National Research University

Higher School of Economics

 As a manuscript

Nikita Epifanov

**Investigation of the influence of powerful beam-plasma impact on the structure and structural-phase state of aluminum, copper and iron alloys**

Dissertation summary

for the purpose of obtaining academic degree

Doctor of Philosophy in Engineering

Academic Supervisor:

Doctor of Sciences in Physics and Mathematics

Gennady Germanovich Bondarenko

Moscow, 2023

**Relevance**

The field of "Radiation Solid State Physics" (RSSP) is currently one of the most promising and actively developing in physical science. RSSP was formed at the border of other fundamental fields: condensed matter physics, nuclear physics, and high-energy physics. The value of RSSP is growing every year, primarily due to its wide range of applications in nuclear power, space research, electronics, nanoelectronics and other fields. The experimental and theoretical results obtained in RSSP open up new avenues for research, allowing us to solve problems in the theory of condensed matter and phase transitions.

In solid state radiation physics, such processes as the interaction of radiation with atoms and molecules of solid materials, the formation of radiation defects, and changes in the electronic structure and properties of materials under the influence of radiation are studied. This includes the study of radiation damage, radiation effects on the electrical, magnetic, optical and mechanical properties of materials, as well as the study of mechanisms of regeneration and restoration of the structure after exposure to radiation.

Experimental analysis methods are valuable in RSSP, such as spectroscopy, microscopy, diffraction, and electron spin resonance spectroscopy, as well as theoretical modeling and computer simulations, are widely used in X-ray diffraction. These methods allow researchers to expand our understanding of the mechanisms of radiation processes in solid materials, develop new materials with improved radiation properties, and develop methods to protect against radiation damage.

RSSP has a wide range of applications, including nuclear power, radiation medicine, electronics, space technology, and radiation safety. Understanding the interaction of radiation with solid materials is a key factor for the effective use of radiation technologies and the development of new materials with high radiation resistance and reliability.

In the technical field, many engineering developments require the use of materials with certain properties. Especially essential are the properties of materials when creating complex structures that must work in extreme conditions. Examples of such structures are fusion devices and nuclear reactors. To ensure the operability of these structures, various materials with different composition, structure and production methods are used. However, when operating under high radiation fluxes and high doses, materials are exposed to radiation damage. This leads to significant changes in their structure. In turn, these changes have a significant impact on the structure, structural and phase state, and physical and mechanical properties of materials. Such changes may include changes in the microstructure, formation of defects, changes in the bonds between atoms, and other processes. Understanding these changes and studying their impact on the properties of materials is an important task in research work. This makes it possible to develop more stable materials or apply additional methods to protect materials from radiation damage. As a result of such research, progress can be made in the development of materials for technical devices operating in extreme conditions. This can contribute to improving and improving the efficiency of thermonuclear fusion and other technical processes. In the context of research in the field of thermonuclear fusion, new requirements arise for materials used in structures and having a functional purpose. They must have high resistance under extreme conditions, including the ability to withstand irradiation with neutrons with an energy of up to 14 MeV and thermonuclear plasma flows. Under such conditions, various specific physical and chemical processes occur, including radiation swelling, radiation embrittlement, radiation-stimulated diffusion, and radiation-induced segregation of components in alloys. In addition, radiation-induced structural-phase transformations and radiation blistering are observed. In this regard, research and development of new materials that ensure efficient operation in the conditions of thermonuclear fusion are relevant. The principal distinguishing feature of a fusion reactor (FR) in comparison with nuclear fission reactors is the presence of a vacuum chamber, which imposes additional requirements on the properties of materials for FR, especially the first wall of the working chamber facing the thermonuclear plasma. Among the factors that determine the durability of the first wall of all types of FR, an important role is played by its radiation destruction due to ion sputtering, plasma disruptions in magnetic confinement reactors and pulsed action on the wall of the scattering plasma in inertial confinement laser fusion reactors are particularly dangerous from the point of view of radiation erosion. The destruction of the surface leads to two of the most negative consequences. First, erosion wear, depending on the design of the first wall, causes either a change in the strength of the structure of the FR working chamber, or excessive wear of screens, the replacement of which is a rather complex operation. Secondly, in reactors with magnetic confinement, as a result of erosion wear of the first wall, the plasma is contaminated with heavy impurities and, consequently, the plasma retention conditions worsen, and the reactor efficiency decreases.

The current stage of research and development of FR materials has an important feature. The absence of a functioning fusion reactor or experimental working setup that fully imitates the reactor operating conditions of materials stimulated intensive research of certain factors of powerful beam-plasma impact on materials using, mainly, charged particle accelerators (ions of various chemical elements), which gives the research a simulation character. This circumstance, as well as the existence of various future FR projects based on two concepts of plasma retention (magnetic and inertial), determines the development of materials that are resistant to extreme impacts, and determines the relevance of the topic of this study. At present, we have accumulated extensive data on the simulation effect of accelerated ions on candidate materials of the first FR wall, and these studies have been ongoing for more than 40 years. However, simulation studies conducted under ion accelerator irradiation cover only a small spectrum of the influence of various FR factors (the absence of such factors as shock waves, "runaway" electrons, plasma disruptions, etc.) on the structure and properties of candidate materials. Simulation conditions that are more close to full-scale ones are created when materials are irradiated in plasma installations, in particular "Plasma Focus" installations. The influence of high-power beam-plasma fluxes generated in такогоsuch installations on the structure and structural-phase state of a number of materials was the subject of study in this paper.

**Degree of the research topic development**

Over the past 20 years, the scientific world has been actively developing a direction related to the use of pulsed action with the help of concentrated energy flows on various materials. The purpose of such an impact is to change the structure and structural-phase state of these materials, as well as their surface and bulk properties. This type of research has found a great response in the field of fusion; recent developments pave a clear path for upcoming physical and technical research, which is still necessary for the successful construction and operation of modern fusion plants and promising demonstration fusion systems. Progress is noticeable at the construction stage of large nuclear fusion facilities ITER (France), LMJ (France), NIF (USA), and Iskra (Russia), which are related to controlled fusion inertial and magnetic plasma confinement.

One of the key issues that remains to be addressed in the pursuit of fusion power generation is the characterization, testing and development of suitable advanced plasma cladding materials that can withstand the extreme radiation and thermal loads expected in fusion reactors. A fundamental understanding of the interaction of plasma beams with walls in conventional thermonuclear devices requires targeted research activities in plasma simulators used in close connection with the means of determining the characteristics of materials, as well as with the achievements of theory and modeling.

Plasma Focus (PF) devices are an important element in the field of thermonuclear energy. These installations are devices designed to create and control the plasma state necessary for the implementation of thermonuclear reactions. The main idea of the "Plasma Focus" is to use a magnetic field to compress and heat the plasma to extremely high temperatures, sufficient to trigger nuclear fusion reactions.

PF devices are also used to study the structural and phase states of metals. Plasma treatment can help to change the structure of materials, create new phases or structural defects, which allows you to get new properties or improve existing ones. Research at these facilities makes it possible to better understand the mechanisms of structural transformations in metals and optimize processing processes to obtain materials with certain properties. One of the key aspects of research in PF installations is the study of the effect of high plasma energy on various materials, including metals. PF installations are capable of generating intense fluxes of energy and particles, which makes it possible to simulate conditions similar to those that occur in nuclear explosions or in plasma reactors. This helps researchers understand the effects of radiation and high temperatures on the structure of materials, their mechanical properties, and their behavior under extreme conditions. They are also objects of research, where experiments and tests are conducted to further improve the methods of controlling plasma processes and increase the efficiency of thermonuclear energy. The results of research conducted at such facilities can lead to the development of new methods for generating and retaining plasma, as well as to optimizing the design of reactors for more efficient energy generation.

In connection with the above, PF installations are a suitable and effective tool for testing heterogeneous candidate materials considered promising for elements of thermonuclear chambers exposed to high-power radiation (first wall, diverters, etc.). These devices are used to irradiate samples with powerful radiation pulses of two types: hot plasma flows (velocities v = (2-3)×10.5 m/s) and fast ion beams (energy Eei ~ 100 keV – with a power flux density of up to P ~1016 W /m2, as well as with a duration of A pulse in the range of 10-100 ns was used to simulate the conditions expected in FR chambers with inertial plasma retention, as well as with magnetic plasma retention during emergency situations (ELM effects, vertical plasma breakdowns, etc.). In addition, a neodymium glass laser was used to irradiate similar samples made of the same materials. In the modulated Q-factor mode (with approximately the same power flux density as the fast ion flux in PF with P ~1010-16 W/m2). It should be noted that the effect of ion fluxes does not lead to the formation of shock waves of significant pressure at the front in the irradiated material.

This area of research, which is devoted to the analysis of the behavior of materials under strong effects of ultrashort pulses generated in PF installations, is a relatively new area of research that has not yet been widely used. Most of the existing studies are focused on assessing the damage of materials and their resistance to intense pulsed energy impacts under conditions simulating extreme circumstances in FR test chambers. In the literature there are works by such authors as V. A. Gribkov et al., V. N. Pimenov et al., V. Ya. Nikulin et al., R. S. Rawat, Zhang T. and colleagues, Väli B. and co-authors, Javadi S. etc. These studies were mainly carried out on refractory metals (W, Mo, V, Ti) and alloys based on them, as well as on steels of various classes.

In the present work, we consider the features of damage and modification of the structural-phase state and properties of surface layers of low-melting metals-aluminum and its alloys, high-conductivity metals-copper and its alloys, as well as low-activation ferritic-martensitic steels, which are of interest for thermonuclear power engineering. The studies were carried out using PF installations that have specific characteristics related to the features of the physical processes occurring in them and the geometry of propagation of high-temperature plasma and fast high-energy ion fluxes during experiments. One of the distinctive features of this work is the use of one of the world's largest PF-1000 plasma focus units with record parameters, located at the Warsaw Institute of Plasma Physics and Laser Microsynthesis.

**Purpose and objectives of the study**

The aim of the study is to identify the features of the influence of high-power pulsed ion fluxes, plasma, and shock waves generated in Plasma Focus installations on the structure of surface layers and the structural and phase state of aluminum, copper, and iron alloys.

To achieve this goal, the following **tasks were solved:**

1. identification of features of changes in the structure and structural-phase state of Al-Li-Mg alloys under high-power beam-plasma action in the PF-1000 and PF-6 installations;
2. determination of the effectiveness of a ceramic protective coating made of aluminum oxide on an aluminum substrate (Al2O3/Alcompositions/Al) under beam-plasma exposure;
3. studying thefeatures of changes in the mechanical properties of copper and its alloys with gallium and nickel under the influence of deuterium radiation fluxes in PF-1000 and PF-6 installations, as well as the combined effect of deuterium ions and plasma on these materials;
4. investigation of the effect of pulsed beam-plasma irradiation on the structures, structural-phase state, and composition of surface layers of Eurofer-97 ferritic-martensitic steels and 10Cr9WV steel.

**The object of research** is samples of alloys based on Fe, Al, and Cu before and after irradiation with high-energy ion pulses, plasma flows, and laser radiation.

**The subject of the study** is structural and phase changes, modification and damage of the surface layer of the above materials.

**Methodology and methods of dissertation research**

The methodology of the dissertation is based on the results of fundamental and applied research in the field of radiation materials science**.**

Experimental research methods were used to solve these problems. Experimental data were obtained by laboratory modeling of thermonuclear reactor factors (irradiation on simulation stands – plasma installations PF-1000, PF-6, "Vortex"), irradiation on a neodymium glass laser installation GOS-1001, optical microscopy, scanning electron microscopy, X-ray microanalysis, X-ray diffractometry, atomic emission spectroscopy, and determination of the temperature of the reactor's surface, kinetic microhardness and elastic modulus.

**Scientific novelty of the work**

1. Features of structural and structural-phase changes occurring in the surface layers of Al-(2.0-2.2)%Li-(5.0-5.2)%Mg alloys under beam-plasma action inthe PF-1000 installation are revealed.
2. New scientific data are obtained on the structural stability of the protective coating of aluminum oxide, deposited on an aluminum substrate under beam-plasma action with a radiation power density *of q* ~ 108 – 109 W /cm2 in the nanosecond range of the pulse duration;
3. For the first time, the results of calculations performed by numerical modeling of the temperature distribution and shock wave amplitude in the surface layers of the studied materials irradiated by high-power pulsed beam-plasma flows are obtained.
4. specific features of changes in the structure and mechanical properties of copper and copper alloys with gallium and nickel alloying additives Cu-10%Ga, Cu-4%Ni, and Cu-4%Ni-10%Ga after irradiation in the PF-1000 installation in two modes: "soft" - by deuterium plasma flows at q = 107 W /cm2 and τ = 100 ns and "t" - together with the deuterium ion fluxes at *q* = 109 – 1011 W /cm2and τ =50 ns and dense deuterium plasma at q =108 – 109 W /cm2 and τ =100 ns;
5. For the first time, a set of experimental data was obtained that investigated the effect of pulsed beam-plasma irradiation on the surface structure, structural and phase changes, and the elemental composition of the surface layers of low-activation ferritic-martensitic steels, such as Eurofer 97 (European steel) and 10Cr9WV of Russian production. The study was carried out at various levels of plasma flow power (qpl) in the range from 107 to 1010 W /cm2 and ion power (qi) in the range from9 109 to 1012 W/cm2;
6. comparative features of changes in the structural and phase state of Eurofer 97 and 10Cr9WV steels under irradiation with high-power and beam-plasma streams are determined; it is established that Eurofer 97 irradiation at the energy level of the radiation density (qpl) is equal to 107 - 108 W/cm2 leads to the appearance of a significant amount of austenite in its structure. At the same time, when 10Cr9WV steel is similarly irradiated, the amount of residual austenite is approximately 20 times less than in Eurofer 97, which is an important factor in assessing the degree of radiation swelling of these steels; structural and phase stability under irradiation of 10Cr9WV steel is ensured by additional pre-radiation heat treatment.

**Theoretical significance of the work**

The results of our research have significantly expanded the database on the regularities of the influence of high-power pulsed fluxes of deuterium plasma and deuterium ions, as well as the shock wave formed during the action of dense plasma on the damage, structure, and phase element composition of surface layers of aluminum, copper, and iron alloys; a model has been developed that allows estimating the amplitudes of shock waves, Abstract-an analytical formula is obtained for calculating shock wave amplitudes in radiation materials science experiments conducted using "Plasma Focus" devices; the distributions of temperature and shock wave amplitude in the surface layers of the studied materials irradiated by high-power pulsed beam-plasma flows are obtained by numerical modeling.

**Practical significance of the work**

The results obtained in this work will make it possible to supplement and expand the experimental data base, necessary for analyzing the processes of changes in the structural-phase state and structure of the studied alloys under high-power beam-plasma irradiation, especially under conditions simulating the effect of fluxes and radiation on materials in the working chamber of FR. In addition, they can be used to predict the radiation stability and degradation behavior of the studied materials under such extreme conditions.

**Main provisions for the defense:**

- Results of the influence of pulsed fluxes of deuterium and deuterium plasma ions on the structure and structural-phase state of aluminum-based alloys;

- new experimental data that allow us to evaluate the structural stability of the protective coating of aluminum oxide deposited on an aluminum substrate under beam-plasma and laser effects;

- calculated estimate of shock wave amplitudes that occur in materials under the influence of powerful deuterium plasma flows, obtained by numerical modeling;

- results concerning the effect of pulsed fluxes of deuterium and deuterium plasma ions on the structure and plasticity of copper, as well as copper-based alloys. The following alloy compositions are considered: Cu-10%Ga, Cu-4%Ni, and Cu-10%Ga-4%Ni.

- results of a study of the effect of high-power pulsed fluxes of deuterium plasma and deuterium ions on the structure, structural-phase state, and redistribution of elements in low-activation Eurofer 97 and 10Cr9WV ferritic-martensite steels.

**Personal contribution of the author**

The author tooka direct part in obtaining experimental data, experiments on irradiation of samples on the plasma installation "Vortex", he personally prepared samples for research and performed structural studies using optical microscopy and scanning electron microscopy; conducted (co-authored) analysis of all the results obtained in the work, personally formulated conclusions on the dissertation.

As part of the study, the author performed numerical calculations on the PF-1000 installation aimed at determining the amplitude of the shock wave that occurs when aluminum and tungsten are exposed to a plasma beam. These calculations made it possible to construct the dependences of the shock wave pressure on the distance when it penetrates into the irradiated materials. Numerical simulations were also exploited to determine the temperature distribution in the surface layers of theAl2O3/Al composition Al when exposed to a laser beam and a laser in the modulated Q-factor and free generation modes. The calculation results made it possible to obtain the distribution of the shock wave pressure amplitude in the material as a function of its depth under beam plasma and laser irradiation in the modulated Q-factor mode. These studies are important for understanding the effects of plasma and laser beams on materials, as well as for developing methods for controlling and optimizing these processes. The results obtained can be used in various fields, including the development of new materials with improved properties and the creation of more efficient surface treatment methods. The author personally participated in the preparation of publications and presentations at international and Russian conferences on the topic of the dissertation.

The irradiation of samples of the studied materials at the PF-1000 and PF-6 installations was performed at the Warsaw Institute of Plasma Physics and Laser Microsynthesis under the supervision of Dr. M. Padukh, who, together with Dr. M. Scholz, is the co-author of joint articles published on the results of irradiation experiments.

**The reliability of the results** presented in this dissertation is ensured by a high degree of reproducibility, as well as the use of modern experimental equipment in combination with additional independent research methods. In particular, scanning electron microscopy, X-ray diffractometry, atomic emission spectroscopy, as well as various methods of radiation solid state physics, plasma physics, laser physics, mathematical analysis and equations of mathematical physics, as well as numerical methods were applied. The applied numerical models were tested for high accuracy and correctness through verification with experimental data, as well as comparison with the results of other studies dealing with similar issues.

**Approbation**

The results of the work were reported and discussed at the following conferences:

1. 10th International Conference “New Electrical and Electronic Technologies and their Industrial Implementation”, Zakopane, Poland, June 27 – 30, 2017, presentation « Damage of Aluminum Samples with Ceramic Coating Based on Al2O3 Oxide Under Pulsed Energy Streams»
2. International Conference on Nuclear and Radiation Physics and Materials book of abstracts, June 17-20, 2019 A. Alikhanyan National Science Laboratory, Yerevan, Armenia, presentation «The changes in the structure and elemental composition of aluminum-based alloys under the influence of accelerated gas ions and streams of hydrogen and deuterium plasma»
3. XVI Russian Annual Conference of Young Researchers and Postgraduates "Physical Chemistry and Technology of inorganic materials", October 1-4, 2019, Moscow, Russia, presentation "Impact of shock waves of high-power plasma flows and pulsed laser radiation on solid-state samples"
4. Physical and Numerical Simulation of Materials Processing (ICPNS 2019), Moscow, Russia, 10-14 October, presentation «Action of shocks generated in solid targets by dense plasma focus devices and at pulsed laser irradiation»
5. XXX International Conference "Radiation Solid State Physics", Sevastopol, August 24-29, 2020, presentation "Changes in the surface layers of copper alloys under the action of pulsed beam-plasma treatment"
6. XVII Russian Annual Conference of Young Researchers and Postgraduates "Physical Chemistry and Technology of inorganic materials", November 10-13, 2020, Moscow, Russia, report "Features of the destructive effect of pulsed laser radiation and high-power ion and plasma fluxes on metals"
7. 18th International School-Conference for Young Scientists and Specialists "New Materials: Non-equilibrium states", Moscow, Russia, December 14-17, 2020, report "Behavior of copper alloys under the influence of powerful pulsed fluxes of deuterium and deuterium plasma ions"
8. EVT-2103194- Second Coordination Meeting on Ways to Generate Energy through Inertial Fusion: Materials Research and Technology Development", Vienna, Austria, June 13-15, 2022, report " Structural and phase changes in candidate materials for fusion plants with inertial plasma retention under intense pulsed irradiation with fast ion and high-temperature plasma fluxes "(on according to the IAEA contract with IMET RAS No. 24080 dated 27.08.2020).

The dissertation consists of an introduction, 6 chapters, a conclusion and a list of references.

The first chapter provides a review and critical analysis of the literature data on the effect of high-power beam-plasma fluxes generated in "Plasma focus" type installations on the structure and properties of metal alloys. In particular, the design of such installations, the characteristics and features of generating beam-plasma flows inside the PF chamber are described; the interpretation of the plasma effect on the materials of the first wall and the FR divertor is also considered. In the final part of the first chapter, modern articles and works on the effect of pulsed plasma fluxes, accelerated ions, and laser irradiation on the structure and properties of metal alloys are analyzed.

The second chapter contains experimental research methods and equipment. The paper describes the PF units used in the work (PF-1000, PF-6, PF "Vortex"), their distinctive features and parameters. The second chapter also describes the main characteristics of the GOS-1001 laser system and the structural methods used for studying materials(optical and scanning electron microscopy with local X-ray spectral analysis, X-ray diffraction analysis, and atomic emission spectroscopy).

The third chapter is devoted to the study of the impact of shock waves generated during irradiation of materials in the "Plasma Focus" installation, as well as during pulsed laser irradiation. Numerical modeling of shock wave formation in irradiated materials is performed; a simple analytical formula is proposed for calculating shock wave amplitudes in experiments on radiation materials science conducted using PF installations and a GOS-1001 laser.

In the fourth chapter of the dissertation, the damage to the surface layer of aluminum alloy 1420, which belongs to the Al-Mg-Li system, was investigated. A series of experiments was conducted with the effect of high-power pulsed streams of deuterium plasma and deuterium ions on the alloy in the PF installation. The results represented that under such irradiation, thermal and radiation-stimulated processes occur in the alloy, which lead to the elements’ redistribution in the surface layer of the alloy. Next, the damage rate of a protective ceramic coating made of aluminum oxide (Al2O3, ɣ-corundum) deposited by anodizing on the surface of a sample consisting of pure aluminum was studied. We irradiate the sample with high-energy energy fluxes of various nature and study the state of the coating after irradiation. As a result of experiments, we determine the threshold values of the power density of pulsed laser radiation, at which the aluminum coating is destroyed and partially peeled off.

The fifth chapter describes the results of experiments conducted in the PF installation onsamples of pure copper and alloys Cu-10%Ga, Cu-10%Ga-4%Ni, and Cu-4%Ni (wt. % ) irradiated with pulsed streams of deuterium plasma and deuterium ions. Damage and deformation effects in the surface layers of materials after irradiation of each of them are studied in two experimental modes. In the Cu-10% Ga alloy, a slight (up to 14%) decrease in the Young's modulus E is observed after irradiation. When this alloy is doped with nickel, an element with a higher E value than copper (in Cu-10% Ga-4% Ni alloy), the E modulus of the initial surface layer practically does not change after irradiation of the material in PF.

In the sixth chapter , the influence of pulsed plasma fluxes and accelerated ions on the structure and structural-phase state of Eurofer 97 and 10Cr9WV ferritic-martensitic steels was studied Eurofer 97 и . It was found that this process causes a significant amount of austenite in the structure of Eurofer 97 steel. In contrast, with similar irradiation of 10Cr9WV steel, the amount of residual austenite is approximately 20 times less, which is an important factor in the context of radiation swelling of steels.

The present work’s conclusion contain the results of the research performed in each of the chapters and recommendations on the topic of the dissertation work.

**Publications**

The main provisions on the topic of the dissertation are set out in articles [1-7] indexed in Scopus, while the journal [1] possesses Q2 quartile, and the journals [2-7] have Q3 quartile.

1. Epifanov N.A., Bondarenko G.G., Gribkov V.A., Latyshev S.V., Nikitushkina O.N., Pimenov V.N. Action of Shocks Generated in Solid Targets by Dense Plasma Focus Devices and at Pulsed Laser Irradiation / Procedia Manufacturing, 2019, Vol.37, pp. 500-507. DOI: 10.1016/j.promfg.2019.12.080, Q2
2. Gribkov, V.A., Demin, A.S., Epifanov, N.A., Kazilin, E.E., Latyshev, S.V., Maslyaev, S.A., Morozov, E.V., Sasinovskaya, I.P., Sirotinkin, V.P., Minkov, K.N., Paduch, M. Damageability of the Al2O3 Oxide Coating on the Aluminum Substrate by Pulsed Beam Plasma and Laser Radiation // Inorganic Materials: Applied Research Vol. 10, Issue 2, 1 March 2019, pp 339-346. DOI: 10.1134/S2075113319020151, Q3
3. Pimenov V. N., Bondarenko G.G., Dyomina E. V., Maslyaev S. A., Gribkov V. A., Sasinovskaya I. P., Epifanov N.A., Sirotinkin V. P., Sprygin G. S., Gaydar A. I., Paduch M. Influence of Pulsed Beams of Deuterium Ions and Deuterium Plasma on the Aluminum Alloy of Al–Mg–Li System // Inorganic Materials: Applied Research. 2019. Vol. 10. No. 3. P. 503-511. DOI: 10.1134/S207511331903033X, Q3
4. Borovitskaya I. V., Pimenov V. N., Gribkov V. A., Epifanov N., Maslyaev S. A., Mikhailova A. B., Bondarenko G.G., Gaidar A. I., Demina E. V., Prusakova M. D. Effect of a Pulsed Plasma Beam on the Structure and the Phase Composition of the Surface Layers in Ferritic–Martensitic Steels // Russian Metallurgy (Metally), 2020. No. 3. P. 238-249. DOI: 10.1134/S0036029520030027, Q3
5. Borovitskaya I. V., Gribkov V. A., Demin A. S., Epifanov N.A., Latyshev S. V., Maslyaev S. A., Morozov Y. V., Pimenov V. N., Sasinovskaya I. P., Bondarenko G.G., Gaidar A. I., Scholz M. Damage and Deformation Effects in the Surface Layers of Copper and Copper-Gallium Alloy under Pulsed Irradiation in a Plasma Focus Unit // Inorganic Materials: Applied Research. 2020. Vol. 11. No. 5. pp. 1093-1102. DOI: 10.1134/S2075113320050056, Q3
6. Pimenov V. N., Borovitskaya I. V., Gribkov V. A., Demin A. S., Епифанов Н. А., Maslyaev S. A., Morozov E. V., Sasinovskaya I. P., Bondarenko G.G., Gaydar A. I., Paduch M. Influence of Pulsed Flows of Deuterium Ions and Deuterium Plasma on Cu–Ni and Cu–Ni–Ga Alloys // Journal of Surface Investigation, 2022. Vol. 16. No. 1. P. 33-41. DOI: 10.1134/S1027451022010153, Q3
7. Borovitskaya, I.V., Pimenov, V.N., Maslyaev, S.A., Mikhailova, A.B., Bondarenko, G.G., Matveev, E.V., Gaidar, A.I., Padukh, M., Demin, A.S., Epifanov, N.A., Morozov, E.V. Effect of High-Temperature Pulsed Deuterium Plasma on the Structure and Mechanical Properties of the Surface of Cu–Ga and Cu–Ga–Ni Alloys. Russian Metallurgy (Metally), 2022, pp. 48-56. DOI: 10.1134/S0036029522010050, Q3