 ISSN 1818-331X

УДК 539.125.52+539.5 https://doi.org/10.15407/jnpae2022.01.033

Sh. A. Alikulov, S. A. Baytelesov, F. R. Kungurov*, D. P. Tadjibaev, D. D. Tojiboev

Institute of Nuclear Physics of the Academy of Sciences of the Republic of Uzbekistan, Tashkent, Uzbekistan

*Corresponding author: fkungurov@inp.uz

EFFECT OF NEUTRON IRRADIATION ON THE STRUCTURE AND STRENGTH OF THE SAV-1 ALUMINUM ALLOY

The aluminum alloy SAV-1 was studied before and after inducing the radiation damage by means of neutrons with the following values of doses 10^{16} - 10^{18} n/cm^2. The measurements were carried out by neutron diffraction methods to analyze the correlation of the structural state with the results of measurements of the strength of the sample obtained using a loading machine. It was found that the changes in the strength characteristics of aluminum alloys were associated with modifications at the grain boundary during irradiation of the samples. Thus, the obtained experimental data allows us to conclude that the SAV-1 alloy represents an interstitial solid solution, and the strength of the alloy changes nonlinearly depending on the radiation dose.

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

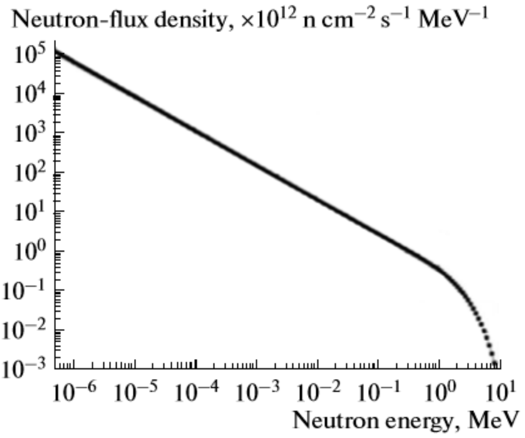
1. Introduction

SAV-1 alloy is characterized by a low degree of activation during the irradiation process and also maintains high corrosion resistance in steam-water environments. However, these materials are susceptible to aging and possess a relatively low melting point. Their application in the reactor core used as load-bearing elements, 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, the high thermal conductivity of aluminum allows the exploitation of aluminum-based products capable to operate under significant thermal loads with a certain rational geometry. The high manufacturability of aluminum alloys enable to fabricate thin-walled products with a complex profile, such as protective shells of heat fission elements, pipelines, tanks, experimental channels, auxiliary structures in the core of the reactor and use alloys as a matrix of the core of dispersive fuel rods, self-burning absorbers, operating in a wide range of radiation fields [1].

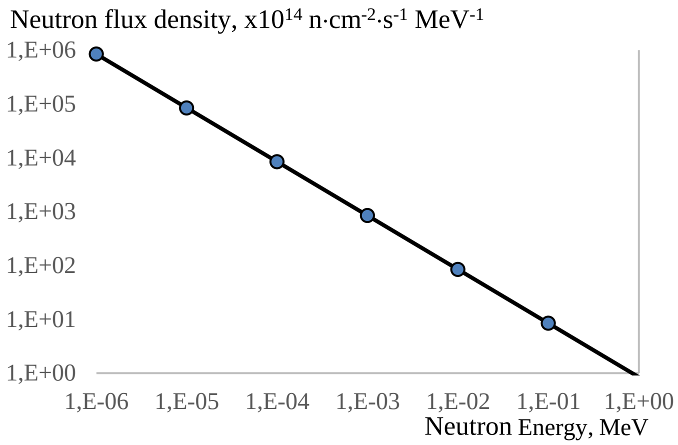
The aluminum alloy SAV-1 (Al-Mg-Si) is the main structural material of the core elements and fuel rod cladding in the WWR-SM reactor of the Institute of Nuclear Physics of the Academy of Sciences of the Republic of Uzbekistan (INP AS RUz). The reactor was built and commissioned in 1959. The WWR-SM reactor has been operating to this day due to the high functional performance properties of the materials used in it, primarily aluminum alloys. The phase composition of alloys of this type depends on the ratio of the concentrations of the main alloying elements – magnesium and silicon, therefore, the main phases in the SAV-1 alloy are consisted of α(Al)+Mg_2Si+Si. In addition to the main phases, intermetallic compounds (Al-Si-Fe, $Al_{10}Mn_2Si$, Al-Si-Mn-Fe, etc.) may be present depending on the chemical composition. When the SAV-1 alloy is irradiated because of nuclear reactions with neutrons ^{27}Al (n, γ) ^{28}Si, the silicon content increases [2]. By interacting with atoms in the alloy, silicon can change the phase ratio and cause stresses that contribute to the appearance of micropores (cracks) and degradation of the material's strength properties. For this reason, the above atomic structures of alloys are investigated to diagnose such defects, which is the main precursor of material destruction [1].

The studies of the radiation resistance of structural materials are carried out by leading scientists at the world nuclear centers [1, 3, 4 - 7, 8, 9]. The SAV-1 has been studied in detail to date. Despite the abundance of information about the latter, it is needed to clarify the changes in values of physical and mechanical properties of SAV-1 depending on the fast neutron fluence and temperatures, since the safety of the operation of reactors depends on the above-mentioned parameters and structures (Fig. 1).

The use of neutron scattering and diffraction methods is very promising. Thus, we investigated the states of SAV-1 alloy before irradiation and after inducing the neutron radiation damage to this alloy with doses of 10^{16} – 10^{18} n/cm^2. The measurements were carried out by the volumetric neutron diffraction method. To determine the correlation of the structural states with macroscopic strength, the loading machine was employed. The samples were irradiated at the IBR-2 reactor (Dubna, Russia) in the horizontal channel No. 3, the average reactor power was 2 MW, and the thermal neutron flux from the surface of the moderator: time-averaged ~10^{13} n/(cm^2·s), the maximum in the pulse was ~10^{16} n/(cm^2·s). Note that, the preliminary thermal preparation of the samples was not carried out in the experiments.



Neutron flux density spectra for IBR-2 reactor



Neutron flux density spectra for WWR-SM reactor

Fig. 1. Comparison of neutron flux density spectra for the IBR-2 and WW-SM reactors.

2. Methods

The measurements were performed at room temperature on a uniaxial loading machine LM-20 (FLNP JINR, Dubna, Russia), which is designed to create mechanical effects on the sample at various strain rates (PID control). The mechanical design of the machine allows increasing forces of both tensile and compressive nature up to a maximum value of 30 kN. The main advantage of the design of the mobile parts of the machine is the practically backlash-free transfer of the load to the sample. In the experiment, the load value was chosen 10 kN, the motor's step rate was chosen 0.25 μm/s.

Samples (SAV-1) for mechanical tests:

for compression: cylindrical rods with size ∅ ~ 6 mm, length 1_0 ~ 12 mm;

tensile cylindrical rods with size ∅ ~ 6 mm, length 1_0 ~ 72 - 78 mm.

In SAV-1 alloys, the main alloying dopants are Mg and Si. Their concentrations increase as a result of nuclear reactions: the concentration of Si - as a result of the reaction Al(n, γ)Si, and the concentration of Mg - as a result of the reaction Si(γ, α)Mg. As can be seen from the Table 1, as a result of neutron irradiation in aluminum alloys, in addition to radiation damage, changes in the concentration of alloying additions occur. If the concentration of alloying additives exceeds the solubility limit, then another phase precipitates. This process, like the migration of impurity atoms to accumulations of defects (dislocations, grain boundaries, and others), affects the change in the properties of materials [3].

Table 1. **The elemental composition of non-irradiated and neutron-irradiated samples of SAV-1 alloy, % [10]**

Fluence, n/cm^2	Al	Si	Mg	Fe	Ni	Cu	Mn
Before irradiation	98.27	0.5	1.06	0.14		0.02	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} [11]	97.09	2.05	0.53	0.32		0.01	
After irradiation 10^{20} [11]	96.86	2.35	0.45	0.33		0.01	

To study the structure averaged over the entire volume of the samples, the neutron diffraction experiments were carried out at the Fourier-stress-diffractometer FSD, located on the 11A channel of the IBR-2 pulsed reactor in the Frank Laboratory of Neutron Physics, Joint Institute for Nuclear Research (JINR, Dubna, Russia). The measurements were carried out for a series of samples from the SAV-1 aluminum alloy (Table 2). A special correlation technique – using a fast Fourier chopper to modulate the intensity of the primary neutron beam and the RTOF method for data accumulation - allowed to obtain diffraction spectra with high resolution ($\Delta d/d \approx 2\cdot10^{-3}$ at a scattering angle of $2\theta = 140°$ and $\Delta d/d \approx 4\cdot10^{-3}$ at $2\theta = \pm 90°$) in a wide range of interplanar spacing, which provides the required accuracy of recording small displacements of diffraction peaks and their broadenings [12, 13].

ISSN 1818-331X NUCLEAR PHYSICS AND ATOMIC ENERGY 2021 Vol. 22 No. 3

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/cm^2	Notes, mm
1	0	Cylinder (∅ 6, h = 50)
2	0	Cylinder (∅ 6, h = 50)
3	0	Powder (vanadium container, ∅ 5, h = 50)
4	0	Disk (∅ 17, h = 3.2)
5	10^{16}	Disk (∅ 17, h = 3.5)
6	10^{17}	Disk (∅ 17, h = 2.9)
7	10^{18}	Disk (∅ 17, h = 3.2)

3. Results and discussions

The measurements of macroscopic strength.

The following parameters were determined during testing of samples: the threshold of tensile strength σ_{ts} (temporary resistance), σ_f fluidity (physical), conditional fluidity $\sigma_{0.2}$ (technical), proportional limit σ_{pl}, elastic limit σ_{el}, true tensile strength S_k, relative elongation δ and constriction ψ (Table 3, [6]).

Table 3. **The main mechanical properties of stretching SAV-1 samples before and after irradiation in the IBR-2 reactor with different fluences**

Fast neutron fluence, n/cm^2	σ_{ts}, MPa	σ_f, MPa	$\sigma_{0.2}$, MPa	σ_{pl}, MPa	σ_{el}, MPa	S_k. MPa	δ, %	ψ, %
Before irradiation	160.4	154.8	154.3	108.6	117.9	147.4	18.0	15.0
10^{16}	190.7	185.0	180.0	83.4	110.0	119.0	16.0	16.0
10^{17}	165.0	159.0	159.0	83.4	100.0	107.0	17.0	16.0
10^{18}	175.0	162.0	162.0	84.0	105.0	110.0	13.5	7.0
Before irradiation [6]							16.5	
$3.5 \cdot 10^{22}$							2.5	

The difference found between the strength of the crystal lattice of the irradiated and non-irradiated SAV-1 alloy is easily explained if we assume that the SAV-1 alloy is an interstitial solid solution since silicon and magnesium do not form chemical compounds with aluminum [3]. Accordingly, the atoms of the main alloying elements silicon and magnesium increase the size of those unit cells in the interstices of which they are located.

Further, the force-extension curve was obtained, and it allows to judge the tensile strength of the sample (Fig 2). Our study shows that material's relative elongation depends on the irradiation dose at 10^{16} n/cm^2. Relative elongation increases due to defects annihilation under neutron irradiation (Table 4).

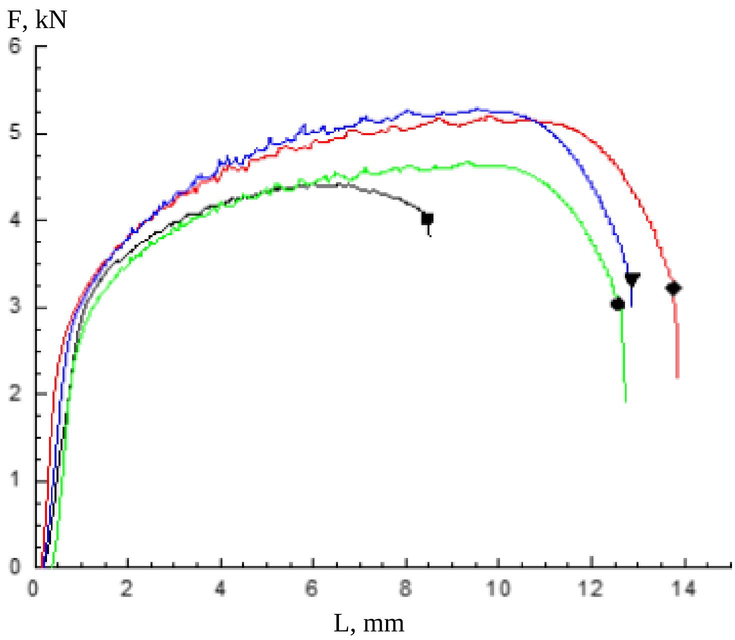


Fig. 2. Tensile diagram (dependence of elongation Δl on load P). F – is the stress stretching parameter which cause the elongation in the fluidity area (kN), L – is the length of the sample at the moment of rupture. Samples: ■ –unirradiated; ♦ - 10^{16} n/cm^2; ● - 10^{17} n/cm^2; ▼ - 10^{18} n/cm^2. (See color Figure on the journal website.)

Table 4. **The conditional stress-deformation of SAV-1 alloy under static tension, before and after irradiation in the IBR-2 reactor at different fluences and literature data [7]**

Fluence, n/cm^2	Relative elongation δ, %	Stress-deformation Q, kg/mm^2
0	16.0	18.16
10^{16}	16.4	19.30
10^{17}	16.8	16.90
10^{18}	13.5	19.10
0 [7]	22.1	14.00
10^{17} [7]	25.2	15.20
10^{22} [7]	18.5	20.10

4. Neutron diffraction results

A noticeable texture of the material was observed in almost all studied samples, which is apparently due to the presence of texture in the initial material of the workpiece from which the samples were made. The measured diffraction spectra were processed by the Pauli method [14]. As a result, the crystal lattice of the material and the parameters of the dependence of the widths of the peaks on the interplanar distance were determined (Figs. 3 and 4).

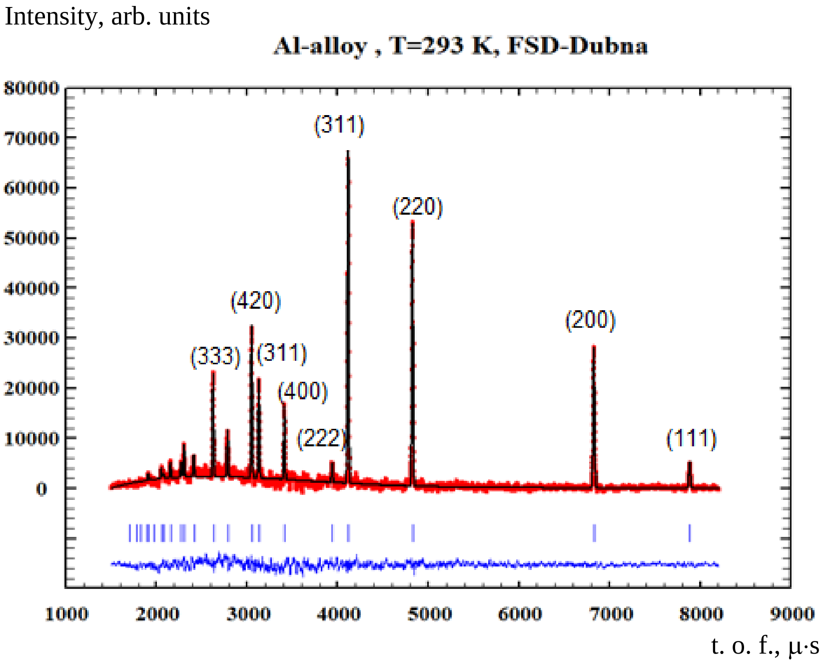


Fig. 3. The diffraction spectrum of the aluminum alloy SAV-1 (sample No. 1), processed by the Pauli method [14]. Experimental points, calculated and difference curves, positions of diffraction peaks are shown. (See color Figure on the journal website.)

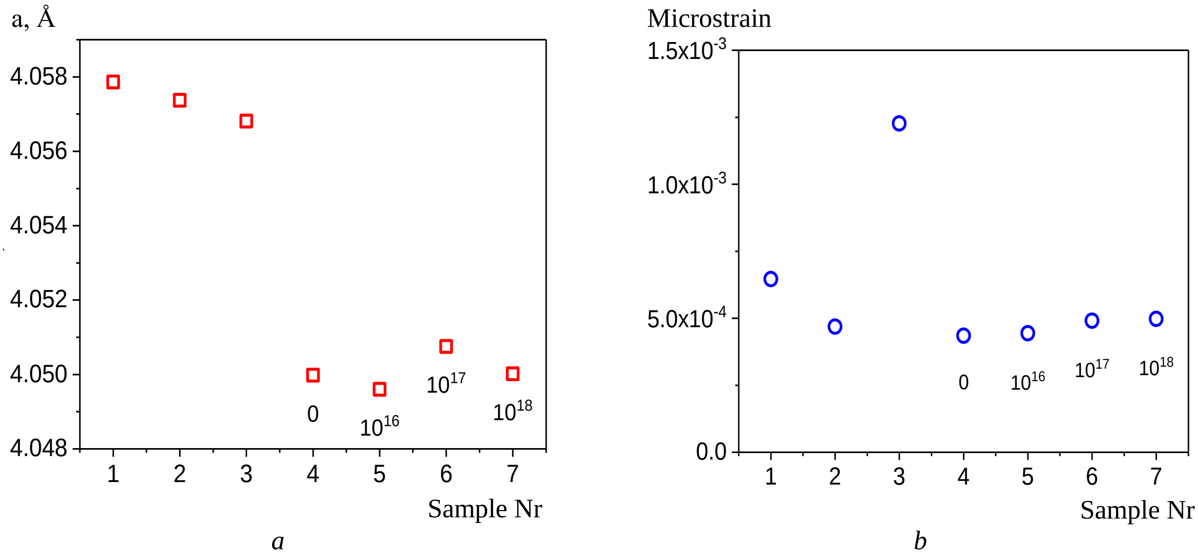


Fig. 4. The parameters of the crystal lattice (*a*) and average microstrain (*b*) for the samples of SAV-1 alloy. The doses of irradiated samples are indicated. (See color Figure on the journal website.)

The size of the crystal lattice unit cell of the solid solution is different in different parts of the lattice, therefore, we can speak only about the average value of the period.

It is known [3] that in interstitial solid solutions the atoms of dissolved elements are located in the interatomic spaces of the crystal lattice and lead to local distortions of the crystal structure of the alloy base. The sizes of these distortions are relatively large compared to the sizes (pores) in which the impurity atoms are located. Therefore, an increase takes place in the volume of distorted cells, despite the presence of a relatively small fraction of impurities. This lead to a noticeable increase in the average lattice period of the alloy and a corresponding expansion occurred in the volume of the unit cell during the formation of an interstitial solution, which is observed experimentally. As a result, the specific configuration of the crystal lattice of the alloy is characterized by the fact that some pores are occupied and others are free.

From the analysis of the broadening of diffraction peaks in comparison with the resolution function of the diffractometer, microstrains were determined, averaged over all observed reflections (*hkl*) (see [12]).

5. Conclusion

The observed difference in the lattice parameters for cylindrical samples and disks is most likely caused by the deformation of the material during the manufacture of disk samples. The level of micro deformations in the studied samples is rather low and, apparently, their presence is due to the appearance of micro deformations in the initial workpiece during the rolling of the material. An exception was observed difference in the lattice parameters for cylindrical samples and disks, which is possibly caused by deformation of sample No. 3 (powder), in which the level of micro deformations is relatively high, which is explained by significant plastic deformation of the alloy material during the manufacture of a powder sample from the aluminum scobs. There was not found a clear dependence of the lattice parameter of the material and micro deformations on the radiation dose for the samples 4 - 7, which indicates the absence of noticeable structural changes at low radiation doses.

It was found that insignificant changes at the grain boundary during irradiation of the samples lead to a change in the strength characteristics of aluminum alloys. Thus, the analysis of the obtained experimental results allows us to conclude that the SAV-1 alloy is an interstitial solid solution, and the strength of the alloy changes nonlinearly by increasing the radiation dose.

REFERENCES

1. V.M. Lebedev et al. Structure of aluminum alloys irradiated with reactor neutrons. Physics of the Solid State 52 (2010) 996.
2. E.F. Sturcken. Irradiation effects in magnesium and aluminum alloys. J. Nucl. Mater. 82 (1979) 39.
3. A. Hoffman et al. Effect of Nuclear Reactions on the Properties of Al-Mg-Si Alloys after Long-Time Exploitation in Research Reactors. Communication of the JINR (Dubna) No. P14-2004-174. 10 p.
4. Yeon Soo Kim, Byoung Jin Cho, Dong-Seong Sohn. Thermal conductivity modeling of U-Mo/Al dispersion fuel. J. Nucl. Mater. 466 (2015) 576.
5. A. Munitz et al. Mechanical properties and microstructure of neutron irradiated cold worked Al-6063 alloy. J. Nucl. Mater. 252 (1998) 79.
6. V.S. Karasev. Plastic properties of SAV-1 alloy after long-time service in WWR-M reactor. Voprosy Atomnoj Nauki i Tekhniki. Fizika Radiatsionnykh Povrezhdenij i Radiatsionnoe Materialovedenie (49) (1989) 39. (Rus)
7. O.P. Maksimkin et al. Influence of neutron irradiation on intergranular corrosion and corrosion cracking of low-alloyed aluminum alloy SAV-1. Voprosy Atomnoj Nauki i Tekhniki. Fizika Radiatsionnykh Povrezhdenij i Radiatsionnoe Materialovedenie 2-97/72 (2011) 108. (Rus)
8. A.M. Mavlyutov et al. Influence of the microstructure on the physicomechanical properties of the aluminum alloy Al-Mg-Si nanostructured under severe plastic deformation. Physics of the Solid State 57(10) (2015) 2051.
9. M. Murayama et al. Atom probe studies on the early stages of precipitation in Al-Mg-Si alloys. Materials Science and Engineering A 250(1) (1998) 127.
10. Sh.A. Alikulov. Influence of neutron radiation on thermal and electrophysical properties of construction materials of the nuclear reactor. PhD Thesis (Tashkent, 2020).
11. U.S. Salikhbaev et al. Effect of reactor irradiation on the microstructure and microhardness of aluminum alloys SAV-1 and AMG-2. Al′ternativnaâ ènergetika i èkologiâ 9(65) (2008) 105.
12. G.D. Bokuchava, Neutron RTOF Stress Diffractometer FSD at the IBR-2 pulsed reactor. Crystals 8(8) (2018) 318.
13. G.D. Bokuchava, I.V. Papushkin, Neutron Time-of-Flight Stress Diffractometry. J. of Surface Investigation: X-ray, Synchrotron and Neutron Techniques 12(1) (2018) 97.
14. G.S. Pawley. Unit-cell refinement from powder diffraction scans. J. Appl. Cryst. 14 (1981) 357.

Ш. А. Алікулов, С. А. Байтелесов, Ф. Р. Кунгуров*, Д. П. Таджибаєв, Д. Д. Тоджибоєв

Інститут ядерної фізики Академії наук Республіки Узбекистан, Ташкент, Узбекистан

*Відповідальний автор: fkungurov@inp.uz

ВПЛИВ НЕЙТРОННОГО ОПРОМІНЮВАННЯ НА СТРУКТУРУ І МІЦНІСТЬ АЛЮМІНІЄВОГО СПЛАВУ SAV-1

Алюмінієвий сплав SAV-1 було досліджено до і після радіаційного опромінення нейтронами при потоках 10^{16} - 10^{18} н/см^2. Вимірювання проводили методами нейтронографії для аналізу кореляції структурного стану з результатами вимірювань міцності зразка за допомогою навантажувальної машини. Установлено, що зміни характеристик міцності алюмінієвих сплавів пов’язані з модифікаціями на рівні зерен під час опромінення зразків. Таким чином, отримані експериментальні дані дають змогу зробити висновок, що сплав SAV-1 є твердим проміжним розчином, а міцність сплаву змінюється нелінійно залежно від дози опромінення.

Ключові слова: алюмінієвий сплав SAV-1, нейтронне опромінення, розсіювання нейтронів, мікроструктура, фазовий склад.

Надійшла/Received 01.04.2021