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STUDY OF THE WEAR RESISTANCE DEGRADATION KINETICS OF ALN CERAMIC UNDER HEAVY ION IRRADIATION

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This work is devoted to the study of changes in the strength properties of AlN ceramics, in particular, the dry friction coefficient and parameters of wear resistance and surface defectiveness, depending on the dose of irradiation with heavy Xe^{22+} ions with an energy of 200 MeV. Interest in these ceramics is due to their high thermal conductivity, hardness and wear resistance, as well as excellent insulating properties, which makes them promising candidate materials in nuclear power, rocket engineering and microelectronics. At the same time, the operation of these ceramics under conditions of external influences, such as mechanical friction, pressure on the surface, as well as the effect of ionizing radiation, requires additional research and obtaining new data on the stability and retention of properties during the entire service life. During the studies carried out, it was found that at low irradiation doses of 10^{10}-10^{11} ions/cm^2, which are characterized by the formation of single point defects and a low probability of surface degradation as a result of the initialization of gas swelling processes, the dry friction coefficient practically does not change, which indicates ceramics high mechanical friction resistance. However, an increase in the irradiation fluence up to 10^{12} ion/cm^2, which is characterized by the processes of overlapping radiation-induced damaged areas, a deterioration in the dry friction coefficient is observed after 15000 test cycles, which indicates fatigue wear of the ceramic surface and degradation as a result of external influences.

Keywords: radiation defects, nitride ceramics, wear resistance, dry friction coefficient, heavy ions.

Introduction

One of the key parameters responsible for the life of ceramic materials is the preservation of long-term resistance to external mechanical and radiation effects arising during their use [1,2]. At the same time, the rapid development of a new direction in materials science associated with the transition from steels and alloys to ceramic materials and their widespread use under conditions of increased radiation backgrounds, mechanical influences and high temperatures requires new knowledge about the mechanisms of material degradation. Interest in these ceramic materials, in particular ceramics based on aluminum or silicon nitride, is due to their excellent mechanical strength, thermal conductivity, as well as corrosion resistance and good insulating properties [3-5]. All these indicators open up broad prospects for the use of these materials as a basis for structural materials for the walls of fuel rods of high-temperature nuclear reactors or as a basis for materials of inert matrices of nuclear fuel. Moreover, in most cases, these materials are subjected to high mechanical stresses and friction during operation, which can lead to the destruction of the contacting surfaces and their deformation [6-8]. In the case when materials during operation are exposed not only to mechanical stress, but also to radiation exposure, taking into account the deformation processes caused by radiation is important, since it can have a negative effect on the mechanical and strength properties of the material surface [9,10]. As a rule, at low radiation doses, the accumulation of radiation damage is limited due to the isolation of point defects and defect regions formed during the passage of incident ions through the material. In this case, the isolation of defective areas leads to the appearance of additional microdistortions and deformations in the structure [11-13]. In the case when the defect areas overlap, the concentration of microdistortions and deformations increases, in this case their accumulation in the structure of the damaged layer can lead to the appearance of nonequilibrium states or amorphization. The accumulation of microdistortions in the structure of the near-surface layer leads to overvoltage of the structure and partial extrusion and swelling of the near-surface layer, accompanied by a sharp change in the surface relief, which can negatively affect not only the strength properties of ceramics, but also the frictional characteristics [14-

16]. In turn, the nature of the effect of surface defectiveness is a very important issue in radiation materials science and the study of the strength properties of ceramics exposed to irradiation [17,18].

The aim of this work is to study the change in the dry friction coefficient and wear resistance of ceramics exposed to irradiation with heavy Xe^{22+} ions at various radiation doses. The strength characteristics were determined at different values of the load on the swinging body in order to determine the change in the value of the dry friction coefficient and wear resistance under various external influences. The choice of the type of irradiation ions and radiation exposure doses is due to the possibility of simulation of radiation damage in the near-surface layer, which is most susceptible to external influences under mechanical stresses.

1. Experimental part

Ceramics based on aluminum nitride (AlN), which has high hardness and resistance to external influences, were selected as objects of research. The samples under study have a polycrystalline structure of the hexagonal type; the density of ceramics, according to the passport data, is 3.26 g/cm^3. Before irradiation, the surface of the samples was mechanically polished in order to eliminate any roughness and irregularities.

Simulation of radiation damage was carried out at the DC-60 (Nur-Sultan, Kazakhstan) heavy ion accelerator. Xe^{22+} ions with an energy of 200 MeV were chosen as the ion flux, the irradiation doses were 10^{10}-10^{12} ion/cm^2. The choice of this type of ions with an energy of 200 MeV is due to the possibility of simulating radiation-induced damage in the structure of the near-surface layer with a thickness of 12-15 microns, comparable in the effect of uranium fission fragments during the uranium fission reaction in a nuclear reactor and further interaction of fission fragments with the materials of the walls of the fuel rods, so and inert nuclear fuel matrices. Irradiation doses were selected based on theoretical calculations and experimental works [18-20], according to which, in the case of irradiation with doses of 10^{10}-10^{11} ions/cm^2, the main defects arising in the structure are point defects and dislocations, which are isolated from each other due to low radiation doses. The isolation of defects is due to the radii of the damaged areas, which for the selected ions with these energies are no more than 5-7 nm. For irradiation doses of 10^{12} ions/cm^2, according to theoretical calculations, the so-called effect of overlapping radiation-induced damaged areas can be observed, which leads to the accumulation of defects and dislocations in the structure of the near-surface damaged layer and the appearance of distortions and deformations in the structure.

Study of the strength properties of the ceramic surface, in particular, dry friction coefficient and wear resistance of ceramics before and after irradiation was determined using the tribological method. The number of test cycles was 20000, the load on the metal ball was from 50 to 200 N.

2. Results and discussion

Figure 1 shows the results of cyclic wear resistance tests at various values of the load on the swinging body in order to determine the value of the dry friction coefficient. As a reference sample, a ceramic sample in its original state, unaffected by external influences. The dry friction coefficient for the initial sample was 0.44-0.45 at a load of 50 N, while no changes in this value were observed during 20000 consecutive cyclic impacts, except within the statistical error. The absence of changes in the dry friction coefficient during long-term tests indicates a high resistance to external mechanical influences, as well as a high wear resistance of the surface of unirradiated ceramics. An increase in the load from 50 to 150 N does not lead to significant changes in the dry friction coefficient for the original sample, which in turn confirms the high wear resistance to external mechanical influences of various forces. An increase in the load to 200 N leads to an insignificant increase in the dry friction coefficient for the initial sample from 0.44-0.45 to 0.46-0.48, which indicates the appearance of a small resistance at high stresses.

For irradiated samples at doses of 10^{10}-10^{11} ion/cm^2, the change in the dry friction coefficient both in the case of the initial stage of testing and during cyclic tests is practically not observed, which indicates a high resistance to external radiation effects of the near-surface layer. Small changes in the initial values of the dry friction coefficient can be caused by a slight imperfection of the surface of the samples caused by the emerging deformations of the crystal structure and a change in the surface roughness. It should be noted that, in this case, the deformations and distortions of the structure are of a local isolated nature due to the formation of isolated defect regions along the trajectory of incident heavy ions in the material [18]. In the case of dielectric ceramics irradiated with heavy ions, the main changes caused by the interaction of ions with the target material are related to both the redistribution of the electron density and the formation of heterogeneities in its distribution.

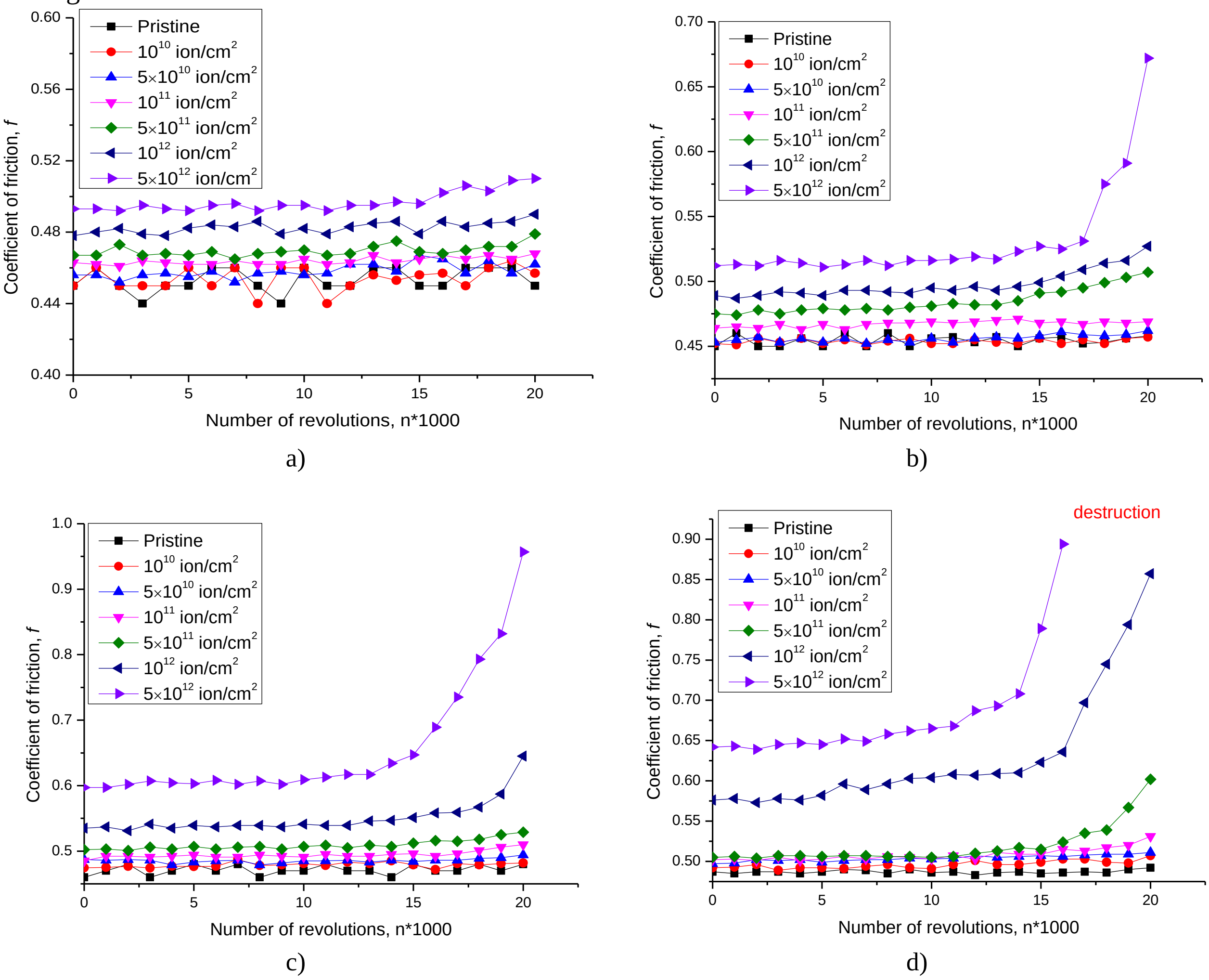

Fig.1. Cyclic tests for determination of dry friction coefficient at different stresses:
a) 50 N; b) 100 N; c) 150 N; d) 200 N

Also, a small contribution is made by atomic displacements arising from inelastic collisions of ions with atoms of the crystal lattice. At the same time, due to the dielectric nature of ceramics, the change in the electron density caused by irradiation does not have the ability to recover and relax, as it happens in metals, where the electron mobility is high enough. The result of such interactions is a change in covalent bonds in the structure, as well as the formation of nonequilibrium regions with altered properties, which leads to deformation and distortion of irradiated layer. However, the nature of these changes, as well as their effect on changes in structural and strength properties, as shown earlier, has a pronounced dependence not only on the energy of incident ions, but primarily on the irradiation fluence.

Analysis of dry friction coefficient dependencies for samples irradiated with doses of 10^{10}-10^{11} ion/cm^2 showed that no significant changes in the value of the coefficient were observed, which indicates the preservation of a high degree of resistance to radiation-induced damage and their effect on the wear resistance of the surface layer. The main changes in the dry friction coefficient are observed for samples irradiated with doses of 5x10^{11}-5x10^{12} ion/cm^2, for which, according to theoretical estimates, the presence of overlaps of defective areas in the structure of the near-surface layer is characteristic. In this case, changes in the dry friction coefficient occur not only at the beginning of the tests, which is associated with deformation of the surface and an increase in the friction resistance, but also a sharp increase in the dry friction coefficient after 15000-17000 test cycles. This increase is primarily associated with a sharp deterioration of the surface associated with the appearance of hillock-like inclusions, the formation of which is caused by the squeezing out of defective regions from the volume, as well as by the swelling of the irradiated layer.

The formation of hillocks or hillock-like inclusions at doses above 10^{11} ion/cm^2, as well as the mechanisms of their formation, were shown in [19,20], according to which deformation processes caused by irradiation lead to disordering of the structure, as well as amorphization of the structure of the damaged layer. Consequently, the resulting defects accumulate in the disorder regions, which causes the appearance of nonequilibrium highly distorted and deformed inclusions, leading to swelling of the surface near the joints and grain boundaries. At the same time, the accumulation of such inclusions leads to a sharp deterioration in the structural and heat-conducting properties, which in turn can also affect the wear resistance.

According to the data presented in Figure 1, an increase in the load at irradiation doses of $5x10^{11}$-$5x10^{12}$ ion/cm^2 leads to an increase in the dry friction coefficient, which indicates an increase in surface defectiveness, as well as a decrease in crack resistance and wear resistance. It should be noted that at a maximum load of 200 N, for samples irradiated with a dose of $5x10^{12}$ ion/cm^2, after 15000 cycles, a sharp increase in the dry friction coefficient by 1.5-2 times was observed, which indicates the destruction of the surface and the formation of a large number of cracks. Evaluation of ceramic surface defect index depending on irradiation dose and subsequent mechanical action was carried out by comparison of dry friction coefficient indices depending on external effect type with reference sample index. The results are shown in Figure 2 as a comparative chart.

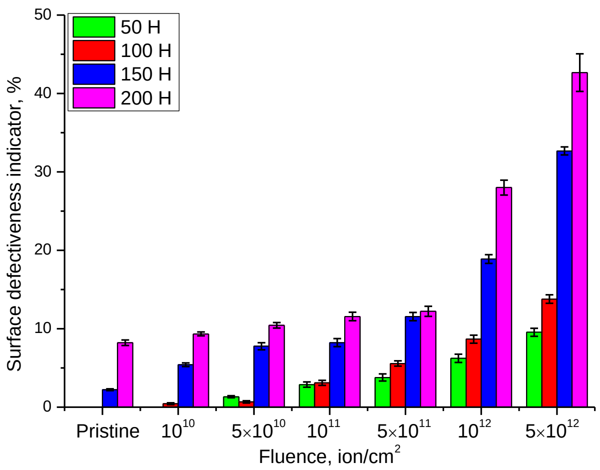

Fig.2. Diagram of the samples surface defectiveness index depending on sample load parameter at the beginning of test

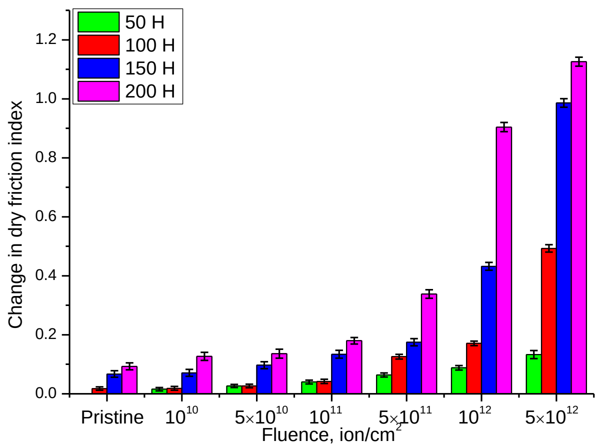

Fig.3. Diagram of dry friction coefficient depending on load parameter

As can be seen from the data of the comparative diagram, the greatest deterioration of surface defects is observed for $5x10^{11}$-$5x10^{12}$ ion/cm^2 radiation doses, while with an increase in load, the surface defects increase by 3-4 times. Such a sharp increase indicates a deterioration in wear resistance and a decrease in crack resistance of the surface of samples exposed to high-dose irradiation. The wear resistance of the ceramic surface during testing was evaluated by comparative analysis of changes in dry friction indicators after a series of cyclic tests. The results are shown in Figure 3. As can be seen from the presented data of the diagram, in the case of irradiation doses of 10^{10}-10^{11} ions/cm^2, the change in the dry friction coefficient after 20000 tests is insignificant and does not exceed 5-7 % of the initial value, which indicates a high resistance to deformation and surface degradation as a result of mechanical tests. However, an increase in the radiation dose leads to a sharp deterioration in the dry friction coefficient, as well as its increase by a factor of 0.5-1.2, which indicates a strong surface destruction and an increase in friction resistance due to the formation of defective inclusions and a decrease in the crack resistance of the surface.

Conclusion

In conclusion, based on the data obtained, it can be concluded that AlN ceramics have a high degree of crack resistance and wear resistance at low mechanical stresses in the irradiated state at doses of 10^{10}-$5x10^{12}$ ion/cm^2. However, in the case of high stresses (more than 100 N), a sharp deterioration in wear resistance is observed for samples irradiated with doses above 10^{11} ion/cm^2, which is associated with the accumulation of defects in the near-surface layer of ceramics and surface deformation as a result of swelling and formation of hillocks. The obtained dependencies of change in wear resistance of irradiated ceramics can be used later for development of design documentation on use of these ceramics as structural materials exposed to both radiation and mechanical stresses.

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REFERENCES

1 Grigoriev S., et al. Wire electrical discharge machining, mechanical and tribological performance of TiN reinforced multiscale SiAlON ceramic composites fabricated by spark plasma sintering. *Applied Sciences*. 2020, Vol. 11.2, pp. 657-665.

2 Chen Juanjuan, et al. Mechanical and tribological properties of h-BN/ZrO2/SiC solid-lubricating ceramic composites. *Tribology International,* 2021, Vol.160, pp. 107061-107080.

3 Li Yongxia, et al. Effect of Mo particle size on microstructure and mechanical properties of spark plasma sintered silicon nitride. *Materials Science and Engineering: A,* 2021, Vol. 814, pp. 141155.

4 Karipbayev, Zh, et al. Time-resolved luminescence excited with N2 laser of YAG: Ce Ceramics formed by electron beam assisted synthesis. *Eurasian Physical Technical Journal,* 2021, Vol. 17.1 (33), pp. 73-76.

5 Tang Peng, et al. Influence of grain orientation on hardness anisotropy and dislocation behavior of AlN ceramic in nanoindentation. *Ceramics International,* 2021, Vol. 47.14, pp. 20298-20309.

6 Dehghani Hadi, et al. The effect of AlN-Y2O3 compound on properties of pressure less sintered SiC ceramics-A review. *International Journal of Refractory Metals and Hard Materials,* 2021, Vol.95, pp. 105420.

7 Wei Zhilei, et al. Preparation of unidirectional porous AlN ceramics via the combination of freeze casting and combustion synthesis. *Journal of Materials Science & Technology,* 2022, Vol.100, pp. 161-168.

8 Kadyrzhanov, K. K., Tinishbaeva K., Uglov V.V. Investigation of the effect of exposure to heavy Xe22+ ions on the mechanical properties of carbide ceramics. *Eurasian Physical Technical Journal,* 2021, Vol. 17 (33), pp. 46-53.

9 Eremin, E. N., Yurov V. M., Guchenko S.A. Wear resistance and tribological properties of high entropy coatings CrNiTiZrCu. *Eurasian Physical Technical Journal,* 2021, Vol. 17 (33), pp.13-18.

10 Zinkle S.J., Skuratov V.A., Hoelzer D.T. On the conflicting roles of ionizing radiation in ceramics. *Nuclear Instruments and Methods in Physics Research section B: Beam Interactions with Materials and Atoms*, 2002, Vol.191.1-4, pp. 758-766.

11 Yano T., et al. Neutron irradiation damage in aluminum oxide and nitride ceramics up to a fluence of 4.2× 1026n/m2. *Journal of nuclear materials*, 2000, Vol.283, pp. 947-951.

12 Yano T., et al. Neutron irradiation effects on isotope tailored aluminum nitride ceramics by a fast reactor up to 2× l026 n/m2. *Journal of Nuclear Materials,* 2004, Vol. 329, pp. 1471-1475.

13 Dukenbayev K., et al. The investigation of various type irradiation effects on aluminum nitride ceramic. *Journal of Materials Science: Materials in Electronics*, 2019, Vol. 30.9, pp. 8777-8787.

14 Kucheyev S.O., et al. Ion-beam-produced damage and its stability in AlN films. *Journal of applied physics*, 2002, Vol. 92.7, pp. 3554-3558.

15 Trinkler Laima, Baiba Berzina. Recombination luminescence in aluminum nitride ceramics. *Physica status solidi (b)*, 2014, Vol. 251.3, 542-548.

16 Zinkle S.J., Skuratov V.A., Hoelzer D.T. On the conflicting roles of ionizing radiation in ceramics. *Nuclear Instruments and Methods in Physics Research section B: Beam Interactions with Materials and Atoms,* 2002, Vol. 191.1-4, pp. 758-766.

17 Hu Quanli, et al. Study of radiation defects for AlN ceramics under O+ irradiation. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 2000, Vol. 166, pp. 70-74.

18 Zinkle S. J., Kinoshita C. Defect production in ceramics. *Journal of Nuclear Materials,* 1997, Vol.251, pp. 200-217.

19 Kozlovskiy A., et al. Dynamics of changes in structural properties of AlN ceramics after Xe+ 22 ion irradiation. *Vacuum,* 2018, Vol. 155, pp. 412-422.

20 Kozlovskiy A. Influence of irradiation temperature on properties change of AlN ceramics. *Vacuum,* 2018, Vol. 158, pp. 93-100.

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