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Dmitriy. I. Shlimas
Engineering Profile Laboratory, L.N. Gumilyov Eurasian National University, Astana, 010008, Kazakhstan

Daryn B. Borgekov
Engineering Profile Laboratory, L.N. Gumilyov Eurasian National University, Astana, 010008, Kazakhstan

Kymbat M. Tynyshbayeva
Engineering Profile Laboratory, L.N. Gumilyov Eurasian National University, Astana, 010008, Kazakhstan

Sholpan G. Giniyatova
Engineering Profile Laboratory, L.N. Gumilyov Eurasian National University, Astana, 010008, Kazakhstan

Gulnaz Zh. Moldabayeva
Department Petroleum Engineering, Satbayev University, Almaty, 050013, Kazakhstan

See next page for additional authors

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ORIGINAL STUDY

Effect of Ion-induced Dislocation Hardening on Diffusion and Gas Swelling Mechanisms in Carbide Ceramics

Dmitriy I. Shlimas [a,b], Daryn B. Borgekov [a,b], Kymbat M. Tynyshbayeva [a], Sholpan G. Giniyatova [a], Gulnaz Z. Moldabayeva [c], Artem L. Kozlovskiy [a,b,*]

[a] Engineering Profile Laboratory, L.N. Gumilyov Eurasian National University, Astana, 010008, Kazakhstan
[b] Laboratory of Solid State Physics, The Institute of Nuclear Physics, Almaty 050032, Kazakhstan
[c] Department Petroleum Engineering, Satbayev University, Almaty, 050013, Kazakhstan

Abstract

The paper presents the assessment results of the application of the method of ion modification of the near-surface layer of SiC ceramics in order to create a dislocation hardening effect to enhance the resistance of ceramics to helium swelling and embrittlement. Interest in this topic is due to the possibilities of expanding the practical application of ion modification in the field of structural materials used in extreme conditions. The choice of heavy ions for the targeted modification of the near-surface layer of ceramics is based on a hypothesis, which is based on the assumption that the isolated structural distortions created in the near-surface layer during the interaction of incident ions with the crystal structure can have a barrier effect on the ballistic nature of the migration of complex defects of the He−V type, as well as implanted helium into the material due to changes in the dislocation density in the damaged layer. According to tribological test data, it was established that the use of Ar^{8+}, Kr^{15+} ions with fluences of 10^{12} - 10^{13} ion/cm^2 allows surface wear rate reduction during mechanical wear tests during determination of the dry friction coefficient. The observed effect of enhancement of the resistance to the damaged layer destruction caused by the accumulation of structural damage due to a rise in the concentration of implanted He^{2+} ions (in this case, the irradiation fluence and the value of atomic displacements are implied) is due to the creation of additional dislocation defects and distortions caused by the impact of heavy ions. The assessment results of the change in the values of the hardness of the damaged layer along the trajectory of the He^{2+} ions revealed that the creation of structural distortions due to preliminary irradiation with heavy ions creates additional barriers for the diffusion expansion of the damaged layer in depth, from which it follows that the created effect of dislocation hardening due to irradiation with low fluences of heavy ions in the near-surface layer plays a positive effect on enhancement of the resistance to destruction caused by gas swelling.

Keywords: Helium swelling, Dislocation hardening, Ion modification, Silicon carbide, Ceramics, Tribological testing

1. Introduction

Interest to study the efficiency of increasing the resistance of ceramic materials to the accumulation of radiation damage during high-dose irradiation is primarily due to the need to expand the understanding of the mechanisms associated with the formation, accumulation and subsequent evolution of radiation defects in the damaged layer, which will make it possible to determine the potential for application of ceramics in nuclear power engineering, and secondly, to expand the capabilities of technological methods for creating high-strength radiation-resistant ceramics [1−3]. At the same time, the creation of new types of ceramic materials that have high resistance to radiation-induced erosion of the near-surface layer, as well as a decrease in strength parameters with the accumulation of structural damage, is one of the promising

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* Corresponding author at: Engineering Profile Laboratory, L.N. Gumilyov Eurasian National University, Astana, 010008, Kazakhstan.
E-mail address: kozlovskiy.a@inp.kz (A.L. Kozlovskiy).

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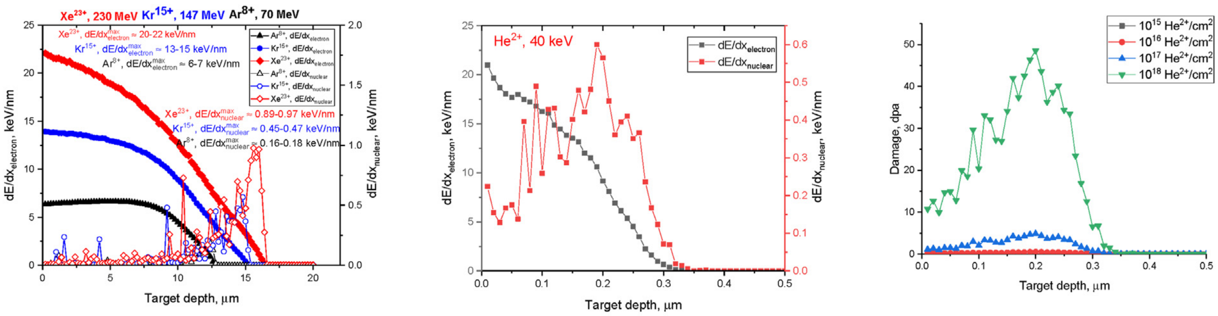
areas of research in the field of materials science [4,5]. In this direction, one of the main technological solutions related to increasing the stability of materials is mechanical deformation of the near-surface layer, which, due to the creation of a large concentration of deformation distortions in the structure, increases the dislocation density, the high concentration of which will lead to the creation of barrier effects [6—8]. Another method for enhancement of the resistance of materials to the ionizing radiation effects is the method of applying thin-film coatings to the surface of ceramics, the use of which makes it possible to enhance the resistance of materials to radiation-induced embrittlement and swelling. In this case, the use of the mechanical deformation method can be accompanied, in addition to hardening, by the creation of metastable inclusions in the near-surface layer, the presence of which, as a result of the radiation damage accumulation, can result in destructive deterioration in the properties of materials [9—12]. This method has also been tested quite well for steels and alloys, but for ceramic refractory materials, this method is not always effective due to the high strength of ceramics, which requires the use of high mechanical loads to create a modified layer. In the case of radiation-resistant coatings, it is necessary to take into account the adhesion properties of the surface, as well as indicators of adhesion strength, materials that characterize the resistance of coatings to peeling from the surface of ceramics, alongside during interaction with aggressive media or during work at high temperatures [13—15]. It is also very important to take into account the thermal stability of coatings (resistance to thermal expansion), which plays a significant role in determination of the stability of materials in the case of operation under conditions of high dose loads and irradiation temperatures [14—17]. Recently, methods of ion implantation with low-energy ions (irradiation fluences of the order of 10^{15}—10^{17} ion/cm^2) [18,19] or the creation of a defective damaged layer of a given thickness in ceramics using irradiation with heavy ions with low fluences (of the order of 10^{11}—10^{13} ion/cm^2) have been considered as alternative methods of material hardening [20,21]. In the case of ion implantation, the main emphasis is placed on creation of the effect of substitution of atoms in the crystal lattice nodes of the base material by implanted ions, thereby simulating the effect of alloying and increasing strength characteristics due to the structural modification of the near-surface layer (usually about 100—500 nm thick) [22,23]. During the use of the heavy ion irradiation method, the modified layer thickness can be on the order of several microns, which not only expands the depth of the modified layer (in comparison with the ion implantation method), but also allows the creation of a barrier layer at a depth much greater than the penetration depth of low-energy ions, which in the case of defect migration will significantly reduce the effect of diffusion of radiation defects into the material. At the same time, this modification method is based on the theory of creating a dislocation-hardened layer (a layer containing a high concentration of dislocations and point defects), the presence of which will reduce the effect of structural volumetric swelling that occurs during the accumulation of nuclear reaction products in the form of helium and hydrogen ions, the agglomeration of which in the near-surface layer plays a very important role in the degradation of ceramics used as structural materials in nuclear reactors [24,25].

The main objective of the presented work is to determine the effectiveness of radiation-induced dislocation hardening of the near-surface layer of SiC ceramics against helium embrittlement and a decrease in strength characteristics. The results presented in the work reflect the verification of the hypothesis on the use of high-energy irradiation with heavy ions to enhance the stability of the near-surface layers, due to the creation of additional structural distortions and dislocations, the presence of which limits the diffusion processes of implanted helium, and also restrains the gas deformation swelling of the near-surface layer during high-dose irradiation.

2. Materials and methods of research

In order to create additional dislocation defects in the near-surface layer caused by irradiation with heavy ions at low fluences, the studied samples of SiC ceramics were irradiated with Ar^{8+}, Kr^{15+} and Xe^{23+} ions with energies of 70, 150 and 230 MeV, respectively, and irradiation fluences of about 10^{11}—10^{13} ion/cm^2, the choice of which is due to the possibility of changing the near-surface layer with a thickness of about 10—12 μm (see the data presented in Fig. 1a). The choice of ions for modification is determined by their differences in ionic radii, as well as ionization losses, the magnitude of which determines the degree of structural deformation and the depth of the damaged layer during irradiation. Moreover, an alteration in the type of ions, according to the simulation results, leads to growth of ionization losses during interaction with electron shells, from which it follows that the most pronounced changes associated with ionization processes, and as a consequence, destruction due to anisotropic changes in electron density and the formation of metastable inclusions will be observed for the case of irradiation with Xe^{23+} ions. It should also be noted that a change in the type of ions will lead to a rise in the size of structurally deformed areas, due to differences in the values of ionization losses, which, in the



a) b) c)

Fig. 1. a) Results of simulation of the values of ionization losses of incident Ar^{8+}, Kr^{15+} and Xe^{23+} ions in the near-surface layer of SiC ceramics, reflecting the change in differences in the energy transferred by incident ions to the crystal structure as a result of interaction; b) Results of simulation of ionization losses of He^{2+} ions in the near-surface layer of SiC ceramics; c) Results of simulation of the change in the atomic displacement value along the trajectory of He^{2+} ions in the near-surface layer of SiC ceramics.

case of an elevation in fluence, can result in more pronounced effect of deformation distortions caused by the occurrence of the effect of overlapping of these areas arising along the trajectory of ion movement in the damaged layer. The choice of irradiation fluence was based on the possibilities of simulation of the emergence of isolated structurally altered regions arising along the trajectory of ion movement in the damaged layer (at irradiation fluences of 10^{11} ion/cm^2) and their partial or complete overlap at higher irradiation fluences. The irradiation was carried out on the DC-60 accelerator (Institute of Nuclear Physics of the Ministry of Energy of the Republic of Kazakhstan, Astana, Kazakhstan). The choice of the type of ions and their energy is determined by the possibilities of creating defective inclusions that arise due to athermal and ionization effects that occur during the interaction of ions with the electronic and nuclear subsystems of ceramics. The estimated atomic displacement value for the selected fluences of heavy ion irradiation is no more than 0.001 dpa, which is quite small compared to the effects that occur with high-dose irradiation with low-energy He^{2+} ions used to simulate the gas swelling processes of the near-surface layer.

Irradiation with low-energy He^{2+} ions with energies of about 40 keV was performed at the heavy ion accelerator DC-60 (Institute of Nuclear Physics of the Ministry of Energy of the Republic of Kazakhstan, Astana, Kazakhstan). Fig. 1b illustrates the simulation results of the ionization losses of He^{2+} ions, reflecting the connection between the values of the distribution of kinetic energy during collisions along the trajectory of ion movement in the damaged layer. When modeling ionization losses, a model was used that takes into account cascade effects, as well as the associated structural changes caused by the effects of displacement and widening of the damaged area. The irradiation fluences were selected in the range from 10^{15} to 10^{18} ion/cm^2, the choice of which is due to the possibility of modeling the kinetics of accumulation of structural deformation distortions in the damaged surface layer in a wide range of atomic displacement values (of the order of 1—40 dpa at irradiation fluences above 10^{16} ion/cm^2 according to the calculation data based on simulation of the atomic displacement values presented in Fig. 1c), characteristic of the structural damage accumulation during long-term operation of structural materials used in the active zone of new-generation reactors.

Tribological tests were performed using the ball-on-disk method, where a 5 mm diameter Al_2O_3 ball was used as a counterbody (ball). The sliding speed was 0.25 m/s, the counterbody load was 100 N. The number of test cycles was 15,000 cycles. The tests were carried out both for the initial samples and for those irradiated with heavy Ar^{8+}, Kr^{15+} and Xe^{23+} ions in order to determine the influence of heavy ions on the change in the friction coefficient, and also, in the case of irradiation with He^{2+} ions, to identify the influence of dislocation hardening on wear resistance.

Determination of degradation resistance due to changes in the near-surface layer was carried out using the scratch test method, performed on a Unitest framework SKU UT-750 (Unitest, USA) installation. The results of the adhesive strength reflect the effectiveness of the influence of high-energy irradiation on elevation of the resistance of the near-surface layer to peeling under mechanical action, which is caused by the accumulation of structural deformations associated with the accumulation of implanted ions, as well as atomic displacements caused by them in the damaged layer.

The influence of the diffusion mechanism of weakening of the damaged layer, the occurrence of which is associated with the migration of implanted He^{2+} ions in the damaged layer into the material at a depth exceeding the maximum path length of the ions, was determined by measuring the hardness values along the trajectory of the ions, as well as at a depth exceeding this value. The measurements were carried out using hardness measurements on side cleavages using the nanoindentation method. The data values were obtained as serial measurements in depth with a step of 50 nm.

The influence of the dislocation hardening effect caused by the deformation action of heavy ions was assessed by comparing the values of the crystal lattice volume before and after irradiation with He^{2+} ions in order to determine the value of the volumetric swelling caused by the cumulative effect associated with the migration processes of implanted helium in the damaged layer.

3. Results and discussion

The volumetric swelling of the near-surface layer of SiC ceramics exposed to He^{2+} ion irradiation with different irradiation fluences was determined by the assessment of the change in the parameters of the crystal lattice and its volume. The magnitude of volumetric swelling of the crystal structure was estimated based on changes in the parameters of the crystal lattice in the initial state and after irradiation, the result of which was an assessment of the deformation of the crystal structure, as well as its volume due to the accumulation of structural distortions. A comparison of the crystal lattice volume of the irradiated samples was carried out with the initial volume value, which made it possible to determine not only the percentage ratio of volumetric swelling associated with helium agglomeration and the deformation distortions caused by these processes, but also the type of deformation distortions caused by an elevation in tensile stresses resulting in crystal lattice deformation. The results of alterations in the volumetric swelling value are presented in Fig. 2 in the form of comparative dependences of changes in volumetric swelling of the near-surface layer of unmodified ceramics subjected to irradiation with He^{2+} ions with different irradiation fluences with similar data obtained for samples pre-irradiated with heavy ions with different fluences. The data are presented depending on the atomic displacement value, which made it possible to compare the kinetics of the dependence of structural changes on the near-surface layer damage degree.

According to the assessment of the change in volumetric swelling of the near-surface layer of ceramics contingent upon the type of preliminary exposure to heavy ions and subsequent irradiation with He^{2+} ions, it was found that the formation of additional dislocations during irradiation with Ar^{8+} and Kr^{15+} ions results in significantly less pronounced changes in volumetric swelling, which indicates the inhibition of migration processes associated with the agglomeration of implanted helium in the near-surface layer. Moreover, in the case of irradiation with Kr^{15+} ions, the volumetric swelling value reduction at an irradiation fluence growth is more pronounced than in the case of irradiation with Ar^{8+} and Xe^{23+} ions (for which the changes in volumetric swelling are minimal in comparison with non-irradiated samples). This behavior of structural changes can be explained by the balance of the distribution of kinetic energy during the interaction of incident particles with the crystal structure, which leads to the creation of structurally isolated regions containing dislocations, but the sizes of these regions are such that the overlapping effect, which can result in creation of complex structural distortions that can be observed during irradiation with Xe^{23+} ions, is not created in the case of irradiation with Kr^{15+} ions.

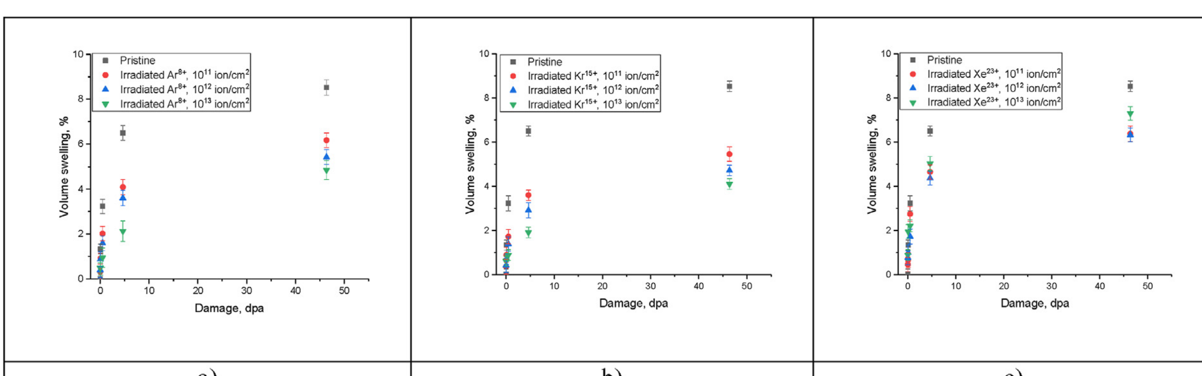


Fig. 2. Assessment results of the change in the volumetric swelling of the near-surface layer of SiC ceramics as a result of the change in the fluence of irradiation with He^{2+} ions, obtained on the basis of changes in the structural parameters of the crystal lattice: a) in case of irradiation with Ar^{8+} ions; b) in case of irradiation with Kr^{15+} ions; c) in case of irradiation with Xe^{23+} ions.

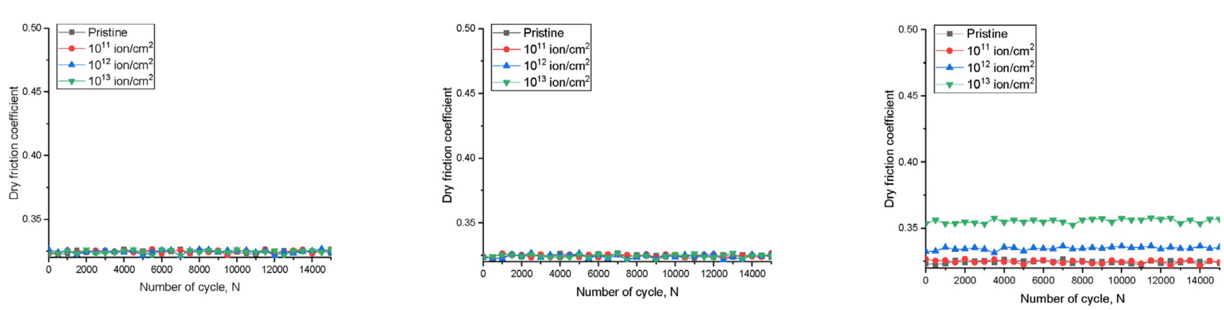
Moreover, the decline in the volumetric swelling value of the crystalline structure of the damaged layer for modified samples in comparison with the data for unmodified ceramics indicates a positive influence of the effect of structural changes associated with the formation of structural distortions and changes in dislocation density in the damaged layer. In this case, the obtained data on the differences in the values of volumetric swelling are direct confirmation of the effect of dislocation hardening created by the interaction of heavy ions with the crystalline structure of the near-surface layer, as well as the formation of isolated structural regions that arise along the trajectory of ion movement in the material (isolation is achieved by irradiation with low fluences, at which, according to the data of works [26,27], the overlap effect is minimal).

The influence of deformation distortion, alongside restraining factors in the form of dislocation hardening caused by the effect of heavy ions, on the softening of the near-surface layer and the reduction of resistance to external mechanical influences was determined using the method of determination of the dry friction coefficient of the samples under study. Changes in the dry friction coefficient depending on the number of test cycles reflect the dynamics of deterioration of the near-surface layer under mechanical influences caused by partial embrittlement of structurally deformed areas associated with the accumulation of implanted helium in the near-surface layer.

Fig. 3 reveals the results of tribological tests of the studied ceramics, performed using the "ball on disk" method, reflecting the effect of irradiation with heavy Ar^{8+}, Kr^{15+} and Xe^{23+} ions on changes in surface wear during friction. The data are presented in order to identify the degradation rate of the ceramic surface in the case of irradiation with heavy ions, in order to subsequently take this factor into account during assessment of changes in the wear rate of samples irradiated with He^{2+} ions.

The results of tribological tests of the studied ceramic samples exposed to irradiation with heavy Ar^{8+} and Kr^{15+} ions depending on the variation of the irradiation fluence did not show significant changes in the dry friction coefficient, indicating a low effect on the wear resistance of ceramics in the case of irradiation with low fluences characteristic of isolated structural changes. It should also be noted that in this case, that under heavy ion irradiation, the main changes in the structure at low irradiation fluences are distributed in a fairly large volume, and the isolated nature does not allow for a negative impact on the stability against destruction in the case of radiation-resistant ceramics. In the case of irradiation with heavy Xe^{23+} ions, the observed changes in the dry friction coefficient, expressed as an increase of about 10 % compared to the initial values at maximum irradiation fluence, can be explained by deformation distortion of the near-surface layer due to the formation of an overlap of structurally altered areas.

Fig. 4 shows the results of tribological tests of the studied ceramics after irradiation with He^{2+} ions with different irradiation fluences, reflecting the degradation of the near-surface layer caused by the structural damage accumulation during the agglomeration of helium in the voids of the crystal structure and the deformation distortions of the damaged layer associated with these processes. The dynamics of the change in the coefficient of dry friction in the case of SiC ceramics (unmodified) depending on the fluence of irradiation with He^{2+} ions indicates a cumulative effect of structural distortions, an elevation in the concentration of which (according to the data presented in Fig. 2, see the results of volumetric swelling) results in destabilization of the surface and deterioration of friction, the main changes of which are observed with prolonged exposure. Moreover, the nature of the surface degradation, which is indicated by the dry friction coefficient growth with a rise in the number of test cycles, indicates the



a) b) c)

Fig. 3. Results of tribological tests of SiC ceramics subjected to heavy ion irradiation in order to create a hardening effect in the near-surface layer: a) in case of irradiation with Ar^{8+} ions; b) in case of irradiation with Kr^{15+} ions; c) in case of irradiation with Xe^{23+} ions.

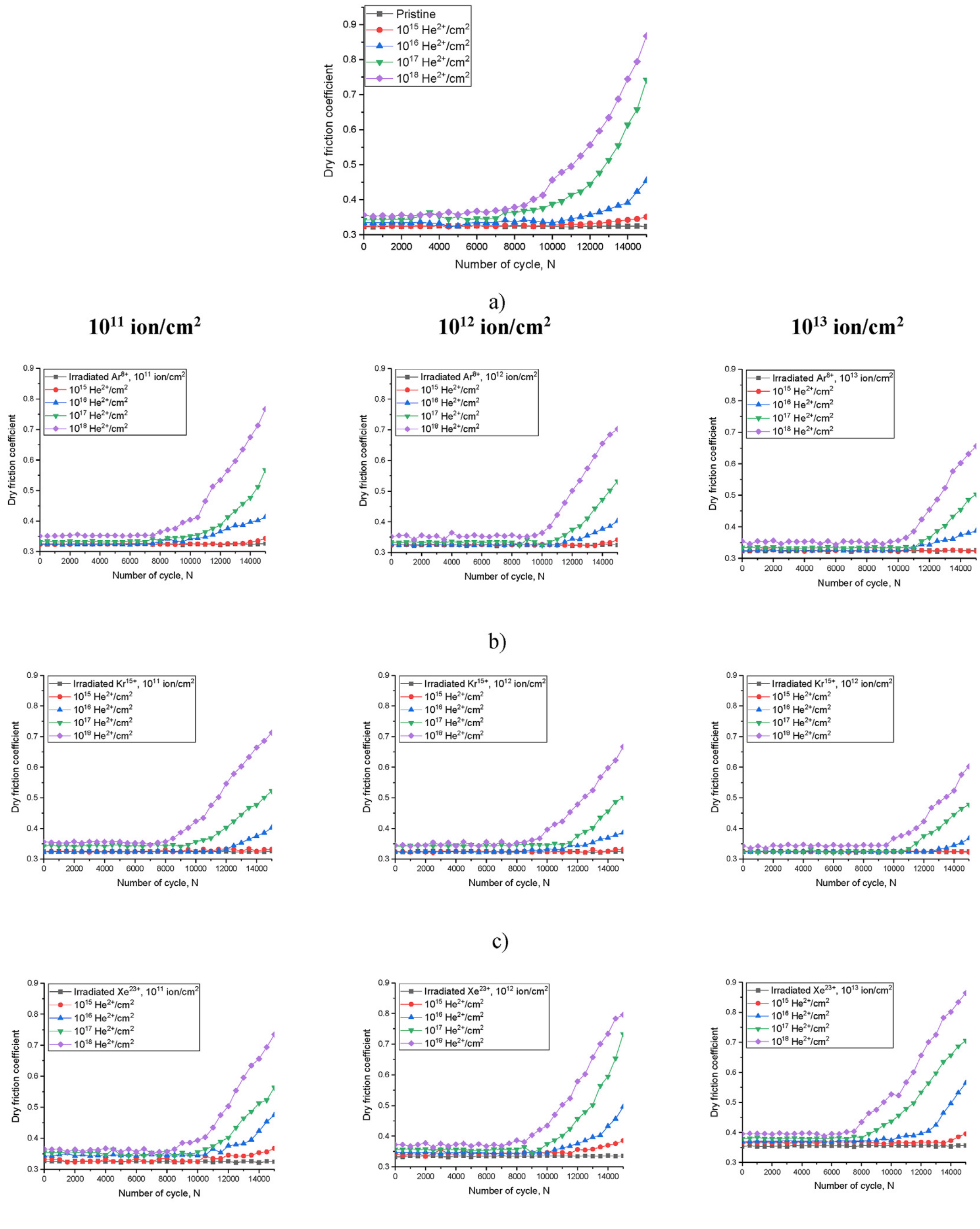


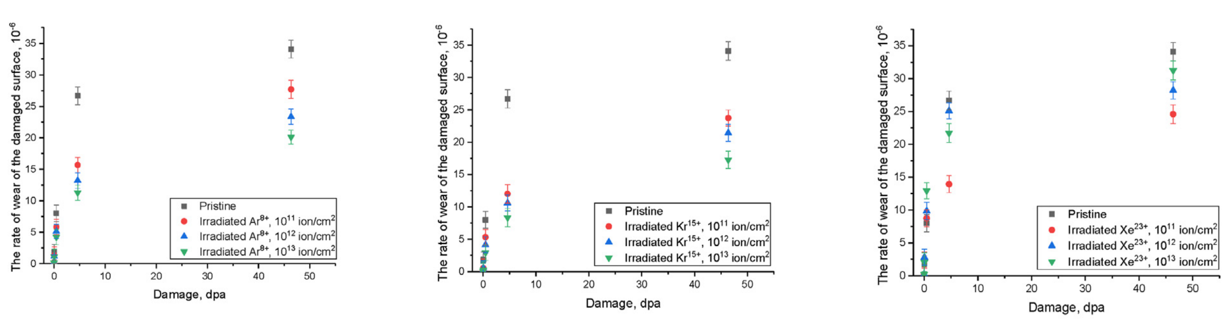
Fig. 4. Results of tribological tests of the studied ceramics after irradiation with He^{2+} ions with different irradiation fluences: a) in the initial state (not modified by heavy ion irradiation); b) irradiated with Ar^{8+} ions with different irradiation fluences; c) irradiated with Kr^{15+} ions with different irradiation fluences; d) irradiated with Xe^{23+} ions with different irradiation fluences.

destructive effect of volumetric swelling, which is most pronounced at fluences of 10^{17}—10^{18} He^{2+}/cm^2, for which, according to several works [28—30], the formation of gas-filled inclusions can be observed in the structure of the damaged layer. In this case, the observed acceleration of surface destruction, expressed in the counterbody resistance growth during friction, can be explained by the effect of the damaged layer destruction due to the opening of gas-filled inclusions, as well as embrittlement of the surface, which results in the surface destabilization, and as a consequence, the creation of additional obstacles during friction.

In turn, for modified ceramics irradiated with heavy Ar^{8+}, Kr^{15+} and Xe^{23+} ions, the trends in the change in the dry friction coefficient depending on the irradiation fluence of He^{2+} ions have significant differences in comparison with the changes observed for unmodified ceramics, as evidenced by the data presented in Fig. 4b–d. It is important to note that the general trend of changes in the dry friction coefficient for samples modified with heavy ions has a similar nature, indicating a destructive change in the surface of irradiated samples as a result of mechanical effects, but the magnitude of the changes, as well as the number of cycles at which changes begin to be recorded, have clearly expressed differences from similar data obtained for unmodified samples of SiC ceramics subjected to irradiation with He^{2+} ions. Such differences indicate a positive effect of preliminary ion modification associated with irradiation of ceramics with heavy Ar^{8+}, Kr^{15+} and Xe^{23+} ions on enhancement of degradation resistance and wear resistance of the near-surface layer of ceramics. It should be mentioned that the observed effects of increased wear resistance can also be explained by a decline in the volumetric swelling of the near-surface layer under high-dose irradiation with He^{2+} ions, the reduction of which, as was shown earlier, is due to the effects of dislocation hardening caused by the interaction of heavy ions with the crystalline structure of ceramics.

Fig. 5 illustrates the assessment results of the change in the surface wear rate, which were obtained by comparative analysis of changes in the dry friction coefficient at the initial value and after the tests, reflecting the surface degradation depending on the concentration of accumulated structural distortions caused by irradiation. The rate of degradation of the damaged layer was estimated using the obtained data on changes in the dry friction coefficient in the initial state and after resource tests for resistance to external influences. In this case, the calculation was carried out for each sample individually, taking into account the changes caused by preliminary modification with heavy ions. The damage rate calculations were performed using data on changes in the structural parameters of ceramics caused by prior exposure to heavy ions. The calculations were performed taking into account the changes caused by heavy ion irradiation, as a result of which the structural parameter values for each series of samples after heavy ion irradiation were used in the calculations. The trends in the wear rate change are presented depending on the atomic displacement value calculated on the basis of the simulation results taking into account the irradiation fluence of He^{2+} ions; the data are presented for each type of heavy ion used for modification depending on the irradiation fluence.

The general form of the presented wear rate dependencies, which in this case can be considered as the degradation degree of the near-surface layer under mechanical influences over a long period of time, indicates that the creation of structurally isolated distorted areas in the near-surface layer due to irradiation with heavy ions makes it possible to reduce the surface degradation degree and elevate the resistance of the near-surface layer to wear resulting from mechanical influences. At the same time, in the case of samples modified with Ar^{8+}, Kr^{15+} ions, an increase in the trend of degradation resistance growth is observed with a rise in the fluence of irradiation with heavy ions from 10^{11} to 10^{13} ion/cm^2, from which it follows that the hardening effect is significantly influenced by the concentration and size of structurally isolated deformed regions formed as a result of irradiation. This is also evidenced by the data obtained for samples irradiated with Xe^{23+} ions, for which a decrease in the trends of degradation resistance is observed, especially for an irradiation fluence of 10^{13} ion/cm^2, which is characterized by the effect of the emergence of overlapping regions of structurally deformed regions, as a result of



a) b) c)

Fig. 5. Results of the assessment of changes in the wear rate calculated on the basis of changes in the dry friction coefficient during cyclic tribological tests: a) in case of irradiation with Ar^{8+} ions; b) in case of irradiation with Kr^{15+} ions; c) in case of irradiation with Xe^{23+} ions.

which the effect of reduced resistance to external influences may arise.

Fig. 6 demonstrates the results of a comparative analysis of the degradation degree of the near-surface layer, calculated on the basis of changes in the dry friction coefficient at maximum irradiation fluence (10^{18} He^{2+}/cm^2), which reflect the maximum degree of wear resistance growth due to hardening due to irradiation with heavy ions. According to the data presented, the greatest efficiency in elevation of resistance to degradation during wear is observed for samples modified with Ar^{8+}, Kr^{15+} ions with fluences of 10^{12}–10^{13} ion/cm^2, for which the increase in resistance is more than 30–45 % depending on the irradiation fluence. In the case of using Xe^{23+} ions, the highest efficiency is observed for samples irradiated with a fluence of 10^{11} ion/cm^2, while an irradiation fluence growth above 10^{11} ion/cm^2 leads to an efficiency reduction in comparison with other types of ions used for modification. This effect in the case of irradiation with Xe^{23+} ions can be explained by differences in the values of ionization losses, an elevation in which leads to a rise in the diameter of structurally distorted regions, which in turn results in formation of an overlap effect with an increase in fluence, which was reported in Refs. [31,32]. In this case, the formation of the overlap effect results in more pronounced alterations in the structure of the damaged layer and its destabilization, which, when irradiated with low-energy He^{2+} ions, results in less pronounced inhibition of deformation distortions associated with the cumulative effect.

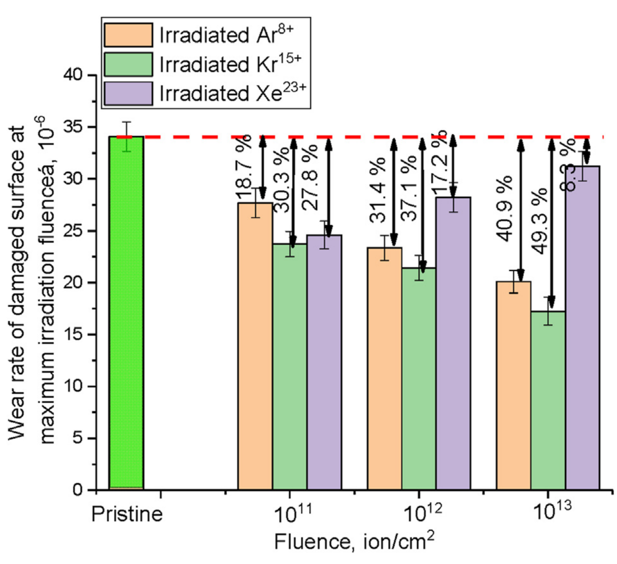


Fig. 6. Results of comparative analysis of changes in the near-surface layer degradation value (surface wear rate), obtained for samples irradiated with He^{2+} ions at a fluence of 10^{18} He^{2+}/cm^2 for samples modified with heavy ions with different irradiation fluences (the red dotted line indicates the surface degradation value in the case of unmodified ceramics, relative to which the calculation of the efficiency of wear resistance elevation was carried out).

Fig. 7 reveals the assessment results of changes in the critical load required for peeling off the near-surface layer as a result of scratch tests for the studied ceramic samples, performed under different irradiation conditions. Analysis of the change in the value of adhesive strength, characterized by the value of the maximum load of samples subjected to modification by heavy Ar^{8+}, Kr^{15+} and Xe^{23+} ions, revealed that an alteration in the irradiation conditions results in insignificant changes in the value of the adhesive strength of the coatings, which can be explained by the low concentration of structurally isolated distorted areas in the damaged layer, as well as by fairly good indicators of the resistance of SiC ceramics to minor radiation damage caused by irradiation with heavy ions at low irradiation fluences, characteristic of the creation of isolated structural distortions in the damaged layer.

The results of the adhesive strength of the near-surface layer, shown in the figure, depending on the type of ionic action (in the case of modification), as well as the degree of structural distortions caused by atomic displacements, indicate a positive dynamic in elevation of the resistance of the near-surface layer to tearing. It should be noted that in the case of ceramics not modified by ion irradiation, high-dose irradiation with He^{2+} ions results in sharp decrease in adhesive strength, the deterioration of which in this case can be explained by effects associated with volumetric swelling, the increase of which is due to the accumulation of structural distortions and deformations in the damaged layer, which leads to its destabilization. At the same time, the accumulation of structural distortions, and as a consequence, in the case of high-dose irradiation, the possible formation of gas-filled inclusions in the damaged layer, associated with the agglomeration of implanted helium in voids and structurally distorted cavities, can contribute to a reduction in the resistance of the near-surface layer to mechanical impacts. In turn, volumetric swelling of the surface layer due to the agglomeration of implanted helium in the voids can create additional deformation distortions due to an elevation in pressure in the cavities, which in the case of mechanical external influences can results in partial peeling or detonation opening of damaged cavities, which was previously reported in Refs. [33,34]. Moreover, the mechanisms of detonation opening of such gas-filled inclusions in ceramics were described in sufficient detail in a number of works [35,36] related to the study of the mechanisms of gas swelling under high-dose irradiation with He^{2+} ions. By evaluating the efficiency of elevation of the resistance to peeling in the

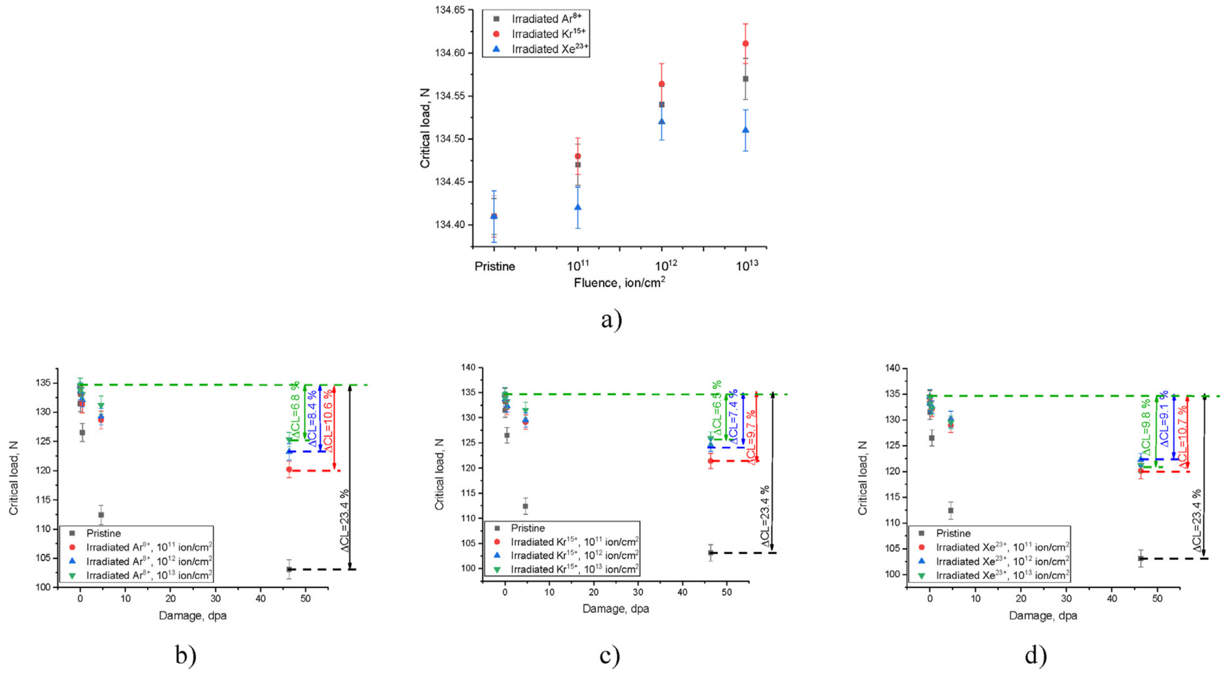


Fig. 7. Results of studies of the adhesive strength of the near-surface layer, determined by the scratch test method: a) results of changes in the critical load value during assessment of the adhesive strength for samples subjected to heavy ion irradiation with different fluences; results for changes in the critical load value after irradiation with He^{2+} ions for samples pre-irradiated with heavy ions: b) irradiated with Ar^{8+} ions with different irradiation fluences; c) irradiated with Kr^{15+} ions with different irradiation fluences; d) irradiated with Xe^{23+} ions with different irradiation fluences.

case of modified ceramics subjected to irradiation with He^{2+} ions, in comparison with the results for unmodified ceramics, it was found that irradiation with Ar^{8+} and Kr^{15+} ions at fluences of 10^{12}–10^{13} ion/cm^2 results in more than twofold increase in the resistance of the surface to peeling in the case of maximum fluence of irradiation with He^{2+} ions. Such high efficiency values are due to a decrease in the degree of volumetric swelling in the case of modified samples. However, in the case of irradiation with Xe^{23+} ions, the observed changes have a slightly smaller efficiency trend, the change of which in this case can be explained by the effect of overlapping structurally modified areas, which contributes to a decline in resistance to deformation embrittlement under high-dose irradiation with He^{2+} ions.

Fig. 8 illustrates the assessment results of the change in the hardness value by the depth of the sample, performed along the trajectory of ion movement in the ceramic material. These dependencies are given in order to reflect the change in hardness, reflecting the formation of the effect of softening of the damaged layer associated with the cumulative effect caused by structural distortions, and also to determine the kinetics of the diffusion expansion of the damaged layer, the changes of which are caused by migration processes.

In the case of unmodified SiC ceramics, a growth in the irradiation fluence of He^{2+} ions, according to the data presented in Fig. 8a, leads to a rise in the damaged layer thickness, at which changes in the hardness values are recorded, indicating diffusion mechanisms that cause softening of the near-surface layer [37–39]. Such effects can be explained by the ballistic transfer of defects deep into the material, which results in destruction of the crystalline structure at a greater depth, exceeding the penetration depth of ions in the damaged layer. At the same time, the exponential trend of changes in hardness values at a depth exceeding the ion path depth, together with changes in this trend with an elevation in irradiation fluence, is a direct confirmation of the ballistic transfer of defects, as well as implanted ions in the damaged layer.

For modified (irradiated with heavy ions) SiC ceramics, in the case of Ar^{8+} and Kr^{15+} ions, the analysis of trends in the change in hardness profiles by depth indicates a positive effect of elevation of the softening resistance of the near-surface layer associated with the creation of restraining defective inclusions of implanted ions and the associated structural distortions of the damaged layer. In this case, the most pronounced effect is observed when irradiated with Ar^{8+} and Kr^{15+} ions with a fluence of 10^{12}–10^{13} ion/cm^2. For samples modified with Xe^{23+} ions, this effect is less pronounced

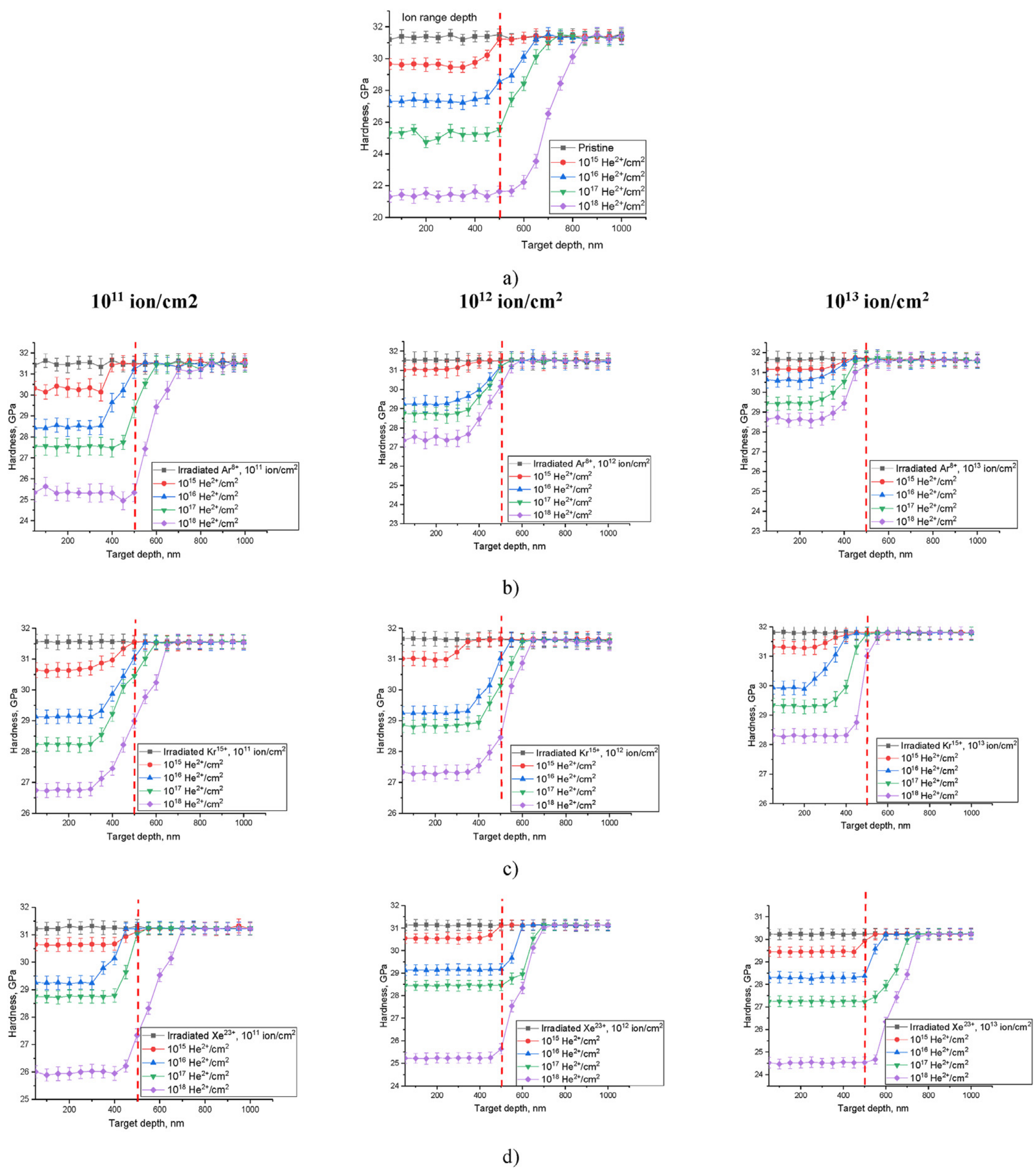


Fig. 8. Results of hardness measurements along the ion trajectory in the material, reflecting the softening effect caused by irradiation with He^{2+} ions in the near-surface layer: a) in the initial state (not modified by heavy ion irradiation); b) irradiated with Ar^{8+} ions with different irradiation fluences; c) irradiated with Kr^{15+} ions with different irradiation fluences; d) irradiated with Xe^{23+} ions with different irradiation fluences.

in comparison with the results obtained for ceramic samples irradiated with Ar^{8+} and Kr^{15+} ions, however, in comparison with unmodified samples, the efficiency of restraining the diffusion expansion of the damaged layer is traced.

4. Conclusion

During the experiments, it was established that the creation of dislocation strengthening in the near-surface layer due to irradiation with Ar^{8+} and Kr^{15+} ions is a fairly effective method for inhibiting diffusion processes of deformation softening of the near-surface layer of SiC ceramics. At the same time, the observed inhibition of volumetric swelling caused by the cumulative effect associated with high-dose irradiation with He^{2+} ions indicates the promise of using the proposed method of creating defective inclusions in the damaged layer to reduce the degradation rate of ceramics associated with gas swelling. In this case, the main mechanism of containment is the creation in the near-surface layer of structurally isolated distorted regions with a changed dislocation density, which serve as barriers for the migration of complex defects of the

He—V type, the formation of which is due to the unification of helium with vacancy defects, the presence of which is due to athermal processes occurring in the damaged layer during high-dose irradiation with He^{2+} ions. The structurally isolated distorted areas created by heavy ions along the ion trajectory in the material create additional obstacles to the migration of point and vacancy defects, thereby slowing down the processes of their agglomeration in the damaged layer. Similar effects are observed for dispersion hardening associated with changes in the grain sizes of materials, in which a decrease in grain sizes leads to the creation of additional grain boundaries that are sinks for point defects, vacancies and dislocations.

It was found that with an elevation in the irradiation fluence of He^{2+} ions above 10^{17} ion/cm^2 in unmodified samples, a steep rise in volumetric swelling, caused by two factors: the accumulation of structural distortions associated with deformation processes in the crystal structure, and the agglomeration of implanted helium in the near-surface layer, which is accompanied by the formation of gas-filled inclusions that have a destructive effect on the near-surface layer, is observed. Moreover, the creation of dislocation defects due to irradiation with heavy Ar^{8+} and Kr^{15+} ions leads to the inhibition of diffusion mechanisms resulting in agglomeration, which is clearly seen from the trends in the change in volumetric swelling.

Analysis of the results of hardness measurements along the trajectory of He^{2+} ions in the near-surface layer revealed that irradiation fluence growth leads to a diffusion expansion of the damaged layer, in which softening effects, caused by the ballistic nature of the transfer of defects into the depths of the material during high-dose irradiation, are observed. At the same time, modification with heavy Ar^{8+} and Kr^{15+} ions results in the damaged layer thickness reduction in ceramics, a decrease of which indicates the inhibition of the processes of diffusion of defects into the depth of the material.

Data availability statement

Not applicable.

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Conflict of interest

The authors declare no conflicts of interest.

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