ABSTRACT

of the dissertation for the degree of Doctor of Philosophy (PhD) in the specialty 6D060400 - "Physics"

Satbayeva Zarina Askarbekovna

«Structure formation in alloy steels during electrolyte-plasma surface hardening»

Work General characteristics. The dissertation work is devoted to experimental studies of changes in the structural-phase states and tribological properties of the surface layers of steels 40KHN, 20KH2N4A and 34KHN1M during electrolytic-plasma surface hardening, as well as the development of a resource-saving method of electrolytic-plasma hardening of structural alloyed steels. The work presents the results of a study of the influence of the technological parameters of the developed method of plasma-electrolytic surface hardening on the structural-phase states and tribological and mechanical characteristics of alloy steels 40KHN, 20KH2N4A and 34KHN1M. Based on experimental work carried out using proven research methods and standard tribo-mechanical testing methods, it was found that electrolyte-plasma surface hardening can significantly improve mechanical and tribological properties due to the formation of modified layers on the surface of the material consisting of both primary and secondary hardening phases.

Topic relevance. Continuous improvement of the operational characteristics of equipment and industrial of machinery, their mainly provided with an increase in their power and productivity, which requires an intensification of the improvement of the performance characteristics of these machines and parts. The condition of the working surface layer, where damage is actively developing, which reduces the service life of a part of any equipment, gives an assessment of the technical and economic indicators of the operation of the equipment. To ensure high cyclic durability, high wear resistance, and reduced sensitivity to stress concentrators, it is necessary to create a gradient of properties in the hardened section of the part, providing for the presence of a hard and wear-resistant surface, a viscous but durable core and compressive stresses in the surface layer. The realization of such a complex of properties is possible when using the method of surface heat treatment.

Currently, along with metallurgical methods and heat treatment in the conditions of manufacturing plants, local surface hardening of wear surfaces using various technologies is also being considered to increase the service life of gears. 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, as well as reduce their material consumption. At the same time, only the most loaded working surface of the part is strengthened, leaving the core intact. At the same time, 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 make it possible to achieve higher operational properties and the quality of hardening. Currently, high-frequency, gas-flame, plasma, electron beam and laser processing are widely used in industry for surface thermal hardening of gears. At the same time, of all the existing methods of hardening, according to its technical and economic indicators, it finds wide and effective application plasma surface hardening. One of the varieties of plasma surface hardening is electrolyte-plasma hardening (EPH). The main distinguishing feature of the electrolyte-plasma hardening method is lower cost, availability of technological equipment and consumables, large size of the hardened zone and high cooling rate compared to traditional methods of plasma surface hardening. Its essence consists in thermal phase and structural transformations occurring during rapid concentrated heating of the working surface of the part by plasma action, followed by rapid cooling due to heat removal deep into the material and the effect of a flowing electrolyte on the heated surface of the material. The resulting quenching-type structures have high hardness, wear resistance and fracture resistance.

Analysis of the characteristics of existing methods and technologies for modifying the surface of structural steels shows that the task of developing a resource-saving method for surface electrolyte-plasma hardening of steel parts for industrial, tool and machine-building purposes with a predominantly high service life is modern and relevant.

The work aim is to study the regularities of the formation of structural-phase states and changes in the mechanical and tribological characteristics of alloy steels during electrolyte-plasma surface hardening.

To achieve this goal, it is necessary to solve the following main **tasks**:

1. To develop a method and determine the optimal mode of electrolyte-plasma surface hardening of alloy steels 40KHN, 20KH2N4A, 34KHN1M;
2. To investigate the change in the structural-phase state of surface layers of alloy steels 40KHN, 20KH2N4A, 34KHN1M electrolytic-plasma surface hardening;
3. To study the influence of technological parameters of electrolyte-plasma surface hardening on hardness, wear resistance and corrosion resistance of alloy steels 40KHN, 20KH2N4A, 34KHN1M;
4. To study the effect of electrolyte-plasma hardening on the thin structure of the surface layer of alloy steel.

Study object – alloy steels of the 40KHN, 34KHN1M, 20KH2N4A grades before and after surface electrolyte-plasma hardening.

Research Subject – features of the electrolyte-plasma hardening process, structural-phase states and tribological properties of the hardened layers of structural steels 40KHN, 34KHN1M, 20KH2N4A.

Research methods. To study the structural and phase states of the hardened surface layer obtained by the method of electrolyte-plasma hardening, the following experimental methods were used: X-ray diffraction analysis, scanning electron and transmission electron microscopy, profilometry. The mechanical and tribological characteristics of the hardened layer were determined by measuring microhardness, wear resistance tests according to the "ball-disc" scheme, as well as tests for abrasive wear.

All the studies of this work were carried out on modern experimental equipment of the Scientific Research Center "Surface Engineering and Tribology", the National Scientific Laboratory of Collective Use of the Sarsen Amanzholov East Kazakhstan University, the laboratory of engineering profile "IRGETAS" of the D. Serikbayev East Kazakhstan Technical University, Tomsk State University of Architecture and Civil Engineering (Tomsk, Russia).

Work Scientific novelty:

– a new method of hardening of alloy steels has been developed, which is carried out in an electrolyte based on an aqueous solution of sodium carbonate and carbamide by local plasma action on the surface of the processed material when voltage is applied between the processed material and a 320V liquid electrolyte cathode for 2 seconds and cooling when the voltage is turned off due to heat removal deep into the material and the action of a directed flow of electrolyte located in the circulation mode.

– for the first time, systematized experimental data on the effect of electrolyte-plasma surface hardening on the structure, phase composition and tribological properties of structural alloy steels 40KHN, 34KHN1M, 20KH2N4A were obtained;

– for the first time morphological features of the fine structure and quantitative parameters of the dislocation structure of 34KHN1M alloy steel before and after electrolytic-plasma surface hardening were established.

The main provisions submitted for protection:

1. A method of electrolyte-plasma surface hardening of alloy steels has been developed. The developing new method of hardening alloy steels, which is carried out in an electrolyte based on an aqueous solution of sodium carbonate and carbamide by local plasma action on the surface of the processed material when voltage is applied between the processed material and the liquid electrolyte cathode 320V for 2 seconds and rapid cooling when the voltage is turned off due to heat removal deep into the material and the effect of a directed flow of electrolyte on the heated surface, allows to obtain a modified surface layer ~0.5-1.5 mm thick consisting of α'-phase, γ-phases and carbide M_3C.

2. Modification of the microstructure and properties of alloy steels during electrolyte-plasma surface hardening. After electrolytic-plasma surface hardening, depending on the degree of alloying of steels, the hardness on average of chromium-nickel and chromium-nickel-molybdenum steels increases by 1.5-2 and ~3 times, and the wear resistance parameter has a certain dependence on the carbon content in the steels, so the wear resistance values of 40KHN, 34KHN1M and 20KH2N4A steels increased by 10 times, ~6 times and 3.5 times, respectively, compared to the original samples.

3. Morphological features and quantitative parameters of the dislocation structure of 34KHN1M steel before and after electrolytic plasma surface hardening. The EPH of steel 34KHN1M promotes the formation of a thin structure consisting of pack and lamellar martensite with volume fractions of 60% and 40%, residual austenite, cementite and complex carbide $M_{23}C_6$, the formation of which contributes to an increase in internal shear stress from 295 MPa to 370 MPa and thereby leads to hardening of the surface of the material by increasing the scalar density of dislocation from $2{,}20 \cdot 10^{10}$ cm^{-2} to $\rho=3{,}47 \cdot 10^{10}$ cm^{-2} and its high value compared to the excess dislocation density, which is $\rho_{\pm}=1{,}97 \cdot 10^{10}$ cm^{-2}in the modified layer.

Scientific and practical significance. The obtained results of theoretical and experimental studies provide new, deeper insights into the process of formation of a modified surface layer in structural alloy steels during electrolyte-plasma surface hardening. This work is great practical importance, since the developed method of electrolyte-plasma surface hardening allows to obtain a modified surface layer on structural alloy steels with improved physical and mechanical properties. The introduction of the developed method, which increases the durability of parts, into machine-building production gives a technical, economic and environmental effect due to the use of simple equipment, not expensive and environmentally friendly electrolyte based on carbamide and sodium carbonate, reducing the duration of the process, increasing labor productivity and reducing the environmental burden on the environment.

The developed method of electrolytic-plasma surface hardening is protected by the patent of the Republic of Kazakhstan for the utility model "Method of hardening steel products" (utility model No. 4891 dated 28.04.2020) and "Installation for plasma surface hardening of steel and cast-iron parts" (No. 5354 dated 04.09.2020). The obtained research results can be useful in choosing the types and modes of hardening treatments of structural steel parts.

Connection of work with scientific-research projects. The topic of the dissertation submitted for defense "Structure formation in alloy steels during electrolytic-plasma surface hardening" corresponds to the priority direction of the development of science "Power Engineering and mechanical engineering", and the work was carried out under the State program, within the framework of grant funding: AP05134936 "Development of technology of electrolytic-plasma surface hardening to increase the durability of heavily loaded gears", performed by on the basis of SRC "Surface Engineering and Tribology" of Sarsen Amanzholov East Kazakhstan University.

Author personal contribution. The author's personal contribution consists in conducting an experiment on electrolyte-plasma surface hardening, analyzing literary data, conducting electron microscopic, X-ray structural studies, carrying out work to determine the hardness, wear resistance of steels, as well as statistical processing of the results. The formulation of the problem, the analysis of the results obtained and the formulation of the main conclusions were carried out jointly with scientific consultants.

The degree of reasonableness and reliability of the results obtained in the work is provided by:

The reasonableness and reliability of the results are ensured by the fact that when they were obtained, proven standard research methods and modern accurate measuring instruments and installations were used, the volume and statistics of experimental data and their comparison with the previously obtained experimental results of well-known scientists of the CIS and far abroad. The research results have been published in scientific journals, reported and discussed at international conferences.

Approbation of the work results. The main results were reported at the 11th International Symposium "Powder Metallurgy: Surface Engineering, New Powder

Composite Materials. Welding", Minsk, Belarus, April 10-12, 2019; 11th International Scientific Conference "Chaos and Structures in Linear Systems. Theory and Experiment", Karaganda, November 22-23, 2019; 28st International Conference on Metallurgy and Materials «Metal 2019», Brno, Czech Republic, may 22nd-24th 2019; 14th International conference «Gas Discharge Plasmas and Their Applications», Tomsk, Russia, September 15-21, 2019; International Scientific and Practical Conference "Materials Science, Mechanical Engineering and Power Engineering: Problems and prospects of development", Barnaul, Russian Federation, June 27-28, 2019; International Scientific and Practical Conference "Materials Science and Metallurgical Technologies", Chelyabinsk, Russian Federation, October 1-3, 2019.; 29st International Conference on Metallurgy and Materials «Metal 2020», Brno, Czech Republic, may 20nd-22th 2020.

In addition, the main scientific results were reported and discussed at scientific seminars of the SRC "Surface Engineering and Tribology" of the Sarsen Amanzholov East Kazakhstan University (2018-2021), at the Department of Physics of the Sarsen Amanzholov East Kazakhstan University, Ust-Kamenogorsk, (2020-2021).

Publications. 14 co-authored publications have been published on the topic of the dissertation, of which: 3 articles have been published in journals recommended by the Committee for Quality Assurance in the Field of Science and Higher Education of the Ministry of Science and Higher Education of the Republic of Kazakhstan, 3 articles have been published in journals included in the Scopus and Web of Science databases, 5 articles in collections of materials of international conferences, as well as 1 monograph in co-authorship and 2 utility model patents of the Republic of Kazakhstan.

Structure and dissertation scope. The work consists of an introduction, four sections, a conclusion and a list of sources used. It is presented on 119 pages, contains 50 figures, 12 tables and a list of used sources from 183 titles.