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STUDY OF THE INFLUENCE OF THE TYPE AND ENERGY OF IONS DURING IRRADIATION ON THE CHANGE IN THE STRUCTURAL AND MECHANICAL PROPERTIES OF HIGH-ENTROPY AlNbTiVZr ALLOY

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Abstract. The main aim of this study is to identify the role of energy and type of incident ions during irradiation of the near-surface layers of the AlNbTiVZr alloy in alteration of the structural and mechanical properties, as well as to determine the role of accumulation of structural damage on the softening of the near-surface layer depending on the irradiation fluence. According to the data obtained, it was established that a change in the type of ions and the energy of ions leads to a growth in the degree of structural damage associated with volumetric swelling, while an increase in the energy of ions leads to an elevation in the degree of deformation distortions of the tensile type, caused by an increase in ionization losses and cascade displacements, which elevate the concentration of defects in the near-surface layer. It has been shown that the development of volumetric swelling processes and the accumulation of defective clusters are the main factors causing a decrease in hardness and deterioration of the mechanical characteristics of the irradiated material. The results obtained demonstrate that the type and energy of incident ions, as well as the irradiation fluence, have a determining effect on the kinetics of degradation of mechanical properties and radiation resistance of the near-surface layers of the alloy under study.

Keywords: high-entropy alloys, radiation resistance, resistance to degradation, radiation defects, structural materials.

1. Introduction

In modern materials science, regarding the study of promising materials for new generation nuclear reactors, high-entropy alloys have occupied a special place in the past few years, a distinctive feature of which is a multicomponent composition, which includes five or more elements in similar atomic concentrations [1-3]. In this case, the use of close ratios of components in the composition leads to the formation of a high entropy of mixing, which in turn stabilizes simple crystalline structures through cationic substitution and changes the physical and mechanical properties of the alloys. Due to these effects arising in the structure of alloys, high-entropy alloys are considered one of the potential materials of the new generation, capable of operating under conditions of high temperatures, large neutron fluxes and exposure to nuclear fission fragments, as well as resistance to degradation processes upon contact with aggressive environments [4,5]. Unlike traditional alloys, in which one element is the main one and the others act as alloying additives, high-

entropy alloys lack a dominant component, in them, the equilibrium ratio of elements leads to the formation of a high configurational entropy of mixing, which determines the stability of the crystalline structure, as well as the emergence of a complex field of local stresses and energy barriers for the diffusion of atoms, which increases strength, ductility, thermal stability and resistance to external influences [6-8]. Another feature of high-entropy alloys is their resistance to the corrosive effects of aggressive environments, including water vapor, liquid metals, or molten salts, which makes high-entropy alloys potentially suitable for use in next-generation reactors operating on alternative coolants such as lead, sodium, or molten salts [9,10].

It should also be noted that in recent years, much attention in the study of the properties of high-entropy alloys has been paid to their resistance to the accumulation of radiation damage, as well as to assessment of the likelihood of the formation of long-lived radioactive isotopes in alloys after high-dose irradiation [11,12]. In this regard, to restrain these processes in the production of high-entropy alloys, elements with low activation, in particular, elements such as iron, chromium, vanadium, titanium, and tantalum, the use of which allows for a significant reduction in the level of radioactive waste and simplification of reactor decommissioning processes, are used [13-15]. High-entropy alloys play a significant role in thermonuclear energy, for installations such as ITER and DEMO, whose materials must withstand high thermal loads, intense neutron irradiation, and surface erosion upon contact with plasma [16,17]. In this case, much attention in this area is paid to high-temperature refractory high-entropy alloys based on tungsten, niobium, molybdenum and tantalum, which are considered as potential materials for the creation of divertors, plasma walls and other structural components of thermonuclear installations [18-20].

High-entropy alloys are also being considered as materials for next-generation nuclear fuel cladding due to their higher mechanical strength, oxidation resistance, and thermal stability compared to traditional zirconium alloys, which improves the safety of nuclear reactor operation and increases the burnout efficiency of nuclear fuel [21,22]. At the same time, despite the great prospects for the use of high-entropy alloys as structural and functional materials for nuclear and thermonuclear energy, the widespread introduction of these alloys today requires the search for and solution of a number of scientific and technological issues, the key of which is the assessment of the mechanisms of destruction and softening of the near-surface layers of alloys exposed to ionizing radiation. In particular, it is necessary to obtain new data on the mechanisms of defect formation and their evolution depending on variations in irradiation conditions, including exposure to various types of ionizing radiation, determine long-term structural stability and establish critical irradiation doses at which the degradation of the near-surface layers becomes irreversible and can lead to destabilization of the entire material.

In this regard, the main aim of this study is to identify the role of energy and type of incident ions during irradiation of the near-surface layers of high-entropy AlNbTiVZr alloy on the change in structural and mechanical properties, as well as to determine the influence of the accumulation of structural damage caused by irradiation on the softening processes depending on the irradiation fluence. Interest in this type of research is driven by the need to expand our understanding of the patterns of ion ranges of different masses and energies in materials, which is an important step in planning experiments on ion modeling of radiation effects, as well as in analysis of the stability of promising materials, including high-entropy alloys, to the effects of intense charged particle fluxes.

2. Materials and methods

A high-entropy alloy based on compounds of aluminum, niobium, titanium, vanadium and zirconium, obtained by spark sintering methods from metal powders mixed in equal proportions of components, was chosen as the object of research. The alloy sample was prepared by mixing the selected components in a stoichiometric ratio of 20 at. % and subsequently melting the mixture using the electric-arc remelting method in an argon atmosphere. The remelting process was repeated at least five times to ensure a uniform distribution of elements within the alloy.

X-ray structural analysis of the alloy samples was performed using a D8 Advance ECO diffractometer; X-rays were generated by a copper tube (Cu K α wavelength = 1.54 Å). Diffraction patterns were recorded in Bragg-Brentano geometry over an angular range of $2\theta = 20-60^\circ$ with a step size of 0.05° . Structural parameters were determined using DiffraC.EVA v.4.2 software. Parameter refinement involved comparing the results with reference values and identifying deviations caused by external factors, such as lattice distortions resulting from alloy fabrication methods or ion irradiation. According to X-ray phase analysis data, the phase composition of the alloy is characterized by a body-centered phase B2, enriched in aluminum and zirconium, as well as

inclusions in the form of Zr_5Al_3 and the Laves phase $ZrAlV$, the presence of which is due to their inclusion near the grain boundaries of the main phase, which leads to the creation of additional strengthening effects due to the formation of interphase boundaries and dislocation effects. The key reason for choosing the $AlNbTiVZr$ alloy as the object of research is its belonging to the class of refractory high-entropy alloys, the combination of elements in which ensures the stability of the material during operation in the operating temperature range of 600 – 1000 °C, as well as possessing high heat resistance and oxidation resistance. The multicomponent composition of the $AlNbTiVZr$ alloy leads to the creation of a large number of structural distortions of the crystal lattice, which in turn complicates the migration of point defects and slows down diffusion processes, thereby reducing the rate of accumulation of radiation damage and degradation of the alloy microstructure.

Modeling of radiation damage in the near-surface layers of the studied alloy samples was carried out at the DC-60 heavy ion accelerator located at the Astana branch of the Institute of Nuclear Physics of the Ministry of Energy of the Republic of Kazakhstan (Astana, Kazakhstan). Irradiation was carried out with O^+ , Ar^+ , Kr^+ and Xe^+ ions with energies of 28 MeV, 70 MeV, 145 MeV and 230 MeV, respectively. Irradiation fluences ranged from 5×10^{10} to 10^{14} ion/cm². Irradiation was carried out at room temperature. The choice of ion types for irradiation is determined by the need for a comprehensive study of the influence of the mass and energy of incident particles on the processes of formation and accumulation of radiation defects in the material. The use of ions with significantly different atomic masses makes it possible to reproduce various mechanisms of energy transfer in the crystal lattice and to evaluate the nature of structural changes that occur under radiation exposure.

The values of ionization losses, as well as changes in their profiles along the trajectory of ion movement in the near-surface layers of alloys at irradiation fluence growth, were determined using the SRIM Pro 2013 software code. The assessment results of changes in the profiles are shown in Figure 1a, reflecting the change in the values of ionization losses of ions along the trajectory, caused by the processes of elastic and inelastic interactions during the collision of ions with the crystal structure. As can be seen from the data presented, ionization losses during the interaction of incident ions with electrons, which are associated with the excitation and subsequent ionization of electrons and electron shells, play a dominant role in alteration of the structural features of the studied alloys during irradiation. Moreover, as the penetration depth increases, the role of electron ionization losses decreases, while the contribution of electronic stopping power and nuclear stopping power grows due to the increase in the concentration of elastic collisions of incident ions with atomic nuclei, which leads to their displacement from the nodes of the crystal lattice. The maximum ion range is about 10 – 14 μm , and it should be noted that alteration of the type and energy of ions does not make a significant difference in the maximum ion range, while alteration of the energy of ions plays a very important role in the value of ionization losses and the kinetics of their changes along the ion range.

Table 1 shows the main characteristics of the interaction of incident ions with the crystalline structure of the alloy during irradiation, reflecting the values of ionization losses, as well as the ion range in the near-surface layers. Data for ionization loss values are given as a range of values observed at the maximum. For electron ionization losses, these values were estimated at an ion range of up to 5 μm , while for nuclear ionization losses, these values were determined based on the maximum achieved during the slowing down of incident ions and their deceleration, at which ion-nucleus interactions dominate.

Table 1. Calculation data for ionization losses and ion range

Parameter	Ion			
Type of ion	O^+	Ar^+	Kr^+	Xe^+
Energy of ion, MeV	28 MeV	70 MeV	145 MeV	230 MeV
Range of ion, μm	$10.7 \pm 0.2 \mu m$	$10.8 \pm 0.3 \mu m$	$12.5 \pm 0.2 \mu m$	$13.8 \pm 0.4 \mu m$
$dE/dx_{nuclear}$, eV/nm	0.2 – 0.3	1.1 – 1.3	2.5 – 3.9	10 – 11
$dE/dx_{electron}$, eV/nm	25 – 30	67 – 76	123 – 145	200 – 240

According to the presented data on the assessment results of ionization losses and ion range in the near-surface layers of alloys, it can be concluded that an increase in ion energy from 28 MeV for O^+ to 145 MeV and 230 MeV for Kr^+ and Xe^+ ions leads to a change in the ion range by no more than 2.0 – 3.0 μm , and in the case of Ar^+ ions with an energy of 70 MeV, the ion range is comparable to the range of O^+ ions. In this case, the change in the type of ions and interaction mechanisms has a clearly expressed dependence on the mass of

the ions and the initial energy. In this case, the analysis of the ionization loss values showed that in the case of heavy Kr^+ and Xe^+ ions, the ionization loss values are more than an order of magnitude higher than those of O^+ ions, which is due to the greater intensity of the interaction of incident heavy ions with the electron and nuclear subsystems, which leads to more intense slowing down of the ions. It should also be noted that lighter O^+ ions, due to the peculiarities of interaction with the electron and nuclear subsystem at lower energy, are able to penetrate to greater depths, due to lower values of ionization losses, especially when interacting with nuclei. According to the presented calculations, it can be concluded that the use of these types of ions allows the formation of a damaged area of approximately the same range in depth in alloy samples, which in turn can be used to describe the structural and mechanical changes in the near-surface layers.

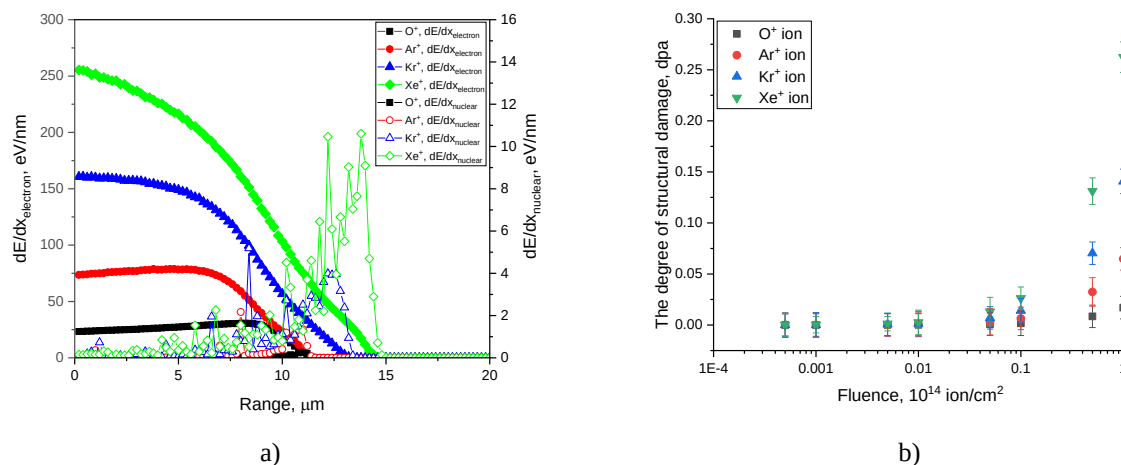


Fig. 1. Results of calculations using the SRIM Pro software code: a) Values of change in ionization losses along the trajectory of ions in the alloy; b) Dependence of the change in the value of atomic displacements for the studied ions upon collision and change in irradiation fluence

Figure 1b shows the results of calculations of the values of atomic displacements depending on the irradiation fluence, characterizing the number of displacements of atoms from the nodes of the crystal lattice as a result of the interaction of incident ions with the crystal structure of the target. To estimate the dpa values, the methodology described in [23] was used. Data are given for all types of considered ions used for irradiation of alloy samples depending on the irradiation fluence. A general analysis of the obtained values indicates that at low irradiation fluences (5×10^{10} - $5 \times 10^{11} \text{ ion/cm}^2$) the degree of structural damage is extremely low and does not differ significantly depending on the type of ions used for irradiation. In this case, the observed effects are explained by the fact that at low irradiation fluences, a limited number of point defects are formed in the material, such as vacancies and interstitial atoms, which can recombine with each other, and the areas where these defects are formed are isolated from each other. At fluences above 10^{12} ion/cm^2 , the differences between the effects of ions depending on their type and energy become more pronounced, which is explained by the fact that heavy ions have a greater mass and higher momentum, as a result of which they transfer more energy to the atoms of the crystal lattice during collisions. This leads to the formation of more intense displacement cascades and an increase in the number of radiation defects formed. At the same time, light ions such as oxygen lose more energy through ionization processes, which reduces the contribution of nuclear collisions and, accordingly, reduces the level of structural damage.

The determination of structural damage in the near-surface layer of the AlNbTiVZr alloy was carried out by the assessment of changes in the structural parameters of the main phase B2 and further calculation of changes in the structural damage degree based on changes in the crystal lattice volume in comparison with the results for the initial samples with a change in the irradiation fluence. To assess the influence of accumulated structural damage caused by irradiation with heavy ions of different energies on the change in the mechanical properties of alloys, as well as to identify the role of changes in ionization losses and structural damage on the degree of softening of damaged layers, a hardness assessment method was used.

Changes in sample hardness before and after testing were determined using an indentation method employing a Vickers diamond pyramid indenter. The load applied to the indenter was approximately 10 N, and the dwell time was about 15 seconds; the indenter was then moved a distance of approximately 30 μm , and the measurements were repeated. At least 20 indentations were performed on each irradiated alloy sample.

3. Results and discussion

One of the key parameters characterizing the degree of influence of heavy ions on the crystal structure is the change in the volume of the crystal lattice of irradiated samples and its comparison with the results of the initial values. In this case, for cubic lattices, the change in the crystal lattice volume characterizes the overall deformation of the crystal structure, and the nature of the changes itself determines the type of deformation distortions caused by the processes of interaction of ions with the material. Also, the use of this parameter makes it possible to quantitatively estimate the degree of radiation-induced structural changes caused by the accumulation of deformation distortions, and the value itself for cubic types of crystalline structures is an integral characteristic of the deformation state, since the lattice parameters in cubic systems are the same in all directions, which means that an increase or decrease in the volume of the crystalline structure reflects a change in interatomic distances, as well as the total effect of radiation defects and their accumulation in the damaged layer.

Figure 2 shows the assessment results of the change in the degree of volumetric swelling of the crystal lattice caused by the accumulation of deformation distortions in the crystal structure, caused by the processes of interaction of incident ions with the target material. The choice of crystal lattice volumetric expansion as an evaluation parameter is based on the following assumptions. Structural damage resulting from the interaction of incident ions with the crystal structure causes distortion due to the formation and subsequent migration of defects and vacancies. In this instance, comparing the crystal lattice volumes of samples before and after irradiation makes it possible to assess the extent of structural change caused by external factors, while the nature of these changes allows for the identification of the type of deformation involved. According to the assessment of the data obtained, the increase in the crystal lattice volume for irradiated samples indicates the formation of tensile deformation stresses in the crystal structure caused by irradiation, the accumulation of which is associated with the formation of vacancies and their subsequent agglomeration and the formation of vacancy clusters. At the same time, the accumulation of vacancy defects leads to a growth in interatomic distances, which consequently leads to an elevation in the crystal lattice parameters. The very nature of changes in the value of volumetric swelling of the crystal lattice, shown in Figure 2a, indicates a cumulative effect caused by a change in the irradiation fluence, as well as the direct influence of the energy and type of incident ions on the degree of deformation distortions. In the case of lighter O^+ ions, changes in the volumetric swelling degree are most pronounced at fluences above 10^{13} ion/cm², while at irradiation with Kr^+ or Xe^+ ions, an intensive growth in the volumetric swelling degree is observed at fluences above $5 \times 10^{11} - 10^{12}$ ion/cm². In the case of irradiation with Ar^+ ions, the nature of changes in the degree of volumetric swelling is similar to the changes caused by irradiation with O^+ ions, but the degree of changes is somewhat higher. The dependencies obtained are a direct confirmation of the role of changes in the type and energy of ions in the deformation-induced distortion of the crystalline structure of the damaged layer. According to the data obtained, the higher the energy of the incident ions, the more intense the change in the volumetric swelling of the damaged layer, which is especially evident at high irradiation fluences.

In this case, an elevation in the irradiation fluence causes a reduction in the distance between structurally altered areas that arise along the trajectory of ion movement in the damaged layer, thereby increasing the density of damaged areas and their subsequent overlap. In this case, the size of the incident ions and their energy play a key role in the size of these regions with increased defectiveness, which in turn leads to the fact that the higher the energy of the ions, the larger the size of these regions, and accordingly the overlapping effect is achieved at lower irradiation fluence values. Also, according to the data presented in Table 1, a change in the type and energy of incident ions leads to an elevation in ionization losses, which, as a consequence, leads to a growth in the intensity of cascade displacements, and, as a consequence, an increase in the concentration of defects in the damaged area, which causes more intense distortions due to a higher density of defects and vacancies in the damaged layer. Based on the obtained data on the dependence of changes in the degree of volumetric swelling, and also taking into account the fact that the growth of deformation distortions occurs when structurally altered areas overlap, it is possible to draw a conclusion about critical fluences at which the nature of deformation processes changes and destabilization of the damaged layer grows.

In this case, at irradiation with O^+ or Ar^+ ions, the formation of overlapping defect regions is observed at fluences above 10^{13} ion/cm², while for heavy Kr^+ and Xe^+ ions, the overlapping of defect regions is observed at fluences above $5 \times 10^{11} - 10^{12}$ ion/cm², which in turn indicates a higher efficiency of heavy ions in the initiation of structural changes due to the accumulation of radiation-induced defects and vacancies. An

assessment of the characteristic sizes of defective areas, taking into account the obtained critical fluence values at which a sharp change in the volumetric swelling degree is observed and taking into account the assumption of a uniform distribution of these areas in the material, showed that for O^+ and Ar^+ ions, the average sizes of structurally altered areas are of the order of 3 – 5 nm, and for Kr^+ and Xe^+ ions, the characteristic sizes are of the order of 10 – 20 nm. In this case, the overlap of defective areas leads to the formation of continuous zones of increased defectiveness, which is accompanied by an increase in the density of deformation distortions of the crystal lattice due to the active accumulation of vacancies, the formation of vacancy clusters, which enhances the effect of local destabilization of the crystal structure of the near-surface layers. The overlap of such damaged regions is accompanied by an increase in the concentration of vacancy defects and the formation of vacancy clusters, nanopores and other defective structures, which are the main source of radiation-induced volumetric swelling. The accumulation of such defects leads to a local increase in interatomic distances and the formation of tensile deformations in the crystal lattice, which ultimately manifests itself in an increase in the volume of the material. It should also be noted that at high ion energies, the contribution of ionization energy losses associated with the excitation of the electronic subsystem of the material grows. This can lead to additional local energy disturbances in the structure of the material and enhance the processes of defect formation and atomic migration. In combination with nuclear collisions, such processes contribute to a more intense development of radiation damage and an increase in volumetric swelling, which is most clearly seen in the dependencies shown in Figure 2a for heavy Kr^+ and Xe^+ ions, for which the maximum change in the volumetric swelling value at a fluence of 10^{14} ion/cm² is 2.8 % and 3.5 %, respectively, while for samples irradiated with O^+ and Ar^+ ions, the maximum change in the volumetric swelling value is about 1.0 – 1.3 % at a fluence of 10^{14} ion/cm².

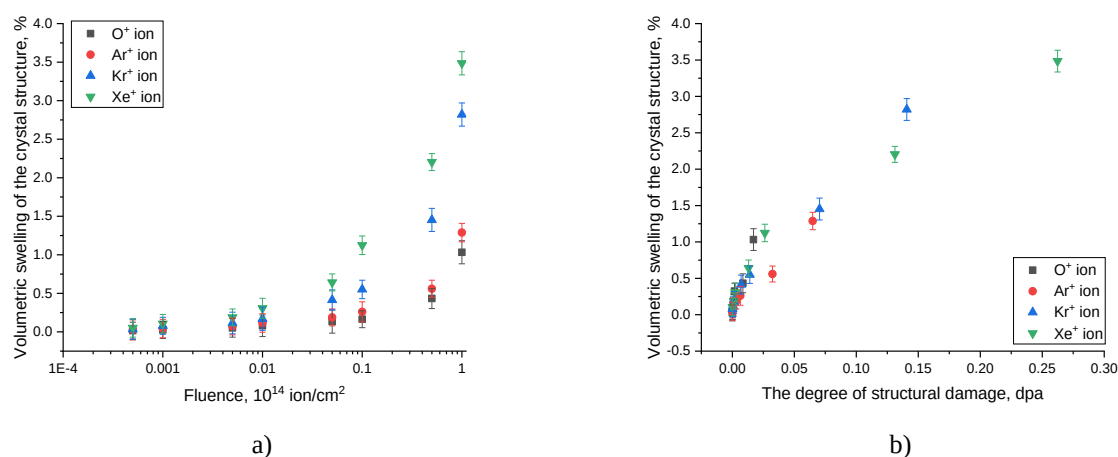


Fig. 2. Results of the assessment of changes in structural properties: a) results of changes in volumetric swelling depending on irradiation fluence; b) results of changes in volumetric swelling depending on the damage degree

For a correct comparison of the degree of volumetric swelling caused by different types of ions during irradiation, the dependence of the change in the volumetric swelling value on the degree of structural damage caused by atomic displacements was plotted. The use of the atomic displacement parameter allows for an objective comparison of the results of irradiation with different ions, since this parameter considers not only the type and energy of the incident particles, but also the total density of defects arising during the collision of ions with the crystal structure of the target material. The need to use such a dependence is due to the fact that when irradiated with different ions, there are significant differences in the mechanisms of energy transfer to the material, the depth of particle penetration, and the nature of the formation of displacement cascades. Light ions, such as O^+ , lose energy to a greater extent through ionization processes, interacting with the electron subsystem of the material. At the same time, heavier ions such as Kr^+ and Xe^+ have significantly greater mass and are able to initiate intense nuclear collisions, forming powerful cascades of atomic displacements. This leads to the formation of different concentrations of radiation defects even at the same irradiation fluence values. In this case, the construction of the dependence of volumetric swelling on the value of atomic displacements makes it possible to determine how effectively the formation of defects affects the change in the crystal lattice volume and the development of deformation distortions in the material. Analysis of the presented dependencies in Figure 2b showed a direct correlation between the change in the volumetric swelling

value and the value of atomic displacements caused by irradiation. According to the given dependencies, a change in the type of ions leads to more pronounced structural degradation due to an increase in atomic displacements caused by changes in ionization losses of ions and energy transfer mechanisms. In this case, heavy ions transfer more energy to the atoms of the target crystal lattice, which leads to the formation of more powerful displacement cascades and an increase in the concentration of vacancies, which leads to increased destabilization of the near-surface layer. Moreover, the evaluation of the obtained dependencies makes it possible to demonstrate more clearly the effect of alteration of the type and energy of ions during irradiation on the kinetics of destabilization of the near-surface layers associated with the accumulation and subsequent aggregation of vacancy defects arising as a result of irradiation. According to the presented dependencies, the ion energy growth leads to an increase in the processes of energy transfer to the electron subsystem, thereby increasing ionization electron losses (see the data presented in Table 1). For light ions, electron braking becomes the dominant mechanism of energy loss, which is accompanied by excitation and ionization of atoms, as well as a local increase in temperature in the ion passage area. These processes contribute to additional changes in the structure of the material and can lead to the formation of tensile deformation distortions in the crystal lattice.

The occurrence of such distortions is associated with the accumulation of vacancies and the expansion of interatomic distances in damaged areas. As the ion energy grows, these effects intensify, leading to an increase in local stresses and an elevation in the crystal lattice deformation degree. As a result, a more pronounced change in the lattice parameters and an increase in the volume of material in the near-surface layer are observed. At high particle energies, the contribution of ionization losses becomes dominant. Electronic excitations can lead to local energy excitation of the lattice, which contributes to additional rearrangement of the material structure and can enhance the processes of defect formation and atomic migration.

The main mechanism that determines the degree of structural damage is nuclear deceleration of ions, associated with elastic collisions of incident particles with atoms of the crystal lattice. In such collisions, part of the ion energy is transferred to the atoms of the material, which can leave their positions at the nodes of the lattice. If the energy of the transmitted pulse exceeds the atom displacement threshold, Frenkel pairs, consisting of a vacancy and an interstitial atom, are formed. At high ion energies, such displacements can initiate cascades of atomic collisions, as a result of which one displaced atom knocks out other atoms from the lattice nodes. As a result, a region of local radiation damage with a high concentration of defects is formed, and in the case of heavy Kr^+ and Xe^+ ions, the sizes of these regions are significantly larger than for lighter O^+ and Ar^+ ions, which in turn leads to increased destabilization effects. The analysis of the obtained dependencies makes it possible to more clearly demonstrate the effect of the type and energy of ions on the kinetics of destabilization of the near-surface layers of the material. Heavy ions such as Kr^+ and Xe^+ cause more intense nuclear braking processes and form more powerful displacement cascades, which leads to accelerated accumulation of defects. As a result, there is an increase in the processes of vacancy clustering, pore formation and volumetric swelling growth, which ultimately leads to more pronounced structural degradation of the near-surface layer of the irradiated material.

Figure 3 reveals the assessment results of changes in the hardness of the studied alloy samples depending on the irradiation fluence. According to the data presented in Figure 3a, it is evident that at low irradiation fluences (below 10^{12} ion/cm²), the changes in the hardness values of the near-surface layer are practically no different from the initial values, and the degree of change is no more than 0.2 – 0.5 % of the initial values. The obtained results indicate that in the case of failure to achieve the effect of overlapping defective areas in the damaged layer, changes in the structure of alloys due to the occurrence of point and vacancy defects do not have a significant effect on the change and destabilization of mechanical properties. With an increase in irradiation fluence above 10^{12} ion/cm², at which the formation of the effect of overlapping defective areas is observed for heavy ions, according to the presented data on changes in hardness, a reduction in values is observed, which indicates a decrease in the resistance of the material to plastic deformation caused by irradiation. The most pronounced change in hardness for samples irradiated with O^+ ions at a fluence of 10^{14} ion/cm² is approximately 520 – 525 HV, which, as a percentage relative to the initial values, is less than 4 %. In the case of irradiation with Ar^+ ions, the reduction in hardness at a fluence of 10^{14} ion/cm² is approximately 515 – 517 HV, which is less than 5 % of the initial values.

In the case of heavy Kr^+ and Xe^+ ions, the decrease in hardness at a fluence of 10^{14} ion/cm² is more pronounced than in the case of irradiation with light ions and is approximately 6 – 8 % of the initial values of the hardness of the alloys. This behavior is due to the fact that heavy ions transfer more energy to the atoms of the crystal lattice, forming more intense displacement cascades and increasing the concentration of vacancy

defects. In this case, the decrease in hardness is associated with the development of processes of volumetric swelling and the accumulation of defective clusters, which lead to a weakening of interatomic bonds and an increase in local tensile deformations in the crystal lattice. The overlapping of defective areas at high fluences contributes to the formation of zones of increased defectiveness, which leads to the softening of the near-surface layer of the material.

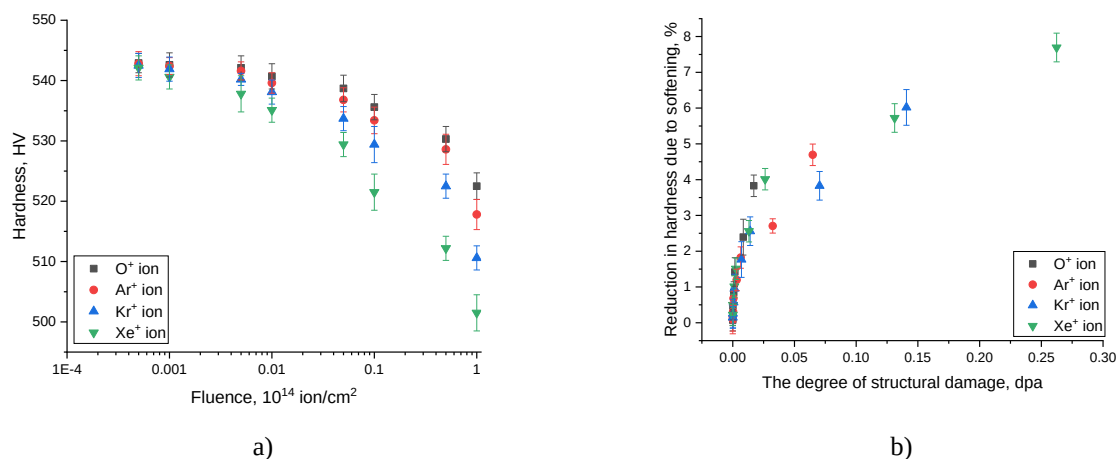


Fig. 3. Results of the assessment of changes in the mechanical properties of alloys: a) results of changes in hardness depending on irradiation fluence; b) results of the assessment of the degree of hardness reduction during softening depending on the value of atomic displacements caused by irradiation

Figure 3b demonstrates the assessment results of the degree of hardness reduction during softening depending on the value of atomic displacements caused by irradiation. Analysis of the data obtained showed that an elevation in the structural damage degree leads to a gradual increase in the value of the reduction in hardness of the alloy under study. At small damage values (up to $\sim 0.01 - 0.02$ dpa), the reduction in hardness remains insignificant and amounts to less than 1 – 2 %, which indicates a weak influence of the initial accumulation of point defects on the mechanical properties of the material.

At this stage, most of the resulting vacancies and interstitial atoms can recombine without causing significant degradation of the structure. As the degree of damage increases to $\sim 0.05 - 0.10$ dpa, a more noticeable decrease in hardness, reaching approximately 2 – 3 %, is observed. This is due to an increase in the concentration of radiation defects and the onset of their clustering, which leads to local distortions of the crystal lattice and a decrease in the material's resistance to plastic deformation. At high damage values ($\sim 0.15 - 0.30$ dpa), the reduction in hardness becomes most pronounced and can reach 6 – 8 %. In this area there is an active accumulation and aggregation of vacancy defects, the formation of defective clusters and local areas of disordered structure. The overlapping of displacement cascades leads to the formation of continuous zones of increased defectiveness, which contributes to the destabilization of the near-surface layer and its softening.

Also, analysis of the data obtained showed that the degree of hardness reduction depends on the type of incident ions. The most significant decrease in hardness is observed upon irradiation with heavy Xe⁺ ions, for which, at maximum damage values (~ 0.27 dpa), the decrease in hardness reaches about 7 – 8 %. Slightly lower values are typical for Kr⁺ ions, where the reduction in hardness is approximately 5 – 6 %. For Ar⁺ ions, the hardness reduction value is at the level of 3 – 4 %, whereas when irradiated with light O⁺ ions, the reduction in hardness remains minimal and does not exceed 2 – 3 %. The obtained dependences are explained by the fact that heavy ions transfer more energy to the atoms of the crystal lattice, forming more powerful displacement cascades and causing a more intense accumulation of radiation defects. As a result, the destabilization degree of the structure grows, which leads to a more pronounced softening of the material. Thus, the results presented show that the reduction in hardness is directly related to the radiation damage degree, and the intensity of material softening increases as dpa grows. In this case, the greatest influence on the change in mechanical properties is exerted by heavy Kr⁺ and Xe⁺ ions, which cause the most significant degradation of the structure of the near-surface layer.

4. Conclusion

Analysis of structural changes in the near-surface layer depending on the type of incident ions made it possible to estimate the onset of the formation of overlapping regions of defective inclusions in the damaged layer, as well as to qualitatively assess the sizes of these regions formed along the trajectory of ion movement in the material. According to the assessment, it was found that for light O^+ and Ar^+ ions the overlap of defective inclusions is observed at fluences above 10^{13} ion/cm², which makes it possible to conclude that the sizes of defective areas are of the order of 3 – 5 nm. For heavy Kr^+ and Xe^+ ions, the overlap of defective regions, which causes an increase in structural changes, is observed at fluences of the order of $5 \times 10^{11} - 10^{12}$ ion/cm², which makes it possible to conclude that the sizes of defective regions as a result of the interaction of ions with the crystal structure are of the order of 10 – 20 nm, and the increase in size compared to light ions is due to the formation of more powerful displacement cascades and an elevation in the contribution of electronic stopping power and nuclear stopping power to structural changes caused by irradiation. The results obtained indicate that the type of incident ions and the irradiation fluence value determine the nature of the formation of the defective structure of the material, as well as the critical conditions under which the overlap of radiation-induced damaged areas begins. Moreover, heavy ions form larger damage zones and cause the overlap of defective areas at significantly lower fluences compared to light ions, which leads to more intense destabilization of the near-surface layer of the material.

Based on the data obtained, it can be concluded that during description of structural damage and changes in the mechanical properties of alloys irradiated with different ions, the most optimal parameter for comparison of changes caused by irradiation is the degree of damage, and not the irradiation fluence.

Studies on the assessment of the mechanical properties of alloys showed that ion irradiation leads to a gradual change in the mechanical properties of the near-surface layer of the alloy under study, expressed in a decrease in microhardness as the irradiation fluence and the structural damage degree grow. It has been established that the softening degree is directly related to the radiation damage value, characterized by the dpa parameter: at low damage values, changes in mechanical properties remain insignificant, whereas with an increase in the damage degree, a more pronounced reduction in hardness is observed. The greatest deterioration in mechanical characteristics was recorded during irradiation with heavy Kr^+ and Xe^+ ions, which is associated with the formation of more powerful displacement cascades and an increased concentration of vacancy defects in the crystal lattice. It is shown that the accumulation and subsequent aggregation of vacancy defects, as well as the overlap of damaged areas at high irradiation fluences, lead to increased deformation distortions of the crystal structure and destabilization of the near-surface layer of the material. Moreover, the development of volumetric swelling processes and the formation of defective clusters are the main factors causing a decrease in hardness and deterioration of the mechanical properties of the irradiated material.

Conflict of interest statement

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

CRedit Author statement

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References

- Pickering, E. J., Carruthers, A. W., Barron, P. J., Middleburgh, S. C., Armstrong, D. E., & Gandy, A. S. (2021). High-entropy alloys for advanced nuclear applications. *Entropy*, 23(1), 98. <https://doi.org/10.3390/e23010098>
- Xiang, C., Han, E. H., Zhang, Z. M., Fu, H. M., Wang, J. Q., Zhang, H. F., & Hu, G. D. (2019). Design of single-phase high-entropy alloys composed of low thermal neutron absorption cross-section elements for nuclear power plant application. *Intermetallics*, 104, 143-153. <https://doi.org/10.1016/j.intermet.2018.11.001>
- Skakov, M. K., Baklanov, V. V., Nurpairova, G. S., Akaev, A. S., Bekmuldin, M. K., & Toleubekov, K. O. (2024). Analysis of methods for simulating the decay heat in corium when modeling a severe accidents at nuclear power plant. *Eurasian Physical Technical Journal*, 21(1), 47. <https://doi.org/10.31489/2024No1/57>
- Shi, T., Lei, P. H., Yan, X., Li, J., Zhou, Y. D., Wang, Y. P., & Lu, C. Y. (2021). Current development of body-centered cubic high-entropy alloys for nuclear applications. *Tungsten*, 3(2), 197-217. <https://doi.org/10.1007/s42864-021-00115-4>
- Moschetti, M., Burr, P. A., Obbard, E., Kruzic, J. J., Hosemann, P., & Gludovatz, B. (2022). Design considerations for high entropy alloys in advanced nuclear applications. *Journal of Nuclear Materials*, 567, 153814. <https://doi.org/10.1016/j.jnucmat.2022.153814>
- Chakraborty, P., & Tewari, R. (2025). High-entropy alloys for nuclear applications. *Journal of Materials Science*, 60(3), 1439-1453. <https://doi.org/10.1007/s10853-024-10511-z>
- Cheng, Z., Sun, J., Gao, X., Wang, Y., Cui, J., Wang, T., & Chang, H. (2023). Irradiation effects in high-entropy alloys and their applications. *Journal of Alloys and Compounds*, 930, 166768. <https://doi.org/10.1016/j.jallcom.2022.166768>
- Yang, T., Guo, W., Poplawsky, J. D., Li, D., Wang, L., Li, Y., & Zinkle, S. J. (2020). Structural damage and phase stability of Al_{0.3}CoCrFeNi high entropy alloy under high temperature ion irradiation. *Acta Materialia*, 188, 1-15. <https://doi.org/10.1016/j.actamat.2020.01.060>
- Kumar, N. K., Li, C., Leonard, K. J., Bei, H., & Zinkle, S. J. (2016). Microstructural stability and mechanical behavior of FeNiMnCr high entropy alloy under ion irradiation. *Acta Materialia*, 113, 230-244. <https://www.osti.gov/biblio/1256811>
- Zhang, L., Zhang, P., Li, N., Zhang, X., & Mei, X. (2024). Effects of single and simultaneous Fe, He ions irradiations on CoCrFeMnNi high entropy alloy. *Journal of Alloys and Compounds*, 994, 174711. <https://doi.org/10.1016/j.jallcom.2024.174711>
- Zdorovets, M. V., Kozlovskiy, A. A., Moldabayeva, G., Ivanov, I. A., & Konuhova, M. (2025). Radiation-induced degradation effects of optical properties of MgO ceramics caused by heavy ion irradiation. *Optical Materials: X*, 26, 100406. <https://doi.org/10.1016/j.omx.2025.100406>
- Turdiyev, M. T., Kasenov, B. K., Nukhuly, A., Bekturganov, Zh. S., Kasanova, S. B., Sagintaeva, Z. I., & Kuanyshbekov, E. E. (2025). Thermodynamic and electrophysical properties of a new semiconductor based on oxides of rare-earth and transition metals. *Eurasian phys. tech. j.*, 22(3 (53)), 36-47. <https://doi.org/10.31489/2025N3/36-47>
- Moldabayeva, G. Z., Kozlovskiy, A. L., Kuldeyev, E. I., Syzdykov, A. K., & Bakesheva, A. (2024). Study of the effectiveness of corrosion resistance growth by application of layered AlN–TiO₂ coatings. *Coatings*, 14(4), 373. <https://doi.org/10.3390/coatings14040373>
- Kareer, A., Waite, J. C., Li, B., Couet, A., Armstrong, D. E. J., & Wilkinson, A. J. (2019). ‘Low activation, refractory, high entropy alloys for nuclear applications’. *Journal of Nuclear Materials*, 526, 151744. <https://doi.org/10.1016/j.jnucmat.2019.151744>
- Wang, B., Yang, C., Shu, D., & Sun, B. (2023). A review of irradiation-tolerant refractory high-entropy alloys. *Metals*, 14(1), 45. <https://doi.org/10.3390/met14010045>
- Ferreirós, P. A., von Tiedemann, S. O., Parkes, N., Gurah, D., King, D. J. M., Norman, P., & Knowles, A. J. (2023). VNbCrMo refractory high-entropy alloy for nuclear applications. *International Journal of Refractory Metals and Hard Materials*, 113, 106200. <https://doi.org/10.1016/j.jrmhm.2023.106200>
- Tong, Y., Velisa, G., Zhao, S., Guo, W., Yang, T., Jin, K., & Zhang, F. X. (2018). Evolution of local lattice distortion under irradiation in medium- and high-entropy alloys. *Materialia*, 2, 73-81. <https://doi.org/10.1016/j.mtla.2018.06.008>
- El Atwani, O., Vo, H. T., Tunes, M. A., Lee, C., Alvarado, A., Krienke, N., & Martinez, E. (2023). A quinary WTaCrVHf nanocrystalline refractory high-entropy alloy withholding extreme irradiation environments. *Nature Communications*, 14(1), 2516. <https://doi.org/10.1038/s41467-023-38000-y>
- Ge, G., Chen, F., Tang, X., Wang, Y., & Li, C. (2022). Irradiation damage versus lattice distortion in AlNbTiVCrx (x= 0, 0.5, 1) high-entropy alloys from first-principles calculations and irradiation experiments. *Journal of Nuclear Materials*, 563, 153630. <https://doi.org/10.1016/j.jnucmat.2022.153630>
- Kombaiah, B., Zhou, Y., Jin, K., Manzoor, A., Poplawsky, J. D., Aguiar, J. A., & Zhang, Y. (2023). Nanoprecipitates to enhance radiation tolerance in high-entropy alloys. *ACS Applied Materials & Interfaces*, 15(3), 3912-3924. <https://doi.org/10.1021/acsami.2c17540>

21. Zong, Y., Hashimoto, N., & Oka, H. (2022). Study on irradiation effects of refractory bcc high-entropy alloy. *Nuclear Materials and Energy*, 31, 101158. <https://doi.org/10.1016/j.nme.2022.101158>
22. Barron, P. J., Carruthers, A. W., Fellowes, J. W., Jones, N. G., Dawson, H., & Pickering, E. J. (2020). Towards V-based high-entropy alloys for nuclear fusion applications. *Scripta Materialia*, 176, 12-16. <https://doi.org/10.1016/j.scriptamat.2019.09.028>
23. Egeland, G. W., Valdez, J. A., Maloy, S. A., McClellan, K. J., Sickafus, K. E., & Bond, G. M. (2013). Heavy-ion irradiation defect accumulation in ZrN characterized by TEM, GIXRD, nanoindentation, and helium desorption. *Journal of Nuclear Materials*, 435(1-3), 77-87. <https://doi.org/10.1016/j.jnucmat.2012.12.025>

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