EFFECT OF IRRADIATION WITH KRYPTON IONS ON THE STRUCTURAL-PHASE STATE OF A MULTICOMPONENT SOLID SOLUTION BASED ON V-Nb-Ta-Ti

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The development of nuclear power in the world places increased demands on the structural materials used, their production technology and performance control. Under the influence of irradiation, these materials undergo structural-phase transformations, which have a negative effect primarily on mechanical properties. High-entropy alloys (HEA) based on a single-phase solid solution and a large number (more than five) of basic elements in equimolar or almost equimolar ratios are promising for obtaining radiation-resistant materials for nuclear power. It is believed that the maximization of the configuration entropy of the HEA contributes to the formation of a single-phase disordered solid solution instead of the precipitation of complex intermetallic or second phases, as a result of which the alloy has a simple microstructure with improved properties compared to traditional alloys [1-3]. Numerous studies have shown that wind turbines have high elastic limit, fatigue strength, thermal and corrosion resistance, creep resistance, radiation resistance. The properties of these alloys are associated with four main effects: high entropy, large lattice deformation, multi-element composition and delayed diffusion [4-6].

Multi-component solid solutions based on V-Nb-Ta-Ti, specifically V, VNb, VNbTa, VNbTaTi were manufactured at the Beijing Technological University. Samples were synthesized using high purity metals (>99.9%) by arc melting and casting in a copper cell, followed by homogenization. Then vacuum annealing was carried out for 24 hours and 72 hours at a temperature of 1150°C with cold rolling up to 85% reduction in thickness.

The samples were irradiated at a DC-60 heavy ion accelerator located in Nur-Sultan, Kazakhstan. Low-energy Kr^{14+} ions with an energy of 40 keV were chosen as the type of irradiation. The irradiation fluence was 5×10^{15} cm^{-2}.

The effect of irradiation on the spatial distribution of elements were carried out by Rutherford backscattering spectroscopy (RBS) and energy-dispersive X-ray analysis (EDX).

The table shows the results of the elemental composition analysis calculated by the EDX and PIXE methods. The equiatomic and homogeneous distribution of elements over the surface was confirmed by the EDX method, and the equiatomic and homogeneous distribution of elements over the depth was confirmed by the PIXE method.

Table 1. Results of the elemental composition in the initial samples of the V-Nb-Ta-Ti system

Sample	PIXE		EDX	
	Концентрация, ат.%			
V	V	100	V	100
VNb	V	50	V	49.5
	Nb	50	Nb	50.5
VNbTa	V	32.0	V	33.9
	Nb	33.0	Nb	34.2
	Ta	35.0	Ta	31.9
VNbTaTi	V	24.5	V	23.6
	Nb	25.5	Nb	26.1
	Ta	26.0	Ta	25.9
	Ti	24.0	Ti	24.5

The calculation of energy losses was carried out in the SRIM 2013 program using the Kinchin-Pease model [7]. Fig. 1 shows the distribution profiles of implanted Kr^{14+} ions and the results of modeling radiation damage (measured in displacement per atom, dpa). The maximum range of krypton ions was 1800 nm with maximum damage for vanadium at a depth of 160-170 nm, and for VNbTaTi alloy – 120-140 nm. The highest value of the damaging dose is 3.5–6.5 dpa, depending on the samples. The concentration of implanted He^{2+} ions does not exceed 23%.

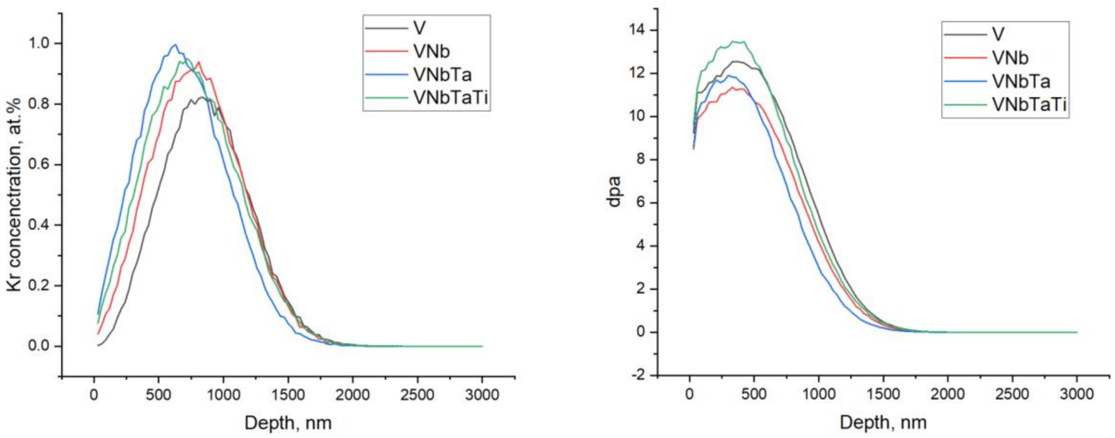

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Fig. 1 Profiles of the distribution of implanted Kr^{14+} ion (a) and the damaging dose (b) in samples V, VNb, VNbTa, VNbTaTi by depth

Irradiation does not lead to a significant violation of the equiatomic elements, as evidenced by the results of EDX and PIXE. According to the results of RBS, krypton is observed only in pure vanadium and both its concentration and depth of occurrence coincide with the results of SRIM. Krypton was not detected on the other alloys, possibly due to the low concentration and close atomic numbers of krypton and neobium.

Table 2. Results of the elemental composition in irradiated samples of the V-Nb-Ta-Ti system

Sample	PIXE		EDX	
	Concentration, ат.%			
V	25 нм	V - 100	V	100
	90 нм	V – 99.2		
		Kr - 0.8		
VNb	V	50	V	49.7
	Nb	50	Nb	50.3
VNbTa	V	29.0	V	36.3
	Nb	35.0	Nb	31.2
	Ta	36.0	Ta	32.6
VNbTaTi	V	21.0	V	25.2
	Nb	29.0	Nb	25.4
	Ta	29.0	Ta	24.3
	Ti	21.0	Ti	25.1

To quantify the effect of radiation damage on the structure of samples, changes in micro- and macro-stresses relative to non-irradiated samples were calculated.

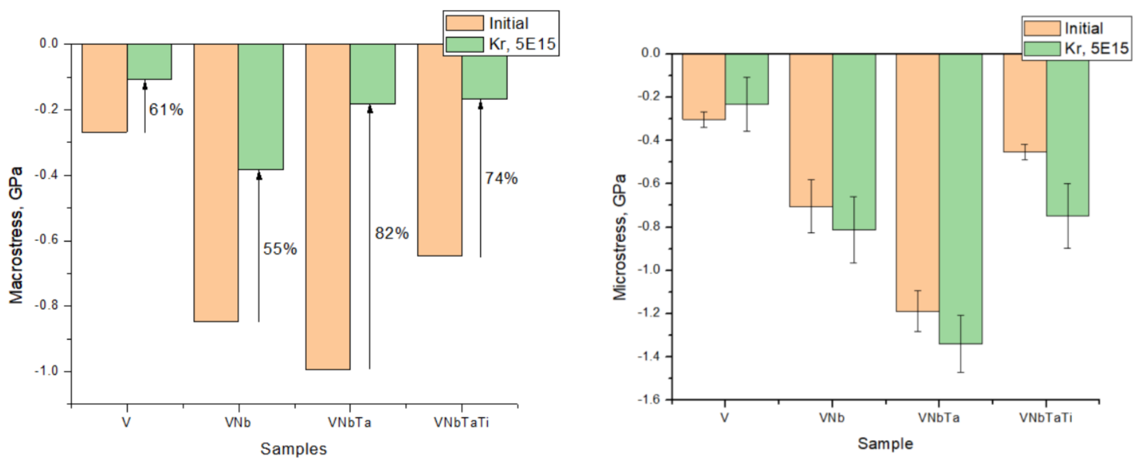

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Fig. 2 Values of macrostress (a) and microstresses depending on the complexity of the composition of the V-Nb-Ta-Ti system for the initial and irradiated samples (b)

There is a decrease in macro stresses as a result of irradiation, which can be explained by several reasons. Irradiation leads to the formation of a large number of radiation vacancies, which cause the growth of tensile stresses and, possibly, for more complex systems, a decrease is observed due to the saturation of existing dislocations with interstitial atoms. Another reason may be thermal annealing, as a result of which most of the previously existing defects recombine. In contrast, an increase in compressive stresses is observed in microstresses, which may be due to radiation-stimulated diffusion of lighter elements to the boundaries of the coherent scattering region. However, it is not possible to assess which of the elements is more stable at the moment. It is also hard to say with certainty that there is a dependence of stresses on the complexity of the composition.

Irradiation with krypton ions leads to the formation of tensile stresses of the first kind, which may be associated with the formation of a large number of radiation vacancies and saturation of dislocations. There is an increase in microstresses in multicomponent solid solutions, which may be due to the radiation-stimulated diffusion of lighter elements to the boundaries of the coherent scattering region, which leads to an increase in microstresses due to the dimensional factor.

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