ABSTRACT
for the degree of a Doctor of Philosophy (PhD)
in the educational program 8D05302 – “Technical Physics”
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Influence of thermal and plasma impacts on the structural state and properties of the carbide near-surface layer of tungsten.

General overview of the work

The dissertation is dedicated to investigating changes in the structural state and properties of the carbide near-surface layer of tungsten resulting from exposure to high thermal loads and high-temperature irradiation by helium plasma. A method for high-temperature testing of tungsten with a carbide layer has been developed in the dissertation, and the main regularities of the influence of high thermal loads and helium plasma irradiation on the structural state and properties of the tungsten carbide surface layer have been established using a plasma beam installation.

Relevance of the Research Topic

As is known, in the field of developing thermonuclear technologies, there is active research on the application of tungsten and its alloys as structural materials for the first wall and divertor in the design of thermonuclear fusion facilities. The study of plasma interaction with surfaces and, most importantly, the prediction of the behavior of structural materials under the real operating conditions of a thermonuclear installation is complicated by the formation of complex processes in the interaction of plasma with the protective lining of the first wall and divertor. The products of these processes, including erosion, accumulate in the divertor region of the thermonuclear installation.

During the operation of thermonuclear installations with a graphite lining of the first wall (JT-60, KTM Tokamak), there is a problem of erosion of carbon-containing materials with subsequent deposition of eroded carbon particles on the surface of other structural materials. In the plasma, these eroded particles will undergo ionization under the influence of high-energy electrons and then, together with hydrogen isotopes, interact with the plasma-facing surface of structural tungsten. The result of plasma interaction with materials is their sputtering and evaporation, changes in structure and phase state, as well as the formation of new chemical compounds on the surface. Depending on the parameters of plasma exposure, the formation of a near-surface carbide layer of tungsten may occur. These facts can influence significantly the interaction of materials facing the plasma with hydrogen isotopes in the boundary plasma.

In this context, specialists face the task of studying the processes of forming near-surface tungsten carbide compounds and establishing the patterns of their influence on the structural state and operational characteristics of the material due to plasma irradiation. When creating a tokamak-based thermonuclear reactor, the selection of structural materials capable of withstanding both constant and intense powerful pulsed plasma impact is a key challenge. Therefore, in our view, experimental and theoretical studies related to the investigation of surface structure changes in materials used for the first walls and divertor plates in thermonuclear installations under the influence of plasma flows are of great significance. However, the experimental complexity and multi-aspect nature of the interaction between the plasma of a thermonuclear reactor and candidate materials, coupled with the high costs of full-scale natural testing, necessitate the conduct of experimental studies using specialized small-scale simulation setups.

The purpose of this work is to identify the key features of changes in the structural state and properties of the near-surface tungsten carbide layer as a result of high-temperature thermal and plasma exposure using a plasma-beam installation (PBI).

To achieve this goal, **the following tasks** and investigations were set:

1) Develop a computational model of the temperature field in tungsten with a near-surface carbide layer under high-temperature plasma irradiation.

2) Devise a method for subjecting tungsten with a carbide layer to high thermal loads using electron beam heating on the plasma beam installation (PBI).

3) Establish the regularities of the influence of high thermal loads on the structural state and properties of the near-surface carbide layer of tungsten.

4) Investigate changes in the structural state and properties of the near-surface carbide layer of tungsten resulting from high-temperature helium plasma irradiation.

Key Provisions for Defense

1) The near-surface carbide layer has a significant effect on the nature of the distribution of the temperature field in tungsten during plasma irradiation. It has been established that at a thermal load of 10 MW/m^2 and 20 MW/m^2 of plasma irradiation, the temperature on the plasma-exposed surface of tungsten with a carbide layer is 905 °C and 1750 °C, respectively, while the temperature of the tungsten surface without a carbide layer is 1115 °C and 2189 °C at appropriate plasma loads.

2) Method of high-temperature exposure to tungsten with a near-surface carbide layer using electron-beam heating on plasma-beam installation in conditions of high vacuum and a gaseous environment.

The method is based on powerful electron-beam impact from a plasma-beam setup in a vacuum and gaseous environment (helium), with a exposure time 3 hours followed by controlled cooling (1 °C/s). The method provides high-temperature heating in the temperature range from 20 °C to 2500 °C and at speeds ranging from 10 °C/s to 500 °C/s. The developed method has allowed achieving the calculated temperatures and parameters of high-temperature heating of tungsten with a surface carbide layer.

3) Features of the structural state changes in the near-surface carbide layer of tungsten under high thermal load.

It has been established that at a temperature of 905 °C (q=10 MW/m^2), the near-surface carbide layer of tungsten is characterized by high thermal stability of the structure and prevents surface erosion. Thermal load at 1750 °C (q=20 MW/m^2) leads to the destruction of the WC carbide layer, the formation of cracks and degradation of the surface structure of the material.

4) Influence of high-temperature irradiation by helium plasma on the structural state and properties of the near-surface carbide layer in tungsten.

It has been established that helium plasma irradiation negatively affects the surface properties of tungsten carbide layers, accelerating the formation of a coral-like structure and helium bubbles at 905°C. It was determined that the surface carbide layer WC exhibits weaker resistance to helium damage compared to the W_2C-based carbide layer. Helium irradiation at a temperature of 1750°C leads to more extensive surface damage with the formation of molten protrusions.

The scientific novelty of the work lies in the fact that, for the first time:

1. a method for high-temperature testing of tungsten by electron-beam exposure in a vacuum and gas environment has been developed and tested (Patent for invention No. 35911 dated October 21, 2022, Bulletin No. 42);

2. the features of changes in the structural-phase state and properties of the near-surface carbide layer of tungsten due to high-temperature exposure and helium plasma irradiation have been identified.

Research Object: Tungsten with a near-surface carbide layer under conditions of high-temperature and plasma exposure.

Research Subject: The influence of thermal and plasma effects on the structural state and properties of tungsten with a near-surface carbide layer.

Research Methods

For calculating the temperature field of the monoblock divertor model of the thermonuclear reactor and simulating the thermal load during plasma irradiation, the ANSYS software package was used. Experiments on thermal and plasma exposure were conducted on a plasma-beam setup. Optical and mass spectrometry methods, contact and non-contact temperature control methods, and probe diagnostics were applied in the experiments to determine the plasma volt-ampere characteristics. Thermal desorption was used to analyze gas accumulation in the sample. The investigation of the structural and phase state of the samples involved metallographic and microstructural analysis methods, including optical, scanning, and transmission electron microscopy, as well as X-ray structural analysis. The surface area of the samples was determined using a stereoscopic microscope in the Altami Studio software environment. Quantitative and qualitative assessment of the microstructure of the samples was carried out using AXALIT software for microstructure analysis. Elemental composition determination was performed using X-ray spectral microanalysis. The physical and mechanical properties of the samples were examined using the Vickers microhardness measurement method on an automatic hardness tester Q10A+, mass measurements on Mettler Toledo MS205DU analytical balances, and surface roughness measurements using a Mitutoyo Surftest SJ-410 profilometer.

Practical Significance of the Work

1. The developed method of high-temperature heating and the methodology for studying the interaction of plasma with the tungsten surface with a carbide layer were tested during the conducted research and implemented in the preparation and execution of experiments for testing structural materials on the plasma-beam setup as part of the scientific and technical activities of the branch of the Institute of Atomic Energy of the RSE National Nuclear Center of the Republic of Kazakhstan (Methodology Development Report No. 12-230-02/1579vn dated August 24, 2022. Implementation Report No. 12-230-02/1584vn dated October 2, 2023).

2. The data obtained in the course of the dissertation work are used in the implementation of the Research Program on the Kazakhstan Material Science Tokamak KTM for 2021-23 as of March 12, 2021.

3. The research results on the influence of the carbide layer on the properties of tungsten under the impact of thermal loads and plasma irradiation can be recommended

to materials scientists involved in the development of elements for a fusion reactor and the analysis of operational resources.

4. An implementation report on the results of the dissertation work in the educational process of the Department of Technical Physics and Thermal Power Engineering of the Non-profit joint-stock company "Shakarim University of the Semey city" has been obtained.

Author's Personal Contribution

The author actively participated in conducting experimental research and selecting research methods, in defining the goals and tasks of the dissertation work, and analyzed the results of patent searches and literature reviews. The analysis of the results obtained during the dissertation research, as well as the formulation of the main conclusions and conclusions, was done in collaboration with scientific advisors.

All experimental work was carried out in close collaboration with leading scientists and specialists from the branch "Institute of Atomic Energy" of the Republican State Enterprise "National Nuclear Center of the Republic of Kazakhstan" (IAE NNC RK).

Relation of work with research programs

The dissertation work was carried out within the framework of the Republican budget program 036 "Development of Atomic and Energy Projects," subprogram 105 "Applied Scientific Research of Technological Character in the Field of Atomic Energy," activity "Scientific and Technical Support for Experimental Studies on the Kazakhstani Materials Science Tokamak KTM" of the Ministry of Energy of the Republic of Kazakhstan. The author participated as the main executor and the leader of the topic:

- topic 01.01. "Experimental studies of the influence of coatings on the properties of materials exposed to plasma on an experimental stand with a plasma-beam installation," section 01. Development of research methods on KTM and means of controlling the physical parameters of high-temperature plasma on KTM in the process of its interaction with materials in 2018-2020 (State registration No. 0115RK02433);

- topic 02.01. "Study of plasma interaction with the carbide surface of tungsten," section 02. "Development and experimental justification of innovative technologies for creating a thermonuclear reactor" in 2021–2023 (State registration No. 0115RK02433).

The reliability and validity of the obtained results are ensured by the correctness and systematic nature of the conducted computational and experimental studies. These results are corroborated by publications in journals recommended by the Committee for Quality Assurance in Science and Higher Education of the Ministry of Science and Higher Education of the Republic of Kazakhstan, as well as in peer-reviewed international scientific journals indexed in the Scopus and Web of Science databases, and contributions to international scientific conferences in both near and distant foreign countries further support the credibility and justification of the findings. Additionally, a patent for the invention, published by RSE “National Institute of Intellectual Property”.

Approbation of the Work Results

The main results of the dissertation work were presented widely and reported on the following scientific event:

1) 14th International Conference “Gas Discharge Plasmas and Their Applications”, Tomsk, Russia, 15 – 21 September, 2019.

2) The XXIV International Conference on ion - surface interactions (ISI-2019) Moscow, Russia, 19 – 23 August, 2019.

3) II International Scientific Forum “Nuclear Science and Technology”, INP, Almaty, June 24 – 27, 2019.

4) 7th International Congress on Energy Fluxes and Radiation Effects (EFRE 2020), Tomsk, Russia, 14 – 25 September, 2020.

5) 15th International Conference “Gas Discharge Plasmas and Their Applications”, Tomsk, Russia, 5 – 10 September, 2021.

6) International online conference “Advanced manufacturing materials and research: new technologies and techniques AMM&R2021, Ust-kamenogorsk, 19 February, 2021.

7) IX International Conference “Semipalatinsk Test Site: Heritage and Prospects for the Development of Scientific and Technical Potential”. 7 – 9 September, 2021, Kurchatov, Kazakhstan, 2021.

8) Seminar-competition of poster reports Shakarim Poster Event. Shakarim University, Semey, 13 April, 2022.

9) International scientific and practical conference “Uvaliev Readings – 2022” “Current problems of science and education in the context of modern challenges.” Ust-Kamenogorsk, 23 – 24 September, 2022

10) International scientific and technical seminar “30 years of scientific and technical cooperation in the field of peaceful uses of atomic energy.” Kurchatov, 17 – 20 May, 2022.

11) 10th International Conference on Nanomaterials and Advanced energy storage systems. Nur-Sultan, 4 – 6 August, 2022.

12) 32nd Symposium on Fusion Technology (SOFT 2022). Dubrovnik, Croatia. 18 – 23 September, 2022.

13) XV International Conference “Solid State Physics”. Astana, 8 – 10 Dec, 2022.

14) Third Annual Meeting of Kazakh Physical Society. Kurchatov. 7 – 11 June, 2023.

15) XXVI International Conference “Interaction of ions with surfaces - ISI2023”. Yaroslavl, RF. 21-25 August, 2023.

16) International conference “Semipalatinsk Test Site”. RSE NNC RK. Kurchatov. 12-14 September, 2023.

17) International Fusion Energy Conference. London. UK. 16–20 October, 2023.

Also, the results of the dissertation work were reported and discussed at scientific seminars of the Department of Technical Physics and Thermal Power Engineering of the Non-profit joint-stock company “Shakarim University of the Semey city”, at meetings of the Scientific and Technical Council of the RSE NNC RK and the “Institute of Atomic Energy” branch, as well as at PhD seminars of doctoral students.

Publications

As a result of the research presented in the dissertation, a total of 20 publications have been produced. These include 1 publication in a peer-reviewed scientific journal recommended by the Committee for Quality Assurance in Science and Higher Education of the Republic of Kazakhstan, 4 publications in journals indexed in Scopus and Web of Science, 1 patent for an invention from RSE NIIP, 12 contributions to proceedings of international conferences, and 2 publications in other outlets.

Structure and Scope of Dissertation

The thesis comprises an introduction, five chapters, a conclusion, and a list of references. It spans 108 pages, includes 46 figures, 11 tables, and a bibliography with 197 sources.