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VANADIUM-BASE ALLOYS*

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B. A. Loomis¹, B. J. Kestel¹ and S. B. Gerber¹

SOLUTE SEGREGATION AND MICROSTRUCTURAL EVOLUTION IN ION-IRRADIATED
VANADIUM-BASE ALLOYS*

ABSTRACT: The microstructural evolution in V+14.7 a/o Cr, V+2.5 a/o Mo, V+2.5 a/o W, V+8.0 a/o Ni, V+5.3 a/o Ti, V+14.7 a/o Cr + 5.2 a/o Ti, V+9.6 a/o Cr + 3.1 a/o Fe+0.7 a/o Zr, and V+3.2 a/o Ti + 1.8 a/o Si alloys, and unalloyed V was determined from observations of specimens by TEM following 4.0-MeV $^{51}\text{V}^{++}$ ion irradiation at 900-970 K to 50 dpa. The RIS of solutes in the ion-irradiated alloys was investigated by AES, EDXS, and EELS analyses. The RIS of solutes and microstructural evolution in the irradiated alloys were correlated with the solute diffusivity and the relative chemical affinity of the substitutional solutes for oxygen.

KEY WORDS: ion-irradiation, vanadium, vanadium alloys, swelling, compositional dependence, precipitates.

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Introduction

The interaction of solute atoms in metallic alloys with irradiation-produced defects that are diffusing in defect gradients to defect sinks, viz., internal and external surfaces, grain boundaries, and dislocations, provide strong driving forces for solute diffusion and solute segregation [1,2,3]. Since the physical and mechanical properties of metallic alloys depend sensitively on alloy composition, the radiation-enhanced diffusion (RED) and radiation-induced segregation (RIS) of solute atoms can impact directly on the void swelling and mechanical properties of alloys utilized for structural materials purposes in an irradiation environment.

Loomis and Gerber have previously investigated the RIS of solute atoms and void swelling in Nb-base alloys on ion irradiation [4]. The results from this investigation were interpreted to show that RIS of solute atoms in Nb and the void swelling of Nb alloys could be correlated by the solute diffusivity and by the relative chemical affinity of the substitutional solute atoms for oxygen [4]. In this paper we present the results of an experimental investigation on the RIS of Ni, Cr, Ti, Mo, and W solute atoms in V and void swelling of these V-base binary alloys on 4-MeV $^{51}\text{V}^{++}$ ion irradiation. In addition, the effects of Fe, Ti, and Si ternary solute additions on the RIS and void swelling of V-base binary alloys are presented for 4-MeV $^{51}\text{V}^{++}$ ion irradiations of these alloys. These experimental results are utilized to assess the importance of solute diffusivity and oxygen affinity for RIS of solute atoms and void swelling of V-base alloys.

Materials and Procedures

The composition of the V alloys prepared for this investigation are listed in Table 1. The V+14.7 a/o Cr, V+2.5 a/o Mo, V+2.5 a/o W, V+8.0 a/o Ni, V+5.3

a/o Ti, V+14.7 a/o Cr+5.2 a/o Ti, and the V+3.2 a/o Ti+1.8 a/o Si alloys were prepared by arc-melting the constituents in a purified Ar atmosphere. The V+9.6 a/o Cr+3.1 a/o Fe+0.7 a/o Zr alloy was obtained from the Fusion Materials Inventory^a. Sheet specimens of these alloys and unalloyed V with 0.13-mm thickness were annealed at 1425 K for 10^4 s. Special attention was given to the surface preparation of the specimens for this study to insure a uniform alloy composition in the near-surface region (~1500 nm thickness). The O, N, and C concentrations in the V alloys and unalloyed V were determined by the vacuum fusion technique.

Specimens of the V and V alloys, each with a diameter of 3.05 mm, were mounted in a tungsten holder for irradiation. The irradiations were performed in the dual-ion, 2-MeV Tandem irradiation facility at Argonne National Laboratory. The specimens were irradiated with 4.0-MeV $^{51}\text{V}^{++}$ ions at a nominal atomic displacement rate of 5×10^{-3} atom displacements per atom (dpa) per second to an irradiation damage level of 55 dpa at the depth for the maximum calculated damage. The dpa levels were calculated by the use of the Brice computer codes RASE 3 and DAMG 2 with some modifications [5]. The depth of the maximum irradiation damage for 4-MeV $^{51}\text{V}^{++}$ ions impinging on V was calculated to 1100 nm. The specimens were irradiated at temperatures ranging from 900 K to 1000 K in an all-metal system evacuated to a total pressure of 3×10^{-6} Pa.

The dependence of the solute concentration on depth in the irradiation-damaged layer (~1500 nm thickness) was determined by use of the Auger Electron Spectroscopy (AES) technique in combination with sputter-ion erosion of the

^aFusion Materials Inventory, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

surface. AES analyses at 300 K were performed using a primary electron beam at 5 keV with a diameter of $\sim 10 \mu\text{m}$ to excite the electron transitions. Depth profiling was accomplished by sputter-ion erosion with 1-keV Ar^+ ions in an Ar atmosphere of 6.5×10^{-3} Pa. The sputter-ion erosion rate was 5.8×10^{-2} nm/s. The concentration of solute in a thin surface layer (~ 100 nm) on the annealed or irradiated specimens was obtained from the ratio of the peak-to-peak amplitude of the constituent peaks in the Auger electron energy-distribution function and the AES elemental sensitivity factors that were determined for the as-prepared alloys.

The irradiated specimens were prepared for observation by transmission electron microscopy (TEM) by sectioning the specimens to a depth that was approximately 100 nm less than the peak damage depth. The sectioning of the specimens was accomplished by electrolytic polishing of the irradiated surface in a 15% H_2SO_4 -15% butyl cellosolve-70% methanol solution at 250 K.

The solute concentrations in the vicinity of grain boundaries and voids and the composition of precipitates in the irradiated specimens were also investigated by use of energy-dispersive x-ray analysis (EDXA) and electron energy loss spectroscopy (EELS) techniques in conjunction with scanning transmission electron microscopy (STEM). The results of these analyses will only be briefly mentioned in this paper for confirmation of the AES analyses or interpretation of the TEM observations. A more detailed description of the EDXS and EELS analyses will be presented in a future publication.

Experimental Results

The TEM observations of the microstructures in the unirradiated alloys showed that the substitutional solutes were in solid solution prior to irradiation which was expected from the published phase diagrams [6]. With

the exception of the V+9.6 a/o Cr+3.1 a/o Fe+0.7 a/o Zr alloy, the alloys contained relatively few ($< 10^{17} \text{ m}^{-3}$) interstitial impurity precipitates. The V-Cr-Fe-Zr alloy microstructure showed a high number density ($\sim 2 \times 10^{17} \text{ m}^{-3}$) of precipitates with an average diameter of 310 nm.

The TEM observations of the unalloyed V and V-base alloys after irradiation at 900 K, 930 ± 10 K, 970 K and 1000 K to ~ 50 dpa suggested that the temperature for maximum irradiation-induced microstructural evolution was 970 K for unalloyed V and 930 ± 10 K for the alloys. The TEM microstructures for the irradiated unalloyed V and V-base alloys at these "maximum" temperatures are shown in Figs. 1, 3, and 5. The data obtained from the analyses of the TEM microstructures are summarized in Table 2. These data include the average diameter (d_v), number density (c_v), and swelling ($\Delta V/V$) for voids and the average diameter (d_p) and number density (c_p) of irradiation-produced precipitates. The RIS effects for the solute atoms that were determined from the AES analyses on the unirradiated and irradiated alloys are presented in Figs. 2, 4, and 6.

The addition of 14.7 a/o Cr to V in a binary alloy results in an increase of the void swelling of V from $< 2.2\%$ to $> 13\%$ on irradiation at 940–970 K to 50 dpa (Figs. 1a and 3b). The "voids" in the microstructure for the V+14.7 a/o Cr alloy irradiated at 940 K (Fig. 3b) have a disc-like shape with an average diameter of 190 nm as opposed to the more usual cube-shape voids in irradiated V alloys. In reality, it is believed that these disc-like "voids" are composed of a high density ($\sim 10^{22} \text{ m}^{-3}$) of ~ 10 -nm diameter voids. The attempt at sectioning the irradiated specimen for resolution of these smaller diameter voids resulted in uncontrollable and total perforation of the large "voids" in Fig. 3b. Credence for the preceding interpretation of the microstructure in the V-Cr alloy irradiated at 940 K was given by the

microstructure for the alloy irradiated at 900 K (Fig. 1b). In Fig. 1b, voids with an average diameter of 5 nm and a number density of $8 \times 10^{21} \text{ m}^{-3}$ are visible within the areas that have been traversed by dislocations gliding on the $\langle 110 \rangle \{111\}$ slip system which resulted in the striking "rosette" patterns. Comparison of the microstructures in Fig. 1b and Fig. 3b suggested that dislocation glide may have been initiated at unidentified precipitates with a diameter of ~ 10 nm and the "voids" in Fig. 3b have diameters comparable to the "rosette" features in Fig. 1b. The results of the AES analyses for the V+14.7 a/o Cr specimens irradiated at 900 K and 940 K are shown in Fig. 2a. These analyses have shown a significant Cr enrichment in the near-surface layer to a depth of ~ 10 nm for the alloys irradiated at 900 K to 50 dpa. However, the AES analyses showed a significant depletion (~ 9 a/o) of Cr at the surface of the specimen irradiated at 940 K. The EDXS analyses on the microstructure of the V+14.7 a/o Cr specimen irradiated at 940 K (Fig. 3b) have likewise shown significant depletion of Cr at the void surfaces and the grain boundaries.

The presence of 2.5 a/o Mo or W in V as a binary alloying addition resulted in a decrease of the void swelling of V (Table 2). The irradiation of the V-Mo and V-W alloys at the peak swelling temperature for V (970 K) caused no visible voids to be formed. The microstructures of the irradiated V+2.5 a/o Mo (Fig. 1c) and V+2.5 a/o W (Fig. 1d) alloys showed in addition to the relatively sparse population of voids, a notable absence of irradiation-produced precipitates. The AES analyses on the V-Mo and V-W alloys irradiated at 935 K to 50 dpa (Fig. 2b and 2c) showed a depletion of the Mo and W concentration in the near-surface layers. The EDXS analyses on the V-Mo and V-W alloys also suggested a small (~ 1 a/o) depletion of Mo or W concentration at void surfaces and grain boundaries, but these results are not considered to be statistically significant at the present time. Moreover, the irradiation-

induced microstructure for the V+2.5 a/o W alloy may have been altered by the presence of Si impurity. The AES analyses on this alloy showed an exceptionally high (~ 2 a/o) Si concentration in the near-surface layers. The exceptionally high Si concentration was also confirmed by the EDXS analyses. It should be noted that the AES analyses for all of the alloys considered in this study showed a small (< 0.1 a/o) concentration of Si in the near-surface layers. The AES analyses also showed a significant level of S impurity in the near-surface layers.

The addition of 8.0 a/o Ni to V resulted in effective suppression of void formation in V on irradiation at 925 K and 970 K to 50 dpa. The effect of the irradiation on the microstructure of the V+8.0 a/o Ni alloy (Fig. 3a) was to cause the formation of a continuous precipitate layer on the grain boundaries. The AES analysis (Fig. 4a) showed an enrichment of Ni concentration in the near-surface layers, and the EDXS analyses revealed that the precipitate on the grain boundaries contained ~ 11 a/o Ni.

The presence of ~ 5 a/o Ti in the form of a binary alloying addition to V or a ternary alloying addition to a V+14.7 a/o Cr alloy effectively suppressed void formation in V and the V+14.7 a/o Cr alloy on irradiation at 925 K and 970 K to 50 dpa. The microstructures for the V+5.3 a/o Ti alloy (Fig. 5a) and for the V+14.7 a/o Cr+5.2 a/o Ti alloy (Fig. 5b) were remarkably similar in that both microstructures showed the presence of irradiation-induced disc-shape precipitates with an average diameter of 7-10 nm and a number density of $2 \times 10^{22} \text{ m}^{-3}$. The precipitates were sited on $\{110\}$ and $\{100\}$ crystallographic planes. The TEM observations suggested that the precipitates in the ternary alloy may have given rise to a more intense coherency strain field in the matrix. The AES analyses showed the Ti concentration was substantially enriched in the near-surface region for the V-5.3 a/o Ti alloy (Fig. 4b) and

the V-14.7 a/o Cr-5.2 a/o Ti alloy on irradiation at 925 K to 50 dpa (Fig. 6b). The Cr concentration in the ternary alloy was depleted in the near-surface region of the specimen for depths to 2.5 nm. The EDXS analyses on the binary and ternary alloys revealed no significant variation of the Ti concentration in the microstructure and an apparent enrichment of the Cr concentration at grain boundaries in the ternary alloy. An EELS analysis on the precipitates in a V+14.1 a/o Cr+6.6 a/o Ti alloy irradiated at 950 K to 200 dpa have shown that the irradiation-produced precipitates have a composition corresponding to Ti_3O [7].

Irradiation of the V+3.2 a/o Ti+1.8 a/o Si alloy at 925 K to 50 dpa resulted in formation of voids with an average diameter of 74 nm and a number density of $1.6 \times 10^{19} \text{ m}^{-3}$ and disc-shape precipitates with an average diameter of 62 nm and a number density of $2 \times 10^{22} \text{ m}^{-3}$ (Fig. 3c). The relatively low density of voids resulted in a swelling of 0.3%. The precipitates in this alloy had a {100} crystallographic habit plane. The voids in the microstructure were surrounded by an ~100-nm zone devoid of precipitates. The EDXS analyses of this alloy microstructure showed that the zones devoid of precipitates were enriched (3.5 a/o) with Si. The composition of the precipitates could not accurately determined but they were strongly enriched with Ti.

The microstructure for the V+9.6 a/o Cr+3.1 a/o Fe+0.7 a/o Zr alloy after irradiation at 925 K to 50 dpa (Fig. 3d) was exceptional in that the microstructure was not significantly different from the microstructure for the unirradiated alloy. The AES analyses on the irradiated alloy have shown that the Fe concentration was enriched (~6 a/o) in the near-surface layer whereas the Cr concentration was depleted at depths to 2.5 nm (Fig. 6a). The EDXS analyses on the irradiated alloy have shown that the intrinsic precipitates

have Zr as a principle constituent. The EDXS analyses have also shown that the grain boundaries in the irradiated alloy were enriched with Fe and depleted in Cr.

Discussion

The swelling ($\Delta V/V$) in unalloyed V and V-base alloys containing Ni, Fe, Cr, Ti, Mo, W, and Si alloy additions was determined following 4.0-MeV $^{51}\text{V}^{++}$ ion irradiation at 900-970 K to ~ 50 dpa. Also, the thermal- and irradiation-induced segregation of these substitutional-atom solutes to grain boundaries and internal and external surfaces was determined from AES and EDXS analyses. These experimental results are summarized in Table 3. In addition to these experimental results, physical parameters that relate to the presence of the solute atoms in V are also presented in Table 3. We have already mentioned that the EDXS results are considered to be tentative since in most instances only one analytical traverse was made on the microstructure. Also, the diffusivity values are considered reliable only to an order of magnitude. The diffusivity values were calculated for 1000 K which required a significant extrapolation of the diffusivity data in some cases.

The experimental results showed that the swelling ($\Delta V/V$) due to voids in ion-irradiated V was decreased significantly with binary alloy additions of Ni, Ti, Mo, and W, but increased significantly with a binary alloy addition of Cr. However, the void swelling of the V-Cr binary alloy was strongly inhibited by an addition of Ti or Fe solute. The Zr solute in the V-Cr-Fe-Zr alloy was believed to have had little impact on the effect of the Fe solute since the Zr solute was incorporated in the intrinsic precipitates. There was some experimental evidence to suggest that Si solute might enhance void formation in irradiated V even with the presence of the potent Ti void

inhibitor.

The reduction in swelling of V by the presence of Mo and W solute was expected on the basis of a relatively low diffusivity of these solutes in comparison with the self-diffusion of V and the effect of Mo solute on the swelling of irradiated Nb from a previous investigation [4]. However, the depletion of the Mo and W solutes by RIS in the near-surface layers of the irradiated alloys was unexpected. This depletion was opposite to the strong enrichment that was observed for Mo solute in an irradiated Nb alloy [4]. The RIS depletion of Mo and W solute in irradiated V might have been expected on the basis of a correlation with a positive volume atom-size misfit [14].

The suppression of void formation by the presence of Ni solute in the binary V+8.0 a/o Ni alloy and Fe solute in the V+9.6 a/o Cr+3.1 a/o Fe+0.7 a/o Zr alloy was also unexpected. Since the Ni and Fe solute atoms were relatively fast diffusing atoms as well as having a negative volume misfit in V, the effect of these solute atoms may have been due to the diffusion of these solutes by an interstitial or interstitial-vacancy mechanism [13]. It can be noted that enrichment of Ni solute and depletion of Fe solute by RIS was also observed in ion-irradiated Nb alloys [4].

The substantial increase in swelling of V by the addition of 14.7 a/o Cr (Table 2) was expected since Agarwal, et al. [15] have previously reported substantial swelling (~20%) for this alloy on 3.5-MeV $^{51}\text{V}^+$ ion irradiation at 925 K to 60 dpa. However, the Cr enrichment by RIS in the near-surface layers of the specimen irradiated at 900 K to 50 dpa, and the Cr depletion in the near-surface layers of the specimen irradiated at 940 K to 50 dpa were seemingly not in agreement with the results of a previous RIS investigation on this alloy [16]. Rehn, et al. [16] have reported that Cr enrichment in the near-surface layers of a V+14.7 a/o Cr alloy achieved a maximum value (~25

a/o) for a specimen irradiated at 950 K to 24 dpa. Furthermore, Rehn, et al. [16] reported significant Cr enrichment (5-15 a/o) of the near-surface layers in specimens irradiated at 730 K and 840 K to ~20 dpa. The EDXS analyses on the V+14.7 a/o Cr alloy that was irradiated at 940 K to 50 dpa in the present study confirmed the AES results in that significant Cr depletion (~2 a/o) was observed at a void surface and a nearby grain boundary. These disparate results on the RIS of Cr solute in V, i.e., the AES results in the present study and the AES results in Ref. [15], may be due to the Si and S impurity (Table 1) in the alloy for the present study.

The inhibition of void formation in the V+5.3 a/o Ti alloy and the V+14.7 a/o Cr+5.2 a/o Ti alloy are believed to be due to the formation of titanium oxide precipitates with the Ti_3O composition according to the EELS analyses. In a previous study on the swelling of ion-irradiated Nb alloys, the suppression of void formation in Nb by Ti, Zr, and Hf solute was attributed to the strong binding of these solute atoms to vacancy-O complex [4]. Eto, et al. [17] have suggested the existence of such a complex with a binding energy of 0.1 eV between the defect and O to explain unusual Snoek damping in neutron-irradiated V. Kaim and Palmer [18] have shown from proton-channeling studies on 2-MeV $^4He^+$ irradiated Nb that irradiation-produced defects interact sufficiently strongly with O atoms to induce a change of the O lattice site in Nb. Lengeler and Pick [19] have shown by X-ray absorption spectroscopy (EXAFS) that O is trapped by Zr in Nb when the specimen is quenched from 1350 K to ambient temperature. The volume misfit of a Zr atom in Nb and a Ti atom in V, are nearly identical. On the basis of these data it seems justified to assert that on irradiation of the V-Ti and the V-Cr-Ti alloys vacancy-O-Ti complex are formed which diffuse and agglomerate to form the observed precipitates (Figs. 5a and 5b). The crystallographic structure of

the Ti_3O precipitates has been investigated by Holmberg [20]. The crystallographic structure has a superstructure of the Ti_2O structure with the O vacancies of the Ti_2O structure in an ordered distribution. One O position out of three in every O layer normal to the "c" axis is vacant which could allow the incorporation of vacancy defects in the Ti_3O precipitates. The absence of voids in the ion-irradiated V+5.3 a/o Ti and V+14.7 a/o Cr+5.2 a/o Ti alloys may therefore be due to the retention of the vacancy defects in the precipitates in addition to recombination of the radiation-produced defects at sinks. The exceptionally higher enrichment of Ti solute in the near-surface layers of the V-Ti and V-Cr-Ti alloys can be correlated with the relatively high diffusivity of Ti in V and the strong affinity for O (Table 3). The enrichment of the Ti in the near-surface layers is contrary to the expected depletion that might be expected from solute atom misfit [14].

Conclusions

1. Void formation in ion-irradiated V is strongly inhibited by additions of Ni, Ti, Mo, and W solute in a binary alloy.
2. Void formation in ion-irradiated V is promoted by the presence of Cr in a binary alloy.
3. The void formation in ion-irradiated V-Cr binary alloys is inhibited by the addition of Ti or Fe solute.
4. The absence of void formation in V-Ti and V-Cr-Ti alloys is attributed to the formation of Ti_3O precipitates that can incorporate vacancy defects.
5. The microstructural evolution and RIS of solutes in the ion-irradiated V-base alloys could not be succinctly related to solute diffusivity or solute atom volume misfit as was the case for Nb-base alloys.
6. The solute affinity for O in V-base alloys has a strong influence on the

microstructural evolution as was the case for Nb-base alloys.

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TABLE 1-Composition of vanadium alloys irradiated with 4.0-MeV $^{51}\text{V}^{++}$ ions.

Alloy ^a	Interstitial impurity concentration (a/o)		
	O	N	C
V	0.019	0.005	0.008
V+14.7 a/o Cr	0.082	0.001	0.025
V+2.5 a/o Mo	0.081	0.001	0.120
V+2.5 a/o W	0.079	0.001	0.036
V+8.0 a/o Ni	0.079	0.001	0.120
V+5.3 a/o Ti	0.082	0.001	0.081
V+14.7 a/o Cr+5.2 a/o Ti	0.083	0.006	0.083
V+9.6 a/o Cr+3.1 a/o Fe	0.079	0.001	0.043
+0.7 a/o Zr			
V+3.2 a/o Ti+1.8 a/o Si	_b	_b	_b

^aAlloys contain 0.05-0.09 a/o Si and ~0.002 a/o S impurity.

^bAnalyses are not available.

TABLE 2-Microstructural data for vanadium alloys irradiated with 4.0-MeV $^{51}\text{V}^{++}$ ions.

Alloy	Temperature (K)	Damage (dpa)	Voids			Precipitates	
			d_v (nm)	c_v (m^{-3})	$\Delta V/V$ (%)	d_p (nm)	c_p (m^{-3})
V	970	50	43	5.3×10^{20}	2.20		
V+14.7 a/o Cr	900	50	5	$8 \times 10^{21\text{a}}$	0.05		
	940	49	190 ^b	9.8×10^{19}	13 ^c		
V+2.5 a/o Mo	935	50	23	4.5×10^{19}	0.03		
V+2.5 a/o W	935	46	30	4.3×10^{20}	0.60		
V+8.0 a/o Ni	925	50	-d	-d	-d	Grain boundary ^e	
V+5.3 a/o Ti	925	50	-d	-d	-d	10	2×10^{22}
V+14.7 a/o Cr+5.2 a/o Ti	925	55	-d	-d	-d	7	2×10^{22}
V+9.6 a/o Cr+3.1 a/o Fe +0.7 a/o Zr	925	50	-d	-d	-d	310 ^f	$2 \times 10^{17\text{f}}$
V+3.2 a/o Ti+1.8 a/o Si	925	46	74	1.6×10^{19}	0.33	62	2×10^{22}

^aVoids are densely packed in discrete regions.^bAverage diameter of disc-shape voids.^c $\Delta V/V$ determined from step-height on the irradiated specimen surface. $\Delta V/V=35.5\%$ for assumption of spherical voids.^dVoids were not observed.^ePrecipitate layer with 50-100 nm width on grain boundaries.^fPrecipitates in unirradiated material.

TABLE 3-Swelling, solute RIS, diffusivity, O affinity, and volume misfit for solute atoms in V.

Alloy ^a	Irrad. Temp. (°K)	$\Delta V/V$ (%)	Solute	Solute RIS		Diffusivity of Solute in V (m ² s ⁻¹) ^f	Relative Oxygen Affinity (k cal Mol ⁻¹) ^e	Solute Atom Volume Misfit ^d (%)
				AES ^b	EDXS ^c			
V+8.0 a/o Ni	925	< 0.1	Ni	+	+	4x10 ⁻²⁰	-45(NiO)	-14
V+14.7 a/o Cr	900	< 0.1	Cr	+		7x10 ⁻²¹	-13(1/3 Cr ₂ O ₃)	-14
V+14.7 a/o Cr	940	13	Cr	-	-	7x10 ⁻²¹	-13(1/3 Cr ₂ O ₃)	-14
V+5.3 a/o Ti	925	< 0.1	Ti	+		1x10 ⁻²⁰	+27(TiO)	+35
V+2.5 a/o Mo	935	< 0.1	Mo	-		< 3x10 ⁻²¹	-33(1/2 MoO ₂)	+12
V+2.5 a/o W	935	0.6	W	-		< 3x10 ⁻²¹	-33(1/2 WO ₂)	+14
V+14.7 a/o Cr	925	< 0.1	Cr	-	+	7x10 ⁻²¹	-13(1/3 Cr ₂ O ₃)	-14
+5.2 a/o Ti			Ti	+	+	1x10 ⁻²⁰	+27(TiO)	+35
V+3.2 a/o Ti	925	0.3	Ti	+	+	1x10 ⁻²⁰	+27(TiO)	+35
+1.8 a/o Si			Si	+	+	--	+ 6(1/2 SiO ₂)	-28
V+9.6 a/o Cr	925	< 0.1	Cr	-	-	7x10 ⁻²¹	-13(1/3 Cr ₂ O ₃)	-14
+3.1 a/o Fe+0.7 a/o Zr			Fe	-	+	1x10 ⁻²⁰	-40(FeO)	-15
V	970	2.2				3x10 ⁻²¹		

^aAlloys and V irradiated to ~50 dpa.^bEnrichment of the solute at the surface is +.^cEnrichment of the solute at a grain boundary or void is +.^dThe volume misfit is defined by $(r_s/r_v)^3 - 1$ where r_s and r_v are half the nearest-neighbor distance of the elemental solute and V, respectively [8].^e $\Delta H_{298}^O (VO) - \Delta H_{298}^O (\text{solute oxide})$ from [9].^fReferences [10], [11], [12], and [13].

List of Figures

Fig. 1-Microstructures for irradiated unalloyed V and V-base alloys: (a) 50 dpa at 970 K, (b) 50 dpa at 900 K, (c) 50 dpa at 935 K, and (d) 46 dpa at 935 K.

Fig. 2-AES analyses for (a) V+14.7 a/o Cr, (b) V+2.5 a/o Mo, and (c) V+2.5 a/o W alloys.

Fig. 3-Microstructures for irradiated V-base alloys: (a) 50 dpa at 925 K, (b) 49 dpa at 940 K, (c) 46 dpa at 925 K, and (d) 50 dpa at 925 K.

Fig. 4-AES analyses for (a) V+8.0 a/o Ni and (b) V+5.3 a/o Ti alloys.

Fig. 5-Microstructures for irradiated V-base alloys: (a) 50 dpa at 925 K and (b) 55 dpa at 925 K.

Fig. 6-AES analyses for (a) V+9.6 a/o Cr+3.1 a/o Fe+0.7 a/o Zr and (b) V+14.7 a/o Cr+5.2 a/o Ti alloys.

(a) V

(b) V + 14.7 at% Cr

200 nm

(c) V + 2.5 at% Mo

(d) V + 2.5 at% W

Fig. 1-Microstructures for irradiated unalloyed V and V-base alloys: (a) 50 dpa at 970 K, (b) 50 dpa at 900 K, (c) 50 dpa at 935 K, and (d) 46 dpa at

Fig. 2-AES analyses for (a) V+14.7 a/o Cr, (b) V+2.5 a/o Mo, and (c) V+2.5 a/o W alloys. ,

(a) V + 8.0 at% Ni

(b) V + 14.7 at% Cr

(c) V + 3.2 at% Ti + 1.8 at% Si

(d) V + 9.6 at% Cr + 3.1 at% Fe
+ 0.7 at% Zr

Fig. 3—Microstructures for irradiated V-base alloys: (a) 50 dpa at 925 K, (b) 40 dpa at 940 K, (c) 46 dpa at 925 K, and (d) 50 dpa at 925 K

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