ABSTRACT
of the dissertation by Maulet Meruyert submitted for the degree of Doctor of Philosophy (PhD) in the educational program 8D05301 – Physics on the topic "Regularities of formation of structure and properties of detonation coatings of Ni-Cr-Al System"

General Characteristics of the Study. The dissertation is devoted to the study of the regularities of structure and property formation of detonation coatings in the Ni-Cr-Al system. The morphology and elemental composition of NiCr-Al coatings were studied by varying the filling volume of the detonation barrel with explosive gas to 25%, 30%, 40%, and 50%. As a result, a method was established for obtaining gradient NiCr-Al-based coatings with controlled elemental distribution using the detonation method. Comparative studies were conducted on the mechanical, tribological, and heat resistance properties of homogeneous and gradient NiCr-Al detonation coatings with elemental distributions. The results obtained in the dissertation are important for the development of NiCr-Al-based protective coatings intended for components exposed to high-temperature oxidation, aggressive corrosive environments, and intensive wear.

Relevance of the Research Topic. The application of protective coatings to the surfaces of components operating at high temperatures is currently widespread. NiCr-Al coating is widely used in the energy sector and for the protection of gas turbine blades as a heat-resistant coating. However, to ensure the formation of a sufficient amount of oxide protective layers on the coating surface, it is crucial to improve the coating application methods and techniques. Among the technologies for applying protective coatings, detonation spraying is considered one of the most promising methods. This technology utilizes the energy of explosive gases to produce coatings with low porosity and high adhesive strength. However, the development of heat-resistant NiCr-Al-based coatings using detonation spraying technology has not been fully explored. In this regard, the topic of the dissertation is dedicated to the study of the structure and properties of NiCr-Al-based detonation coatings, with a particular emphasis on stabilizing the aluminum content in the coating composition, which is a critical issue.

Aim of the Study: to investigate the regularities of structure and property formation of NiCr-Al-based detonation coatings and to develop a method for producing gradient NiCr-Al-based coatings with enhanced mechanical and corrosion properties using the detonation method.

To achieve the objective of the study, the following **tasks** must be addressed:

– to study the formation of the structure of NiCr-Al-based coatings during detonation spraying;

– to develop a method for obtaining gradient NiCr-Al-based coatings with controlled elemental distribution using the detonation spraying method;

– To conduct a comparative study of the mechanical, tribological, and heat resistance properties of homogeneous and gradient NiCr-Al-based coatings with elemental distributions obtained by detonation spraying.

Objective of the Study – NiCr-Al-based coatings obtained by the detonation spraying method.

Subject of the Study – The structural-phase state, as well as the mechanical-tribological, corrosion, and heat resistance properties of NiCr-Al coatings obtained by the detonation spraying method.

Research Methods. To accomplish the stated objectives, the following modern experimental methods were used to study the composition, structure, and properties of the coatings: scanning electron microscopy (SEM); X-ray phase analysis (XRD); micro- and nanoindentation methods; adhesion testing using the pull-off method; and tribological tests according to the "ball-on-disk" and "linear reciprocating wear" schemes.

During the course of the work, research equipment from the Scientific Research Center "Surface Engineering and Tribology" at Sarsen Amanzholov East Kazakhstan University, Academician E.A. Buketov Karaganda University, Wrocław University of Science and

Technology (Wrocław, Poland), and AGH University of Science and Technology (Kraków, Poland) was used.

Scientific Novelty of the Research:

– For the first time, the regularities of structure formation in NiCr-Al-based coatings were identified depending on the variation in the filling volume of the detonation barrel with explosive gas during detonation spraying. As a result of comprehensive research, a method was developed for obtaining gradient NiCr-Al coatings with enhanced mechanical and corrosion properties using the detonation spraying technique and controlled elemental distribution. The distinctive feature of this method lies in obtaining a gradient NiCr-Al-based coating on a single-doser detonation unit by varying the filling volume of the detonation barrel with an oxygen-acetylene mixture. This method is protected by a utility model patent of the Republic of Kazakhstan titled "Method of Obtaining Functionally Graded Coating" (No. 8922, published on 07.03.2024);

– For the first time, comprehensive comparative studies were conducted on the mechanical, tribological, and heat resistance properties of gradient and homogeneous NiCr-Al(20%) coatings with elemental distributions obtained by the detonation spraying method.

Key Provisions Submitted for Defense:

1. *Formation regularities of NiCr-Al-based coatings by detonation spraying method*. The phase composition of the NiCr-Al(20%) coating during detonation spraying can be flexibly controlled by varying the volume of the explosive gas mixture. When the detonation barrel is filled with 25% and 30% of an oxygen-acetylene explosive gas mixture with a ratio of $O_2/C_2H_2 = 1.856$, a coating consisting of $CrNi_2$, Al, and NiAl phases is formed. However, when the explosive charge energy is increased to 40% and 50%, the resulting coating consists solely of the $CrNi_2$ phase;

2. *Method for obtaining a gradient coating by detonation spraying*. The gradient structure of element distribution in the NiCr–Al(20%) coating increases its microhardness and adhesive strength by approximately 30%, and its wear resistance by a factor of two compared to the homogeneous coating. A gradual decrease in the filling volume of the detonation barrel with an oxygen-acetylene mixture ($O_2/C_2H_2 = 1.856$) from 50% to 25% ensures the formation of a gradient-structured NiCr-Al(20%) coating, in which the Al content gradually increases from the substrate to the surface of the coating, while the Ni and Cr contents correspondingly decrease;

3. *Results of the study on the heat resistance of the NiCr-Al(20%) coating with a gradient elemental distribution*. The high-temperature resistance of gradient-structured NiCr-Al(20%) coatings is significantly higher compared to homogeneous coatings, which is attributed to the better compatibility of the thermal expansion coefficients between the coating and the substrate, as well as the suppression of internal oxidation processes. High-temperature oxidation tests of the NiCr-Al(20%) coating under both laboratory and industrial conditions revealed the formation of protective Al_2O_3 oxide layers on the surface of the gradient coatings due to the retention of Al in the surface layers. High-temperature tribological test results showed that the wear resistance of the gradient coating is approximately 2.5 times higher compared to the homogeneous composite coating.

Practical Significance. The results obtained in the dissertation can be used to develop protective coatings resistant to oxidation and intensive wear under high-temperature and aggressive corrosive environments, with the aim of extending the service life of equipment in the field of power engineering and mechanical engineering.

Relevance of the Work to Scientific Research Projects. The dissertation was carried out within the framework of the priority area of scientific development "Energy, Advanced Materials, and Transport" and was implemented under the following grant projects and program-targeted funding supported by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan:

– AP08957765 "Development of functionally graded coatings based on Ni-Cr-Al for corrosion protection of high-temperature elements of thermal power equipment," grant funding for 2020–2021;

– AP22688426 "Enhancement of protective properties of detonation coatings based on NiCrAl," grant funding for young scientists under the "Zhas Galym" project for 2024–2026;

– BR24992876 " Development and approbation of surface treatment technologies and obtaining composite protective coatings to improve the operational properties of tools machine parts and equipment" program-targeted funding for 2024–2026.

Author's Personal Contribution. The author's personal contribution includes conducting experimental and research work, analyzing the results obtained in the dissertation, and writing scientific articles. The definition of the dissertation's objectives and tasks, as well as the formulation of the main conclusions, was carried out in collaboration with the scientific supervisors.

Validity and Reliability of the Results. Modern methods were used in the dissertation to study the structural-phase states, mechanical-tribological, and heat resistance properties of the coatings. The results of the research conducted in the dissertation do not contradict established scientific concepts and previously known findings.

Approbation of Scientific Works. The main results of the dissertation were presented and discussed at the following scientific events: 2020 IEEE 10th International Conference on "Nanomaterials: Applications & Properties," Sumy, Ukraine, November 9–13, 2020; International Scientific and Technical Youth Conference "Promising Structural and Functional Materials," Tomsk, Russia, November 20–24, 2023; International Scientific and Practical Conference "Integration of Energy and Mechanical Engineering: Innovative Technologies and Practices," Almaty, Kazakhstan, November 24, 2023; International Practical Internet Conference "Challenges of Science," Almaty, Kazakhstan, November 22, 2023; as well as at scientific seminars of the Research Center "Surface Engineering and Tribology" at Sarsen Amanzholov East Kazakhstan University and the scientific-production company LLP "PlasmaScience".

Publications. A total of 18 works has been published on the topic of the dissertation, including 2 articles in peer-reviewed scientific journals indexed in the Web of Science and Scopus databases, 7 articles in journals recommended by the Committee for Quality Assurance in the Field of Science and Higher Education of the Republic of Kazakhstan, 8 papers in international conference proceedings, and 1 patent for a utility model of the Republic of Kazakhstan.

Structure and Volume of the Dissertation. The dissertation consists of an introduction, four chapters, a conclusion, a list of 138 references, and two appendices. The total volume of the dissertation is 108 pages, including 62 figures and 10 tables.