ISSN: 3060-4613

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13.00.02	Ta'lim va tarbiya nazariyasi va metodikasi (sohalar bo'yicha)
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11.00.00	Geografiya fanlari

№6(6)

2026

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Pedagogika, psixologiya fanlariga ixtisoslashgan ilmiy jurnal

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26.09.2023-yildan

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Litsenziya raqami: **№136361**

MUNDARIJA

CHANGES IN THE STRUCTURE AND STRENGTH OF THE ALUMINUM ALLOYS SAV-1 IRRADIATED WITH FAST NEUTRONS

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Abstract: The aluminum alloy SAV-1 was studied before and after neutron irradiation with doses ranging from 10^{16} to 10^{18} n/cm². The measurements were carried out using volumetric methods, namely small-angle neutron scattering and neutron diffraction. A loading machine was employed to investigate the correlation between structural changes and the strength characteristics of the samples. It was found that changes in the strength characteristics of aluminum alloys were associated with modifications occurring at the grain boundaries during irradiation. The obtained experimental data allow us to conclude that the SAV-1 alloy represents an interstitial solid solution, and its strength changes nonlinearly depending on the radiation dose.

Key words: aluminum alloy SAV-1, neutron irradiation, neutron scattering, microstructure, phase composition.

Annotatsiya: SAV-1 alyuminiy qotishmasi 10^{16}–10^{18} n/sm² diapazonidagi neytron nurlanishi ta'siridan oldin va keyin tadqiq qilindi. O'lchovlar hajmiy usullar, ya'ni kichik burchakli neytron sochilishi va neytron difraksiyasi yordamida amalga oshirildi. Namunalardagi strukturaviy o'zgarishlar hamda mustahkamlik xususiyatlari o'rtasidagi bog'liqlikni aniqlash maqsadida yuklash mashinasidan foydalanildi. Aniqlanishicha, alyuminiy qotishmalarining mustahkamlik xususiyatlaridagi o'zgarishlar nurlanish jarayonida donalar chegaralarida yuz beradigan modifikatsiyalar bilan bog'liqdir. Olingan eksperimental ma'lumotlar SAV-1 qotishmasi kiritma qattiq eritma ekanligini hamda uning mustahkamligi nurlanish dozasiga bog'liq holda chiziqli bo'lmagan tarzda o'zgarishini ko'rsatadi.

Kalit so'zlar: SAV-1 alyuminiy qotishmasi, neytron nurlanishi, neytron sochilishi, mikrostruktura, fazaviy tarkib.

Аннотация: Алюминиевый сплав SAV-1 был исследован до и после нейтронного облучения дозами от 10^{16} до 10^{18} н/см². Измерения проводились объемными методами, а именно методом малоуглового рассеяния нейтронов и нейтронной дифракции. Для изучения взаимосвязи между структурными изменениями и прочностными характеристиками образцов использовалась испытательная нагрузочная машина. Установлено, что изменения прочностных характеристик алюминиевых сплавов связаны с модификациями, происходящими на границах зерен в процессе облучения. Полученные экспериментальные данные позволяют сделать вывод о том, что сплав SAV-1 представляет собой твердый раствор внедрения, а его прочность изменяется нелинейно в зависимости от дозы облучения.

Ключевые слова: алюминиевый сплав SAV-1, нейтронное облучение, рассеяние нейтронов, микроструктура, фазовый состав.

INTRODUCTION

SAV-1 is characterized by a low degree of activation during irradiation and maintains high corrosion resistance in steam-water environments. However, these materials are susceptible to aging and possess a relatively low melting point. Their application as load-bearing elements in reactor cores, even in the case of the most heat-resistant alloys based on sintered aluminum powder, is limited to temperatures of 450-500°C. Despite this limitation, the high thermal conductivity of aluminum allows the use of aluminum-based products capable of operating under significant thermal loads when an appropriate geometry is applied. The high manufacturability of aluminum alloys makes it possible to fabricate thin-walled products with complex profiles, such as protective claddings of fuel elements, pipelines, tanks, experimental channels, auxiliary reactor-core structures, and matrices for dispersion fuel rods and self-burning absorbers operating under a wide range of radiation fields [1].

The aluminum alloy SAV-1 (Al-Mg-Si) is the principal structural material used for core elements and fuel rod cladding in the WWR-SM reactor of the Institute of Nuclear Physics of the Academy of Sciences of the Republic of Uzbekistan (INP AS RUz). The reactor was built and commissioned in 1959 and continues to operate successfully due to the high-performance characteristics of the materials used, particularly aluminum alloys. The phase composition of alloys of this type (avial alloys) depends on the concentration ratio of the primary alloying elements, magnesium and silicon. Therefore, the main phases in SAV-1 consist of α(Al), Mg_2Si, and Si. In addition to these primary phases, intermetallic compounds such as AlSiFe, $Al_{10}Mn_2Si$, and AlSiMnFe may also be present, depending on the chemical composition. During neutron irradiation, nuclear reactions result in an increase in silicon content through the Al(n,γ)Si reaction [2].

By interacting with atoms in the alloy, silicon can alter the phase balance and induce stresses that contribute to the formation of micropores and microcracks, leading to degradation of the material's mechanical properties. Therefore, the atomic structure of these alloys is investigated to diagnose such defects, which are considered primary precursors to material failure [1].

LITERATURE REVIEW

Studies on the radiation resistance of structural materials are being conducted by leading researchers at major nuclear research centers worldwide [1], [3], [9], [10], [12], [13], [14], [15]. The SAV-1 alloy has been extensively studied; however, further clarification is required regarding the changes in its physical and mechanical properties as functions of fast-neutron fluence and temperature. Since reactor operational safety depends directly on these parameters and structural characteristics, the application of neutron scattering and diffraction techniques is particularly promising. Therefore, we investigated the structural states of SAV-1 before irradiation and after neutron irradiation with doses ranging from 10^{16} to 10^{18} n/cm².

The measurements were performed using volumetric methods, namely small-angle neutron scattering and neutron diffraction. To determine the correlation between structural states and macroscopic strength characteristics, a loading machine was employed. The samples were irradiated at the IBR-2 reactor in Horizontal Channel No. 3. The average reactor power was 2 MW. The thermal neutron flux at the moderator surface was approximately 10^{16} n/cm²·s (time-averaged), while the maximum pulse flux reached approximately 10^{16} n/cm²·s. It should be noted that no preliminary thermal treatment of the samples was performed before irradiation.

RESEARCH METHODOLOGY

The measurements were carried out at room temperature using a uniaxial loading machine LM-20 (FLNP JINR, Dubna), designed to apply mechanical loading to samples at various strain rates under PID control. The machine allows both tensile and compressive loading with forces up to 30 kN. A key advantage of the system is the practically backlash-free transmission of load to the specimen. In the present experiment, the applied load was 10 kN, while the motor step rate was set at 0.25 µm/s. Compression tests: cylindrical specimens with a diameter of approximately 6 mm and a length of 10-12 mm. Tensile tests: cylindrical specimens with a diameter of approximately 6 mm and a length of 72-78 mm.

Table 1: **The elemental composition of unirradiated and neutron-irradiated samples of SAV-1**

Fluence n/cm²	Al %	Si%	Mg%	Fe%	Ni%	Cu%	Mn%
Beforeirradiation	98,27	0,5	1,06	0,14		0,02	0,01
Beforeirradiation [3]	97,2-98,5	0,6-1,2	0,45-0,9	0,2	0,03	0,01	0,01
After irradiation 10^{17}	97,77	1,1	0,82	0,28		0.02	0.01
After irradiation 10^{18}	97,32	1,75	0,62	0,30		0,01	-
After irradiation 10^{19} [4]	97,09	2,05	0,53	0,32		0,01	
After irradiation 10^{20} [4]	96,86	2,35	0,45	0,33		0,01	

In SAV-1 alloys, the principal alloying elements are Mg and Si. Their concentrations increase as a result of nuclear reactions: the silicon concentration increases through the Al(n,γ)Si reaction, while the magnesium concentration increases through the Si(γ,α)Mg reaction. As can be seen from the data presented in the table, neutron irradiation of aluminum alloys causes not only radiation-induced damage but also changes in the concentrations of alloying elements. When the concentration of alloying elements exceeds the solubility limit, a new phase precipitates. This process, together with the migration of impurity atoms toward defect accumulations (such as dislocations, grain boundaries, and other structural defects), significantly influences changes in the physical and mechanical properties of the material [3]. To investigate the structure averaged over the entire sample volume, neutron diffraction experiments were performed using the Fourier Stress Diffractometer (FSD) installed at Channel 11A of the IBR-2 pulsed reactor at the Frank Laboratory of Neutron Physics, Joint Institute for Nuclear Research (JINR, Dubna). The measurements were carried out on a series of SAV-1 aluminum alloy samples (see Table 2). A specialized correlation technique, employing a high-speed Fourier chopper to modulate the intensity of the primary neutron beam together with the Reverse Time-of-Flight (RTOF) data acquisition method, made it possible to obtain diffraction spectra with high resolution ($\Delta d/d \approx 2 \times 10^{-3}$ at a scattering angle of $2\theta = 140°$ and $\Delta d/d \approx 4 \times 10^{-3}$ at $2\theta = \pm 90°$) over a wide range of interplanar spacings. This provided the accuracy required to detect small shifts and broadenings of diffraction peaks [5, 6].

Table 2: **The parameters of irradiated and non-irradiated samples of SAV-1 alloy, for which measurements were carried out in the FSD device**

№	Fluence, n/cm²	Notes
1	**0**	Cylinder (∅6 mm, h =50 mm)
2	**0**	Cylinder (∅6 mm, h=50 mm)
3	**0**	Powder (vanadium container, ∅5 mm, h=50 mm)
4	**0**	Disk (∅ 17 mm, h=3,2 mm)
5	**10^{16}**	Disk (∅ 17 mm, h=3,5 mm)
6	**10^{17}**	Disk (∅ 17 mm, h=2,9 mm)
7	**10^{18}**	Disk (∅ 17 mm, h=3,2 mm)

To evaluate differences in the sizes and shapes of dispersed particles ranging from 1 to 100 nm, small-angle neutron scattering (SANS) data obtained using the YuMO time-of-flight spectrometer at JINR (Dubna) were analyzed [7, 8]. The measurements were performed at sample-to-detector distances of 5.28 m and 13.04 m, providing a scattering vector range (Q) from 0.006 to 0.3 $Å^{-1}$, corresponding to structural features ranging from approximately 2 to 100 nm. The diameter of the sample exposed to the neutron beam was 17 mm. The obtained neutron scattering spectra were corrected for neutron absorption, sample thickness, and background scattering from the substrate. Calibration was performed using a vanadium reference sample, and the neutron scattering intensity was normalized to absolute units (cm^{-1}).

ANALYSIS AND RESULTS

During the mechanical testing of the samples, the following strength characteristics were determined: ultimate tensile strength, σ_{ts} (temporary resistance); yield strength, σ_Y (physical yield point); 0.2% offset yield strength, $\sigma_{0.2}$ (technical yield point); proportional limit, σ_{p1}; elastic limit, σ_{e1}; true tensile strength, S_k; relative elongation, δ; reduction of area (constriction), ψ.

Table 3: **The main mechanical properties of stretchingSAV-1 before and after irradiation in the IBR-2 reactor with different fluences**

Fast neutron fluence, n/cm²	σts, MPa	σy, MPa	σ0,2,MPa	σpl, MPa	σel, MPa	Sk. MPa	δ,%	ψ,%
before irradiation	160,4	154,8	154,3	108,6	117,9	147,4	18	15
10^{16}	190,7	185	180	83.4	110	119	16	16
10^{17}	165	159	159	83.4	100	107	17	16
10^{18}	175	162	162	84	105	110	13,5	7
SAV-1 [9] before irradiation							16,5	
3,5•1022							2,5	

The observed difference between the lattice strength of irradiated and non-irradiated SAV-1 alloy samples can be readily explained by assuming that SAV-1 behaves as an interstitial solid solution. This assumption is justified by the fact that silicon and magnesium do not form stable chemical compounds with aluminum [3].

Accordingly, the atoms of the principal alloying elements, silicon and magnesium, occupy interstitial positions within the aluminum crystal lattice, leading to an increase in the dimensions of the unit cells in which they are located. As a result, local lattice distortions occur, affecting the mechanical and structural properties of the alloy.

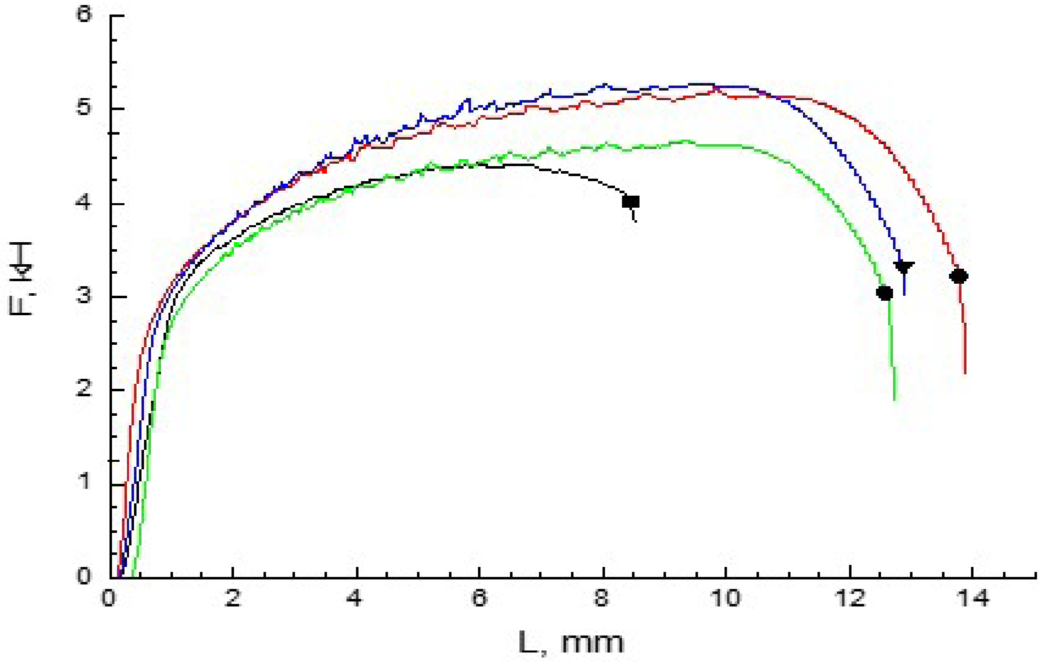

Figure 1: **F is the stress stretching parameter which cause the elongation in the fluidity area (kN), L is the length of the sample at the moment of rupture.**

Samples: ■ –unirradiated ; ♦ - 1016n/cm^2; ● - 1017n/cm^2; ▼-1018n/cm^2.

Table 4: **Effect of Neutron Fluence on the Mechanical Properties of SAV-1 Aluminum Alloy**

Fluence/cm^2	Relative elongation δ%	Stress-deformation Q kg/mm^2
0	16	18,16
10^{16}	16,4	19,3
10^{17}	16,8	16,9
10^{18}	13,5	19,1
0 [10]	22,1	14
10^{17} [10]	25,2	15,2
10^{22} [10]	18,5	20,1

A pronounced crystallographic texture was observed in almost all investigated samples. This feature is most likely associated with the texture already present in the original material from which the specimens were manufactured. The measured diffraction spectra were processed using the Pawley method [11]. As a result, the crystal lattice parameters of the material and the parameters describing the dependence of diffraction peak widths on the interplanar spacing were determined (Figs. 3 and 4). The dimensions of the unit cells within the crystal lattice of the solid solution vary from one region of the lattice to another. Therefore, only the average value of the lattice parameter can be considered. It is well known [3] that, in interstitial solid solutions, dissolved atoms occupy interstitial sites within the crystal lattice and cause local distortions of the crystal structure of the matrix material. The magnitude of these distortions is relatively large compared with the size of the interstitial sites occupied by impurity atoms. Consequently, the volume of distorted unit cells increases despite the relatively low concentration of impurities.

As a result, a noticeable increase in the average lattice parameter of the alloy occurs, accompanied by a corresponding expansion of the unit-cell volume during the formation of the interstitial solid solution. This effect was confirmed experimentally. Consequently, the crystal lattice of the alloy is characterized by a specific configuration in which some interstitial sites are occupied by alloying atoms, whereas others remain vacant. Based on the analysis of diffraction peak broadening relative to the instrumental resolution function of the diffractometer, the microstrain values averaged over all observed (hkl) reflections were determined (see [5]).

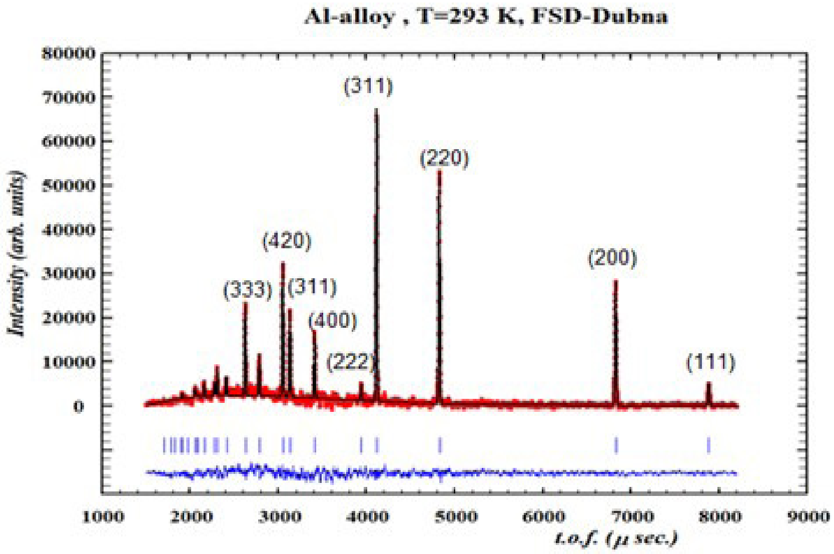

Figure 2: **Neutron Diffraction Pattern of the SAV-1 Aluminum Alloy at 293 K**

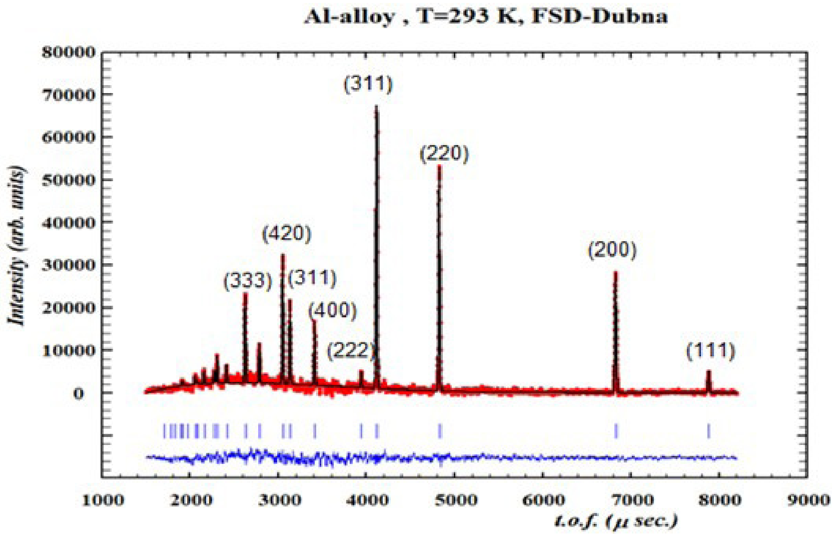

Figure 3: **The diffraction spectrum of the aluminum alloy SAV-1 (sample No. 1), processed by the method of Pauli [11]. Experimental points, calculated and difference in curves, positions of diffraction peaks are shown.**

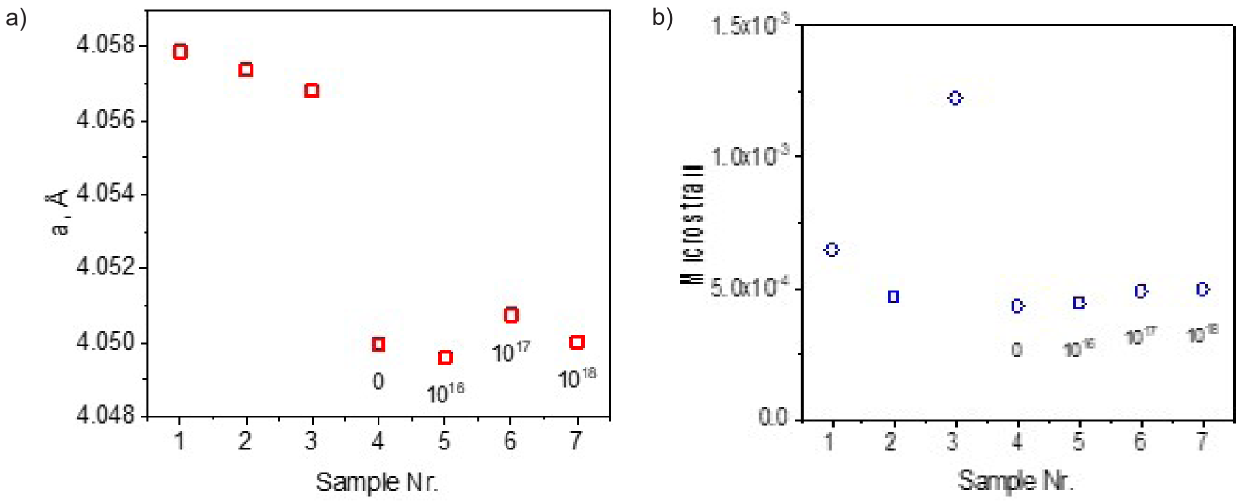

Figure 4: **The parameters of the crystal lattice (a) and average microstrain (b) for the samples of SAV-1. The doses of irradiated samples are indicated.**

Figure 5 illustrates the small-angle neutron scattering (SANS) intensity as a function of the scattering vector Q for aluminum alloy samples before irradiation and after irradiation with neutron doses of 10^{16}, 10^{17}, and 10^{18} n/cm². According to the relationship $D \approx 2\pi/Q$, the scattering vector range of $0.0063\ \text{Å}^{-1} < Q < 0.3\ \text{Å}^{-1}$ corresponds to a structural size hierarchy of $2\ \text{nm} < D < 100\ \text{nm}$. The SANS results indicate that no significant structural changes occur within the size range of 2 to 100 nm, as all scattering curves remain within the limits of experimental uncertainty. Therefore, neutron irradiation does not induce noticeable diffusion of individual elements or precipitation of secondary phases either within the grains or at the grain boundaries. It should be noted that neutrons possess a high penetration capability in matter, whereas X-rays are effectively absorbed within a depth of approximately 100 µm. Consequently, it can be concluded that the average volume changes in structural features ranging from 2 to 100 nm are insignificant.

The neutron diffraction results obtained for the size range $0.05\ \text{nm} < D < 1\ \text{nm}$ are in good agreement with the conclusions drawn from the small-angle neutron scattering data. These findings appear to contradict the results obtained by X-ray diffraction, electron microscopy, and macroscopic strength measurements. This discrepancy can be explained by the fact that the latter methods provide information primarily from the surface layers of the samples. The atomic lattice at grain boundaries is more susceptible to neutron-induced damage than the lattice within the grain interior. As a result, subtle structural modifications occurring at grain boundaries may remain undetectable by bulk-sensitive techniques such as neutron diffraction and small-angle neutron scattering, while they can be observed using electron microscopy and X-ray diffraction. It is precisely these localized changes at grain boundaries that lead to significant variations in the mechanical strength of the material. Figure 5. Dependence of the small-angle neutron scattering intensity on the scattering vector Q for aluminum alloy samples: (a) before irradiation; (b) after irradiation with a dose of 10^{16} n/cm²; (c) after irradiation with a dose of 10^{17} n/cm²; and (d) after irradiation with a dose of 10^{18} n/cm². The small-angle neutron scattering method was applied to investigate the supramolecular structure of SAV-1 alloy samples in both the initial state and after irradiation with fast neutron fluences up to 1×10^{18} n/cm². The results revealed a decrease in the volume fraction of scattering structures (pores) with radii of 40–50 nm in the irradiated material, which was largely compensated by an increase in the total fraction of similar structures with radii below 20 nm. The neutron scattering results correlate well with the mechanical testing data and the observed changes in the elemental composition of the irradiated alloys.

CONCLUSION

The observed difference in lattice parameters between cylindrical samples and disk-shaped specimens is most likely associated with deformation introduced during the manufacturing process of the disk samples. The level of microstrain in the investigated samples was generally low and appears to be related to residual deformation introduced into the original billet during the rolling process. An exception was sample No. 3 (powder sample), which exhibited a relatively high level of microstrain. This behavior can be explained by the significant plastic deformation of the alloy during the preparation of the powder from aluminum chips. No clear dependence of either the lattice parameter or the microstrain level on radiation dose was observed for samples 4–7, indicating the absence of significant structural changes at relatively low irradiation doses.

The effectiveness of the combined application of neutron diffraction and small-angle neutron scattering techniques was demonstrated through the performed experimental investigations. The average volumetric characteristics determined by small-angle neutron scattering (2–100 nm) and neutron diffraction (0.01–1 nm) exhibited only minor changes after irradiation up to 1×10^{18} neutrons/cm². It was established that even minor modifications occurring at grain boundaries during irradiation can lead to measurable changes in the strength characteristics of aluminum alloys. Thus, the analysis of the obtained experimental results allows us to conclude that the SAV-1 alloy behaves as an interstitial solid solution and that its mechanical strength changes nonlinearly with increasing radiation dose.

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13.00.00	Pedagogika fanlari
13.00.01	Pedagogika nazariyasi. Pedagogik ta’limotlar tarixi
13.00.02	Ta’lim va tarbiya nazariyasi va metodikasi (sohalar bo‘yicha)
13.00.03	Maxsus pedagogika
13.00.04	Jismoniy tarbiya va sport mashg‘ulotlari nazariyasi va metodikasi
13.00.05	Kasb-hunar ta’limi nazariyasi va metodikasi
13.00.06	Elektron ta’lim nazariyasi va metodikasi (ta’lim sohalari va bosqichlari bo‘yicha)
13.00.07	Ta’limda menejment
13.00.08	Maktabgacha ta’lim va tarbiya nazariyasi va metodikasi
13.00.09	Ijtimoiy pedagogika
07.00.00	Tarix fanlari
19.00.00	Psixologiya fanlari
01.00.00	Fizika-matematika fanlari
02.00.00	Kimyo fanlari
03.00.00	Biologiya fanlari
09.00.00	Falsafa fanlari
10.00.00	Filologiya fanlari
11.00.00	Geografiya fanlari

MAKTABGACHA VA MAKTAB TA’LIMI

Mas’ul muharrir: Ramzidin Ashurov
Ingliz tili muharriri: Murod Xoliyorov
Musahhih: Alibek Zokirov
Sahifalovchi va dizayner: Iskandar Islomov

2026. №6(6)

“Maktabgacha va maktab ta’limi” jurnali 26.09.2023-yildan
O‘zbekiston Respublikasi Prezidenti Adminstratsiyasi huzuridagi
Axborot va ommaviy kommunikatsiyalar agentligi tomonidan
№C–5669363 reyestr raqami tartibi bo‘yicha ro‘yxatdan o‘tkazilgan.
Litsenziya raqami: № 136361.

Manzilimiz: Toshkent shahar, Yunusobod tumani
19-mavze, 17-uy.