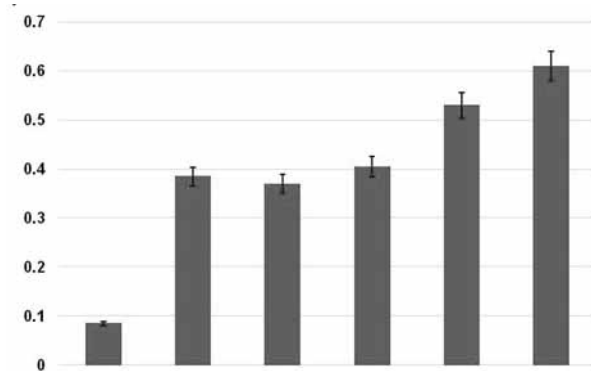
A metallographic analysis of the 40CrNi steel surface confirmed surface irregularities after the PSH and showed that the PSH in electrolytes with a high content of sodium carbonate and a lower content of carbamide is accompanied by the formation of small



**Fig. 4. Images of the surface relief of samples of steel 40CrNi before and after the PSH**

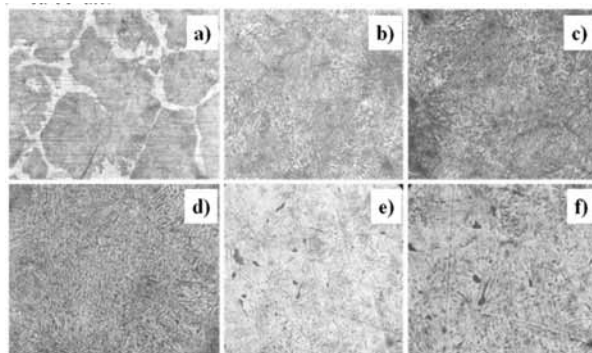
Rys. 4. Obrazy reliefu powierzchniowego próbek stali 40CrNi przed i po PSH

pores on some surface areas (**Figure 6**). A large number of such pores are observed, especially in samples treated in electrolyte No 5. Perhaps this is due to the relatively intense heating of the surface due to the low electrical resistance of the electrolyte containing 10% carbamide and 20% sodium carbonate.



**Fig. 5. Dependence of roughness of steel 40CrNi samples on electrolyte composition**

Rys. 5. Zależność chropowatości próbek stali 40CrNi od składu elektrolitu



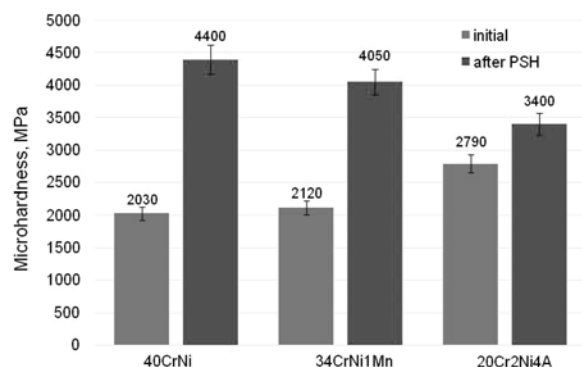
**Fig. 6. The microstructure of the surface of steel 40CrNi before and after the PSH. Initial state (a); in electrolytes No. 1 (b), No. 2 (c), No. 3 (d), No. 4 (e), No. 5 (f)**

Rys. 6. Mikrostruktura powierzchni stali 40CrNi przed i po PSH. Stan początkowy (a); w elektrolitach nr 1 (b), nr 2 (c), nr 3 (d), nr 4 (e), nr 5 (f)

Therefore, it can be concluded that the best from investigated electrolyte composition for electrolyte-plasma surface quenching of steels that does not cause erosion of the surface layer to erosion, oxidation, or decarburization are electrolytes containing up to 15% sodium carbonate and 15% carbamide. In addition, when using this electrolyte, a stable discharge is formed.

Considering that one of the most important properties of the surface layer, which largely affects wear resistance, is hardness [L. 19, 20], changes in the microhardness of the surface layer of steel 40CrNi after PSH in an electrolyte from an aqueous solution containing 15% sodium carbonate and 15% carbamide are studied in this work. **Figure 7** shows a diagram of the microhardness of the surface layer of steels 40CrNi, 20Cr2Ni4A, and 34CrNi1Mn before and after PSH.

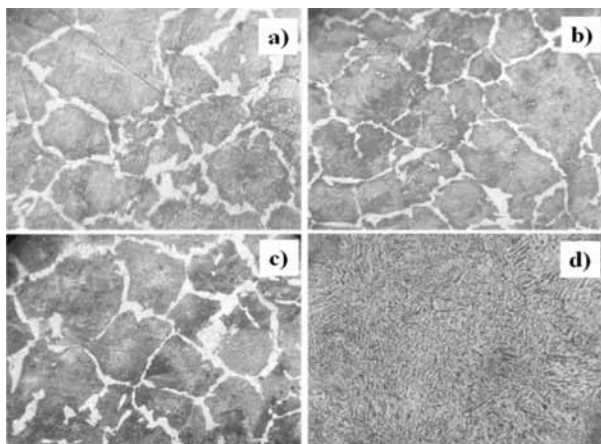
**Figure 8** shows the surface structure of the original (a) and treated samples. Metallographic analysis showed that, in the initial state, steel 40CrNi has a typical ferrite-pearlite structure of pre-eutectoid steel (**Figure 8**). Pearlite has a lamellar structure. Ferrite is predominantly in the form of a fine mesh along the boundaries of



**Fig. 7. Microhardness of steels 40CrNi, 34CrNi1Mn and 20Cr2Ni4A**

Rys. 7. Mikrotwardość stali 40CrNi, 34CrNi1Mn i 20Cr2Ni4A

the former austenitic grains. The amount of ferrite is 16.3%. After the PSH with a heating time of 1 s and 2 s, no changes in the microstructure are observed, i.e. the effect of hardening is due to a high heating temperature is not observed. The images show that, at the PSH with a heating time of 3 s, a fine-grained martensitic structure is formed on the surface.

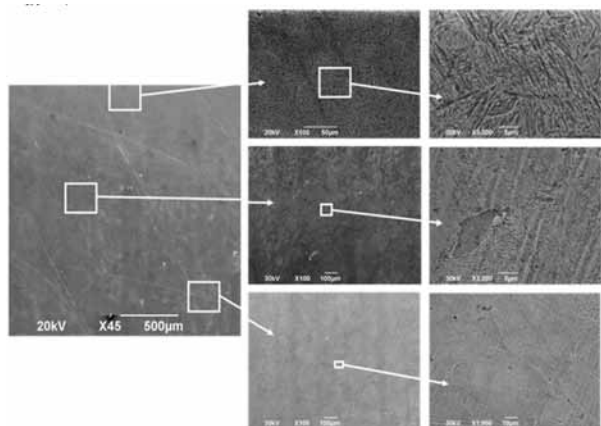


**Fig. 8. The microstructure of structural steel 40CrNi before (a) and after surface plasma hardening at holding time 1 s (b), 2 s (c), 3 s (d)**

Rys. 8. Mikrostruktura stali konstrukcyjnej 40CrNi przed (a) i po plazmowym utwardzeniu powierzchni w czasie 1 s (b), 2 s (c), 3 s (d)

The microstructure of the cross-section of 40CrNi steel after surface plasma hardening is shown in **Figure 9**. From **Figure 9**, it can be seen that the cross-sectional structure of the steel is conventionally divided into 3 zones: Zone 1 – hardened layer, Zone 2 – heat-affected layer, and Zone 3 – matrix.

The hardened layer is a homogeneous fine-grained martensitic structure. As the depth increases, a non-uniform structure is formed in the heat-affected zone, which is martensite and pearlite. Then, this zone moves



**Fig. 9. The microstructure of the cross-section of steel 40CrNi after PSH with a heating time of 3 s**

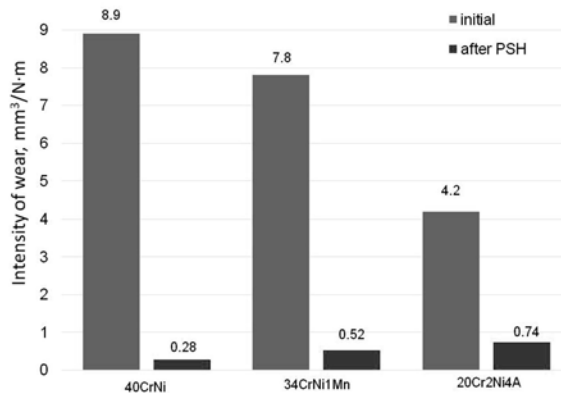
Ryc. 9. Mikrostruktura przekroju stali 40CrNi po PSH z czasem nagrzewania 3 s

to the pearlite-ferritic structure, i.e. to the structure of the matrix. The thickness of the modified layer is 1–1.2 mm.

In the selected modes of the PSH, steel 20Cr2Ni4A and 34CrNi1Mn were also processed. The tests were carried out according to the "ball – disk" scheme, and the path length was 35 m, the speed was 2 cm/s, and the load was 5 N. **Figure 10** shows the wear rates ( $\text{mm}^3/\text{Nm}$ ) for samples of steels 40CrNi, 20Cr2Ni4A, and 34CrNi1Mn before and after PSH. Tests were conducted by the "ball-disk" scheme. It can be seen that all of the treated samples show a significant decrease in wear rate in comparison with the initial one, which indicates a significant increase in the wear resistance of the steels.

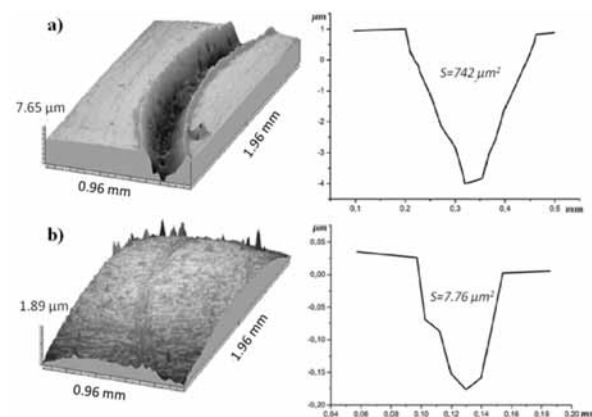
Surface imaging was taken of the contact zone of the initial and processed 40CrNi steel specimen samples the help of a non-contact optical profilometer machine (**Figure 11**).

Assessing the 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 PSH is much smaller compared to the untreated sample.



**Fig. 10. The intensity of wear of samples of steel 40CrNi, 20Cr2Ni4A, and 34CrNi1Mn before and after PSH**

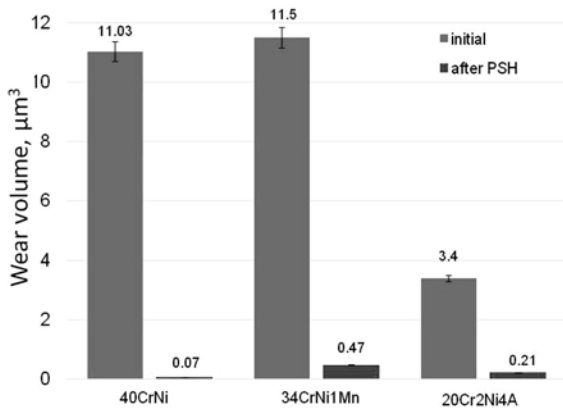
Rys. 10. Intensywność zużycia próbek stali 40CrNi, 20Cr2Ni4A i 34CrNi1Mn przed i po PSH



**Fig. 11. The profiles of the tracks of the original (a) and hardening of the PSH (b) of steel samples 40CrNi**

Rys. 11. Profile torów oryginału (a) i po utwardzeniu PSH (b) próbek stalowych 40CrNi

**Figure 12** shows the amount of the wear of samples of 40CrNi, 20Cr2Ni4A, and 34CrNi1Mn steels before and after the hardening of the PSH. It is seen that the amount of the wear of the hardened samples is less than that of the non-hardened samples, which indicates an increase in the resistance to abrasive wear of the steels 40CrNi, 20Cr2Ni4A, and 34CrNi1Mn after surface hardening.



**Fig. 12. Resistance of samples of steels 40CrNi, 20Cr2Ni4A, and 34CrNi1Mn to abrasive wear**

Rys. 12. Odporność próbek stali 40CrNi, 20Cr2Ni4A i 34CrNi1Mn na zużycie ścierne

Thus, the main advantage of the PSH is the possibility of obtaining a modified martensite layer with carbide particles on the surface of the steel. In this case, the viscous core of the material does not change, which consists of a ferritic-pearlitic structure. The formation of

a modified layer of fine-grained martensite with carbide particles in the surface layers will positively affect the performance properties of the parts, because the small carbides save the matrix from abrasion.

## CONCLUSIONS

When analysing the experimental results obtained in the work, we can draw the following conclusions:

- The best from investigated electrolyte composition for surface plasma quenching of steels that does not lead to erosion, oxidation, and decarburization of the surface layer are electrolytes containing up to 15% sodium carbonate and 15% carbamide.
- An increase in the concentration of sodium carbonate in the electrolyte leads to an increase in the surface roughness parameter.
- After the PSH, a modified layer with a thickness of 1–1.2 mm with high hardness and wear resistance is formed, consisting of a hardened layer of fine-grained martensite and an intermediate layer of perlite and martensite.
- After the PSH with a heating time of 3 min, the microhardness of steels 40CrNi and 20Cr2Ni4A doubles, and the steel 34CrNi1Mn increases 1.6 times, depending on the initial state.
- The wear resistance of all steel samples increases, on average, up to 30 times. The high wear resistance of steels after the PSH is possibly associated with the formation of fragmented martensite with dispersed carbides.

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