

# Influence of electrolytic-plasma surface quenching on the structure and strength properties of ferritic-pearlite class wheel steel

B.K. Rakhadilov<sup>1,2</sup>, Y.Y. Tabiyeva<sup>\*,1,3</sup>, G.K. Uazyrkhanova<sup>3</sup>,  
L.G. Zhurerova<sup>2,3</sup>, D. Baizhan<sup>1</sup>

<sup>1</sup>S. Amanzholov East-Kazakhstan State University, Ust-Kamenogorsk, Kazakhstan

<sup>2</sup>Limited partnership «PlasmaScience», Ust-Kamenogorsk, Kazakhstan

<sup>3</sup>D. Serikbayev East-Kazakhstan State Technical University, Ust-Kamenogorsk, Kazakhstan

E-mail: erkezhan.tabieva@mail.ru

DOI: 10.29317/ejpfm.2020040208

Received: 17.04.2020 - after revision

This paper examines the influence of electrolyte-plasma surface hardening on the structure and microhardness of wheel steel mark 2. In the work electrolyte-plasma surface quenching was carried out in an electrolyte made from an aqueous solution of 10% carbamide  $(\text{NH}_2)_2\text{CO}$ +20% sodium carbonate  $\text{Na}_2\text{CO}_3$ . The work investigated the strength limit, fluidity and wear intensity of the wheeled steel after electrolyte-plasma surface quenching. After electrolytic-plasma surface quenching, a batch, high-temperature plate and low-temperature plate martensite is formed on the surface of the sample. Investigations have been carried out on microhardness determination on cross-section of wheel steel samples after quenching in aqueous solution of electrolyte. It is found that after electrolytic-plasma surface quenching, the microhardening values of this hardened surface layer increased on  $\approx 3$  times compared to the steel matrix, and the thickness of the hardened layer is 1000-1500  $\mu\text{m}$ . According to the results of the scanning transmission electron microscopy, the electrolyte-plasma surface quenching caused a change in the morphological constituents of steel mark 2. In the initial state, the matrix of steel is a  $\alpha$ -phase, the morphological components of which are fragmented ferrite, unfragmented ferrite and pearlite.

**Keywords:** electrolytic-plasma surface quenching, wheel steel, microhardness, morphology, martensite, transmission electron microscopy.

## Introduction

The development and introduction of new resource-efficient technologies that increase the quality of products largely determine the effective development of industrial sectors. The stable and efficient operation of the machine-building industry is impossible without the use of new technologies, which provide the necessary complex of strength and plastic properties of the structural steels. This requires an understanding of the nature of the processes in steels. The elucidation of the physical mechanisms of formation and evolution of structural-phase states in steels is one of the important tasks of modern physics of condensed state and material science, because it underpins the development and creation of effective ways to improve performance. In most cases, the durability of machines and mechanisms depends on the durability of the parts, many of which are subject to significant impact variables. In these cases, the parts shall be principally of high strength and hardness of the surface layer combined with sufficient core viscosity. This can be achieved through the use of various surface hardening techniques. Surface hardening is one such method. Surface hardening is achieved by the short-term heating of the surface layer of metal to the temperature of quenching and subsequent rapid cooling. Nowadays, various methods of surface quenching are used in industrial production [1-5], one of which is an electrolyte-plasma surface quenching [6-11], characterized in that the entire surface of the part is heated in solution. At the same time, heating takes place fairly quickly and depending on the time of heating it is possible to adjust the depth of the quenching layer. However, the main attention was paid to the influence of surface hardening on mechanical and tribological properties, and there was almost no analysis of the effect on the structural-phase state of the material. The purpose of this work is to investigate the influence of electrolyte-plasma surface injection on the structure and strength characteristics of wheeled steel.

## Experimental procedure

In this work EPSQ was subjected to samples of steel mark 2, used for the manufacture of locomotive wheel sets in accordance with the requirements of GOST 398-96. The chemical composition of steel: 0.55-0.65% C; 0.5-0.9% Mn; 0.22-0.45% Si; No more 0.1% V; No more 0.03% S; No more 0.035% P; the rest of Fe, also the permissible mass fraction (%): Ni  $\leq$  0.25, Cr=0.20, Cu=0.30 to GOST 398-96.

Blanks of steel samples of mark 2 for study were cut out of a bandage in the form of a parallelepiped measuring  $15 \times 15 \times 10 \text{ mm}^3$ . The technology of preliminary heat treatment of steel wheels provides for their hardening and subsequent tempering. In this work, in its initial state, steel mark 2 was heat-treated by quenching at 890-920 °C (exposure 2 h) with subsequent tempering at 580-620 °C (exposure 2.5 h, cooling in warm water at 30-60 °C) [12]. EPSQ was carried out at the electrolyte-plasma treatment facility developed by the authors of works [12-13]. A schematic diagram of the installation for the EPSQ is shown

in (Figure 1). The power source was a powerful rectifier, giving a maximum of 360V/60A output in the form of direct current. Samples were processed by rapid heating for 2 s and then cooling in a flow-through electrolyte. A water solution of urea and sodium carbonate was chosen as the electrolyte. Technological parameters of electrolytic-plasma surface quenching: the processing time was 2 seconds,  $T_{max} = 850-900\text{ }^{\circ}\text{C}$ ;  $U = 300\text{V}$ ;  $I = 40\text{A}$ ; electrolyte composition (% mass): 10% carbamide  $(\text{NH}_2)_2\text{CO}$  + 20% sodium carbonate  $\text{Na}_2\text{CO}_3$  + 70% water.

Electrolyte-plasma surface quenching of the steel was carried out in the cathode mode in electrolyte-plasma treatment machine, the scheme (Figure 1a) and processing (Figure 1b) shown in Figure 1.

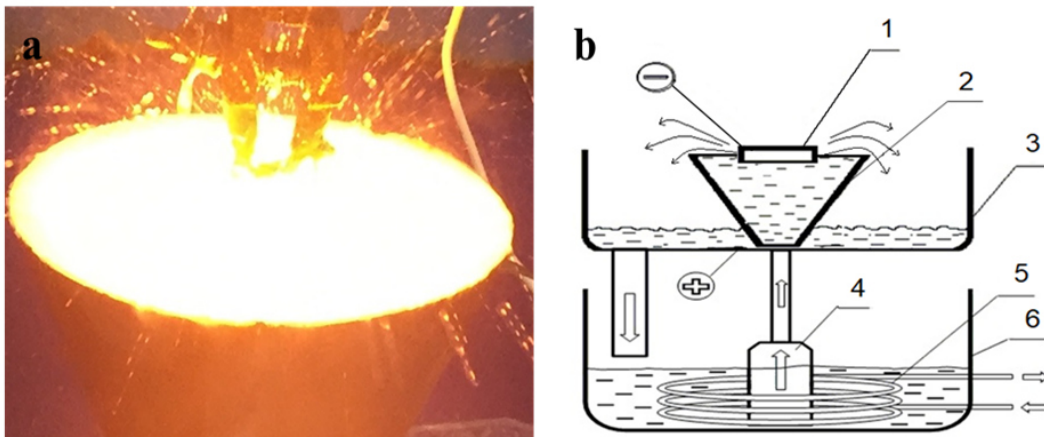


Figure 1. The process of surface quenching the sample with an electrolyte plasma (a) and the functional scheme of the installation (b) [14]: 1-in-process part; 2-conic stainless steel electrolytic cell; 3-bottom plate; 4-pump; 5-heat exchanger; 6-bath filled with electrolyte.

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 the 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 the 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  $\text{CuK}\alpha$  radiation. Test samples for abrasive wear was performed on an experimental setup for testing for abrasive wear according to the scheme "rotating roller - flat surface" in accordance with GOST 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 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 GOST 23.208-79 which coincides with the American standard ASTM C 6568.

## Results and Discussion

A study of the structure and properties of wheel steel mark 2 before and after EPPI showed that after electrolyte-plasma surface hardening, the mechanical

properties of wheel steel increase. The structural-phase conditions of the toughened surface layers of steel of mark 2 were investigated to determine the structural factors affecting wear, hardness and other characteristics of the steels.

Table 1 shows the testing results of steel mark 2. It has been determined that the strength limit and the yield stress of steel mark 2 are increased after the EPSQ, although only the surface layer of 1-1.5 mm thickness has been modified. Symbols in this table:  $\sigma_B$  - tensile strength (temporary resistance);  $\sigma_{0.2}$  - yield strength;  $\delta$  - elongation after rupture;  $\psi$  - relative narrowing at break.

Table 1.  
Strength characteristics of steel mark 2.

Material	$\sigma_B$	$\sigma_{0.2}$	$\delta$	$\Psi$	HV
	MPa		%		MPa
Before EPSQ	458	315	14	22.5	1448
After EPSQ	569	352	16	27	4200

Studies have shown that, in the initial state, the matrix of steel is a  $\alpha$ -phase, a solid solution of carbon and alloying elements in  $\alpha$ -Fe with an OCC crystalline lattice. The morphological components of the  $\alpha$ -phase are the plate pearlite and ferrite Figure 2 (a-c). The plate pearlite, which has a 35% volumetric fraction of PV, which is almost perfect (Figure 2a), is present in the form of a non-fragmented (Figure 2b) and fragmented (Figure 2c). The bulk portion of non-fragmented ferrite is  $\approx 10\%$ , and the fragmented is  $\approx 55\%$ . Volume fractions were calculated using the method based on the Cavalieri-Aker-Glagolev principle [11]. It postulates the relationship between the shares of area ( $P_S$ ) and volume ( $P_V$ ):

This is one of the fundamental relations of stereology postulated by Saltykov [11].

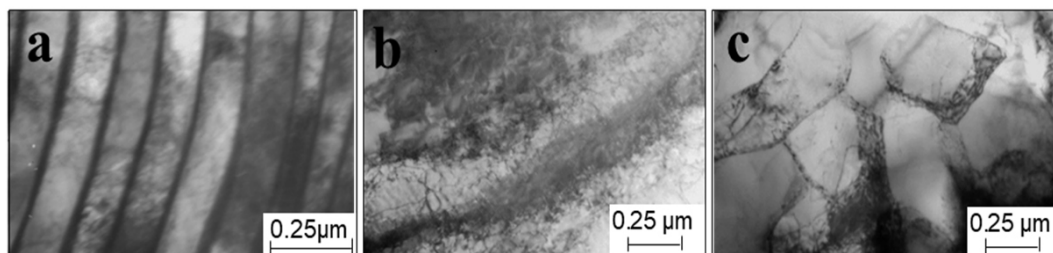


Figure 2. Types of morphological constituents in steel of mark 2 in the initial state: a-Plate pearlite; b-Non-fragmented Ferrite; c-fragmented Ferrite.

Surface quenching has led to martensitic transformation, that is to the formation of packet-plate martensite: packet and plate (low temperature and high temperature). Packeted martensite (Figure 3a) is a structural formation consisting of a set of nearly parallel crystals (ribs) of elongated shape forming a packet. The formation of the packet martensite appears to have come from a fragmented ferrite. This is indicated by the fact that the bulk fraction of the packet martensite is 60%, that is, almost as much as the original fragmented ferrite was. The low-temperature plate martensite, which has a volume fraction of 10%, is sufficiently large, separately arranged, the martensite (plate) crystals with a dispersion structure (Figure 3b). A comparison with the initial state of steel shows that the laminated low-temperature

martensite was most likely formed from non-fragmented ferrite, which also had a 10% volume fraction. High temperature plate martensite, with a volume of 30%, represents large, separate martensite crystals (plates), often extending through all grains as well as crystals of arbitrary shape, which have no clear cut and no separate partition boundaries (Figure 3c). It's probably formed from a lamellar pearlite.

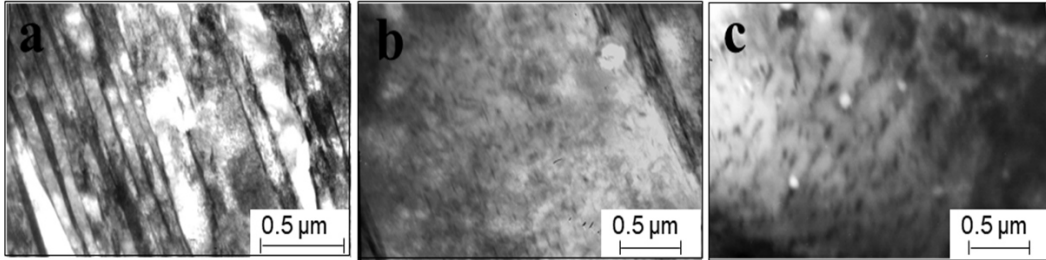


Figure 3. Types of morphological constituents in steel marks of steel 2 after electrolytic-plasma surface quenching: a) batch (trunk) martensite; b) laminated low-temperature martensite; c) laminated high-temperature martensite.

The tribological characteristics of the specimens before and after EPSQ were characterized by wear and tear (Table 2). After the EPSQ of the samples, there is an increase in wear resistance under dry friction conditions.

Table 2.

Wear Intensities of steel mark 2 before and after EPSQ.

No.	Name of the samples	Intensity of wear, $\text{mm}^3/(\text{H}\cdot\text{m})$
1	Source	$4.83 \times 10^{-4}$
2	After EPSH, 2 s	$2.04 \times 10^{-4}$

Studies have shown that surface hardening of steel 2 subjected to electrolyte-plasma surface hardening in an electrolyte plasma, structural changes were detected.

Figure 4 (a-c) shows the microstructure of the steel cross section after treatment in an electrolyte containing an aqueous solution of 10% carbamide  $(\text{NH}_2)_2\text{CO}$  and 20% sodium carbonate  $\text{Na}_2\text{CO}_3$  with a treatment time of 2 seconds at a temperature of  $860^\circ\text{C}$ . As can be seen from Figure 4, the electrolytic-plasma surface quenching led to a change in the microstructure of the cross section, where the zoning of structures typical of electrolyte-plasma treatment is visible. The cross-sectional structure consists of 3 zones: 1 zone - a zone of surface hardening with a thickness of 1000-1500  $\mu\text{m}$ , 2 zone - a zone of thermal influence, 3 zone - a matrix.

As is known, one of the most important properties of the surface layer, which significantly affects the strength characteristics, is microhardness, the value of which in the initial state (matrix) of steel mark 2 is  $\approx 140$  HV. In this work, we studied the changes in the microhardness of a specimen of steel mark 2 over a cross section after electrolytic plasma surface quenching. According to the obtained results, shown in Figure 5, the average microhardness in the surface quenching zone is  $\approx 420$  HV, in the heat-affected zone it is  $\approx 260$  HV and, accordingly, in the steel mark 2 matrix, the microhardness remains unchanged.

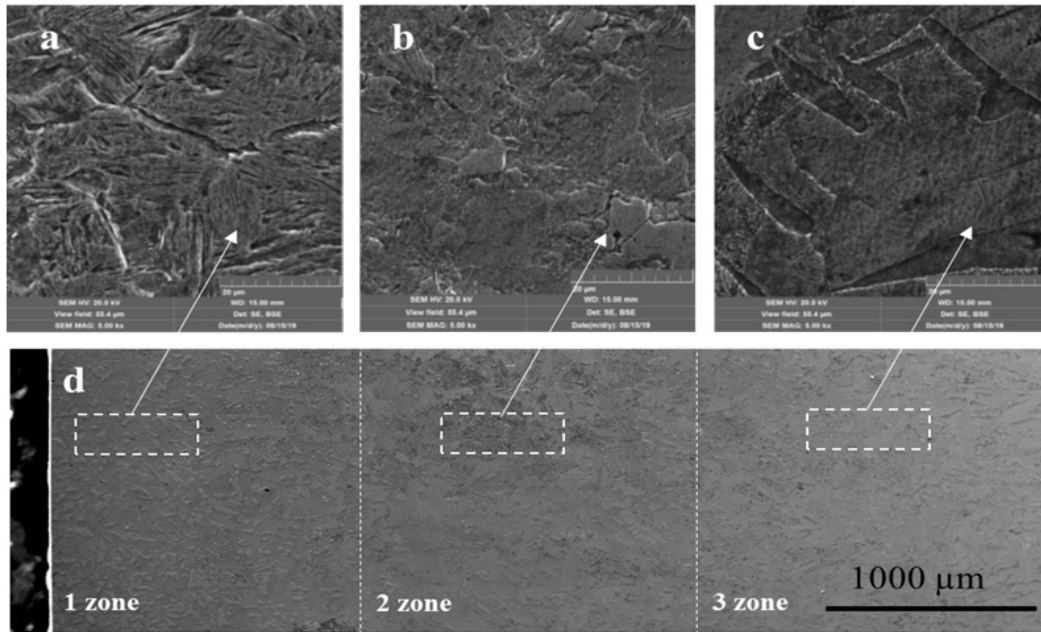


Figure 4. Pictures of the microstructure along the cross section of steel mark 2 after electrolytic-plasma surface quenching: a) a hardened layer; b) a transition layer; c) non-hardened layer; d) general view.

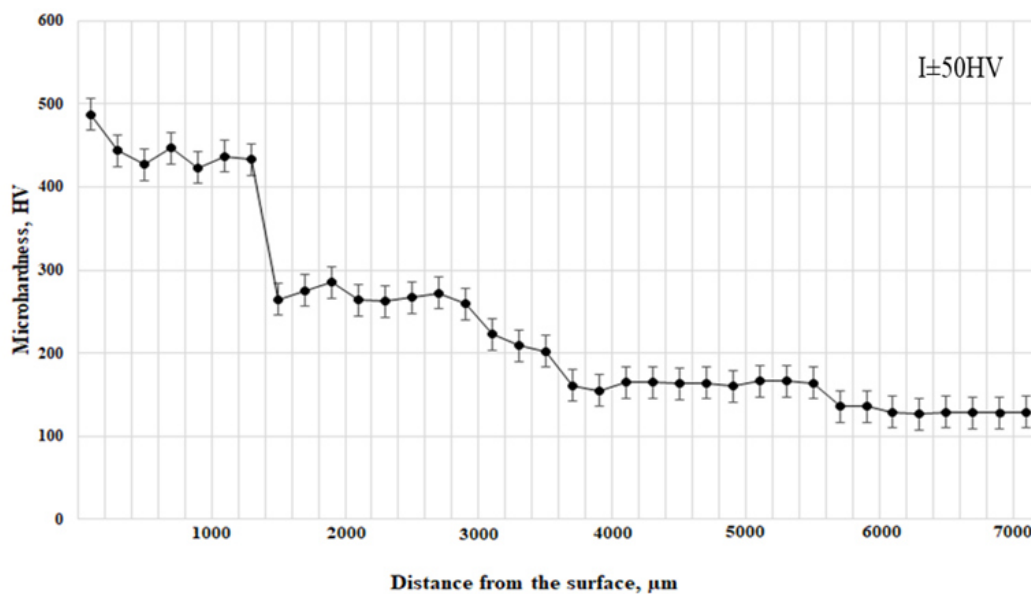


Figure 5. Distribution of microhardness over the cross section of steel mark 2 after electrolytic-plasma surface quenching.

## Conclusion

Analyzing the results obtained on the phase composition, fine structure and mechanical properties of the wheel steel mark 2 before and after electrolytic-plasma surface quenching, the following main conclusions can be drawn:

- It is established that in its initial state, matrix of steel 2 represents  $\alpha$ -phase the volume ratio of unfragmented ferrite is  $\approx 10\%$  and 55% of fragmented, perlite with a volume of  $\approx 35\%$ ;

- It was found that the morphological components of the structure of steel mark 2 after EPSH on  $T_{max} = 850-900^\circ\text{C}$  and the time of exposure 2 s: martensite in the form of packet martensite with a share of volume 60%, Lamellar cold and lamellar

temperature martensites with volumetric fractions  $\approx 10\%$  and  $\approx 30\%$  respectively;

- It was found that the process of electrolytic-plasma surface quenching leads to a change and hardening of the surface layer of grade 2 steel, the thickness of the hardened layer is  $\approx 1000-1500 \mu\text{m}$ , and the microhardness increases by 3 times.

## 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 (BR 05236748).

## References

- [1] L. Wang et al., *Materials Science and Engineering A* **359** (2003) 31-43.
- [2] O.P. Ostash et al., *Materials Science* **44**(4) (2008) 34-48.
- [3] E.I. Meletis et al., *Surface and Coatings Technology* **150** (2002) 246-256.
- [4] M. Skakov et al., *Materials Testing* **57**(4) (2015) 360-364.
- [5] M. Lobanov et al., *The Physics of Metals and Metallography* **117**(3) (2016) 254-259.
- [6] J. Yi et al., *IEEE Transactions on Control Systems Technology* **3** (2012) 663-676.
- [7] A. Albou et al., *Scripta Materialia* **68** (2013) 400-403.
- [8] M.G. Shtaiger et al., *Modern technology. System analysis. Modeling* **2** (2018) 98-106.
- [9] M.V. Grechneva, *Proceedings of Irkutsk State Technical University* **21**(5) (2017) 10-23. (in Russian)
- [10] S. Kusmanov et al., *Materials Chemistry and Physics* **175** (2016) 164-171.
- [11] A.R. Rastkar et al., *Surf. Interface Anal.* **44** (2012) 342-351.
- [12] B. Rakhadilov et al., *Materials Science and Engineering* **142** (2016) 1-7.
- [13] M. Skakov et al., *Applied Mechanics and Materials* **682** (2014) 104-108.
- [14] Y. Tabiyeva et al., *Eurasian Journal of Physics and Functional Materials* **3**(4) (2019) 355-362.