CONF-860421--34

EFFECT OF HELIUM ON SWELLING AND MICROSTRUCTURAL EVOLUTION IN
ION-IRRADIATED V-15Cr-5Ti ALLOY*

B. A. Loomis, B. J. Kestel, S. B. Gerber, and G. Ayrault
Materials Science and Technology Division
Argonne National Laboratory
Argonne, Illinois 60439

Received by OSTI

MAY 19 1986

CONF-860421--34

DE86 010510

March 1986

The submitted manuscript has been authored
by a contractor of the U. S. Government
under contract No. W-31-109-ENG-38.
Accordingly, the U. S. Government retains a
nonexclusive, royalty-free license to publish
or reproduce the published form of this
contribution, or allow others to do so, for
U. S. Government purposes.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Submitted to the Second International Conference on Fusion Reactor Materials,
April 13-17, 1986, Chicago, Illinois.

*Work supported by the U. S. Department of Energy, BES-Materials Sciences, and
the Office of Fusion Energy, under Contract W-31-109-Eng-38.

MASTER
JHR

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

EFFECT OF HELIUM ON SWELLING AND MICROSTRUCTURAL EVOLUTION IN
ION-IRRADIATED V-15Cr-5Ti ALLOY*

B. A. Loomis, B. J. Kestel, S. B. Gerber, and G. Ayrault
Materials Science and Technology Division
Argonne National Laboratory
Argonne, Illinois 60439

March 1986

The submitted manuscript has been authored
by a contractor of the U. S. Government
under contract No. W-31-109-ENG-38.
Accordingly, the U. S. Government retains a
nonexclusive, royalty-free license to publish
or reproduce the published form of this
contribution, or allow others to do so, for
U. S. Government purposes.

Submitted to the Second International Conference on Fusion Reactor Materials,
April 13-17, 1986, Chicago, Illinois.

*Work supported by the U. S. Department of Energy, BES-Materials Sciences, and
the Office of Fusion Energy, under Contract W-31-109-Eng-38.

EFFECT OF HELIUM ON SWELLING AND MICROSTRUCTURAL EVOLUTION IN ION-IRRADIATED V-15Cr-5Ti ALLOY*

B. A. Loomis, B. J. Kestel, S. B. Gerber, and G. Ayrault
Materials Science and Technology Division, Argonne National Laboratory,
Argonne, Illinois 60439 U.S.A.

1. Introduction

The V-15Cr-5Ti alloy is a potential candidate material for structural components in a magnetic fusion reactor (MFR) [1]. Irradiations of this alloy with neutrons ($E > 0.1$ MeV) and energetic (3-4 MeV) metallic ions have demonstrated an inherent resistance to swelling that results from production of irradiation damage [1]. However, the simultaneous production of helium atoms from nuclear transmutation reactions and irradiation damage in the V-15Cr-5Ti alloy in the MFR environment may have an impact on the swelling resistance and microstructural evolution of this alloy [2-4]. The helium production rate in the V-15Cr-5Ti alloy in the MFR environment has been calculated to be 57 appm/MW·Y/m² or 5.2 appm/dpa (dpa=displacements per atom) [1].

In this paper we present the results of an investigation on the effects of implanted helium on the swelling and microstructural evolution that results from energetic single- and dual-ion irradiation of the V-15Cr-5Ti alloy. Single-ion irradiations were utilized for a simulated production of the irradiation damage that might be expected from neutron irradiation of the alloy in a reactor with a fast neutron energy spectrum ($E > 0.1$ MeV). Dual-ion irradiations were utilized for a simulated production of the simultaneous creation of helium atoms and irradiation damage in the alloy in the MFR environment. The implantation of helium atoms and the production of displaced

*Work supported by the U. S. Department of Energy, BES-Materials Sciences, and the Office of Fusion Energy, under Contract W-31-109-Eng-38.

atoms from neutron interactions with lattice atoms can be expected to induce significant changes in local concentrations of the constituent alloy atoms and to have an impact on the microstructural evolution [5]. Therefore, experimental results are also presented in this paper on the radiation-induced segregation (RIS) of the constituent atoms in the single- and dual-ion irradiated alloy.

2. Materials and Procedure

The V-15Cr-5Ti alloy for this investigation was prepared by arc-melting the constituent metals in a purified argon atmosphere. The Chemical analysis for the alloy is presented in Table 1. Specimens of the alloy (0.13-mm thick) were annealed at 1100°C for 7.2×10^3 s to give a fully recrystallized microstructure with a dislocation density of $\sim 5 \times 10^{12} \text{ m}^{-2}$.

Alloy specimens, each with a diameter of 3.05 mm, were mounted in a four-by-four array in a tungsten holder for simultaneous (dual) irradiations with 3.0-MeV $^{51}\text{V}^+$ and energy-degraded 0.87-MeV $^3\text{He}^+$ ions. The specimens were irradiated at 425, 540, 625, 640, and 675°C in a cryogenically pumped chamber evacuated to 1.3×10^{-6} Pa in the Dynamitron irradiation facility at Argonne National Laboratory. Also, specimens of the alloy were mounted in a tungsten holder for single-ion irradiation with either 4.0-MeV $^{51}\text{V}^{++}$ ions or 4.0-MeV $^{58}\text{Ni}^{++}$ ions, dual-ion irradiation with 3.0-MeV $^{51}\text{V}^{++}$ ions or 3.0-MeV $^{58}\text{Ni}^{++}$ ions and 0.25-MeV $^3\text{He}^+$ ions, and helium implantation using 0.50-MeV $^4\text{He}^+$ ions followed by irradiation with 4.0-MeV $^{58}\text{Ni}^{++}$ ions. These specimens were irradiated at 600, 650, 675, 725, and 750°C in a cryogenically pumped chamber evacuated to 1.1×10^{-6} Pa in the 2-MeV Tandem irradiation facility at Argonne National Laboratory.

Deposited energy densities as a function of ion range in the alloy from a computerized TRIM code were converted to displacements per atom (dpa) and

helium atom deposition using a threshold energy of 40 eV [6]. The depths in the alloy specimens for peak irradiation damage during 3.0-MeV $^{51}\text{V}^+$ and 4.0-MeV $^{51}\text{V}^{++}$ ion irradiation were computed to be 910 nm and 1300 nm, respectively. The depths in the alloy for peak irradiation damage during 3.0-MeV and 4.0-MeV $^{58}\text{Ni}^{++}$ ion irradiation were computed to be 850 and 1150 nm, respectively. The depths for peak deposition of helium atoms during 0.25-MeV $^3\text{He}^+$ and 0.50-MeV $^4\text{He}^+$ ion implantation were computed to be 670 and 1110 nm, respectively. The specimens were irradiated to displacement damage levels ranging from 15 to 300 dpa at a damage rate of $\sim 5 \times 10^{-3}$ dpa/s. In the case of specimens implanted with helium prior to 4.0-MeV $^{58}\text{Ni}^{++}$ ion irradiation, the helium concentration was 780 appm. The helium implantation rate for the dual-ion irradiations was either 3, 5, 9, 10, or 50 appm/dpa. In the case of the simultaneous irradiations of the specimens with 3.0-MeV $^{51}\text{V}^+$ and "degraded" 0.87-MeV $^3\text{He}^+$ ions, the energy of the $^3\text{He}^+$ ions was degraded to give a helium deposition-depth distribution that was similar to the damage-depth distribution produced by the $^{51}\text{V}^+$ ions.

The dependence on depth in the irradiation-damaged layer (~ 1500 -nm thickness) of the RIS of solute atoms was determined by use of the Auger Electron Spectroscopy (AES) technique in combination with sputter-ion erosion of the specimen surface. AES analyses at ambient room temperature were performed using a primary electron beam at 5 keV with a diameter of 10 μm to excite the electron transitions. Depth profiling was accomplished by sputter-ion erosion with 1-keV argon ions in an argon atmosphere of 6.5×10^{-3} Pa. The sputter-ion erosion rate was ~ 180 nm/s for specimens eroded to a depth of ~ 100 nm. It should be noted that the AES analyses did not show the presence of Ni atoms which might be attributed to the irradiations with Ni ions.

The specimens were sectioned from the irradiated surface to a depth of ~50 nm in front of the peak damage region or the peak helium deposition region, then thinned from the backside to perforation in a 80% CH₃OH-20% H₂SO₄ solution at 5°C. The microstructure of the unirradiated and irradiated alloys were observed by transmission electron microscopy (TEM) in a Philips EM 400 electron microscope operated at 120 KV. The thickness of the specimens for TEM was typically 90 nm. The concentrations of alloy constituents in the vicinity of grain boundaries and in precipitates in the alloy were determined by use of energy dispersive x-ray spectroscopy (EDXS) and electron energy loss spectroscopy (EELS) techniques in conjunction with scanning transmission electron microscopy (STEM) imaging.

3. Experimental Results

3.1. TEM for the unirradiated alloy

The microstructure that was characteristic for the V-15Cr-5Ti alloy prior to irradiation is shown in Fig. 1. The microstructure contained precipitates with a diameter of 2-6 μm (3.5×10^9 particles intersected/ m^2) and precipitates with a diameter of 45 to 100 nm and a number density of $3.6 \times 10^{19}/\text{m}^2$. The average grain diameter in the annealed material was 40 μm . Since the irradiation-induced change in the microstructure of the alloy was rather subtle, it was necessary to observe the microstructure in the alloy after further annealing for the time of the irradiation, e.g., 2.5×10^4 s (6.9 h) for 125 dpa. The microstructure of the alloy after an anneal at 725°C for 2.5×10^4 s is shown in Fig. 2. This heat treatment resulted in the formation of precipitates with a diameter of 4-8 nm and a number density of $5 \times 10^{21}\text{m}^{-3}$.

3.2. Single-ion irradiations

The TEM observations of the microstructure in the V-15Cr-5Ti alloy specimens following irradiations at 425°C to 750°C with either 3.0-MeV $^{51}\text{V}^+$,

4.0-MeV $^{51}\text{V}^{++}$, or 4.0-MeV $^{58}\text{Ni}^{++}$ ions to damage levels of 50 to 300 dpa showed an absence of voids and the presence of a high density of disc-shape precipitates. The microstructure for the alloy following irradiation at 725°C with 4.0-MeV $^{51}\text{V}^{++}$ ions to 125 dpa contained precipitates with a diameter of 20-30 nm and a number density of $2 \times 10^{22}\text{m}^{-3}$ (Fig. 3). These thin (~2 nm), coherent precipitates had a {110} habit plane.

The microstructure for the alloy specimens after 4.0-MeV $^{58}\text{Ni}^{++}$ ion irradiation at 600, 675, 700, and 750°C to 200 dpa are shown in Fig. 4. Voids were not visible in the microstructures of these irradiated specimens. The principle effect of these irradiations on the unirradiated alloy microstructure was the formation of a high density of disc-shape precipitates in the matrix and on the dislocation structure. An increase of the irradiation temperature from 600 to 750°C resulted in an increase of the average diameter of the precipitates from ~1 nm to ~90 nm. In the case of the irradiation at 600°C, the precipitates were uniformly distributed in the matrix with a diameter (~1 nm) near to the resolution limit of the electron microscope. An increase of the irradiation temperature above 600°C resulted in the redistribution of these small diameter precipitates and growth of the precipitates. The microstructures suggested that the precipitates were sited primarily on the dislocation structure. An increase of the radiation damage level from 125 dpa to 300 dpa on irradiation at 725°C resulted in growth of the precipitates from 25-nm average diameter to 40-nm average diameter (Fig. 5).

3.3. Dual-ion irradiation

The irradiation parameters for the V-15Cr-5Ti alloy specimens that were irradiated with 3.0-MeV $^{51}\text{V}^{+}$ ions and "degraded" 0.87-MeV $^3\text{He}^{+}$ ions were (1) 30 dpa + 10 appm He/dpa at 425, 540, and 625°C, (2) 30 dpa + 50 appm He/dpa at 625 and 635°C, (3) 60 dpa + 3 appm/dpa at 625 and 640°C, and (4) 15 dpa + 10

appm He/dpa at 650 and 675°C. Dual-ion irradiation of the alloy at temperatures less than 625°C resulted in the formation of a dense dislocation network ($5 \times 10^{14} \text{m}^{-2}$) which is shown in Fig. 6a for the specimen irradiated at 540°C to 30 dpa (10 appm He/dpa). Cavities, which were voids that may have contained helium, were only observed in the microstructures of specimens that were irradiated at 640°C (Fig. 6c), 650, and 675°C (Fig. 6b). Cavities with a bi-modal size distribution were distributed uniformly in the matrix with a number density of the order of 10^{23}m^{-3} . The diameter of the cavities ranged from 2-4 nm (largest diameter at the arrow in Fig. 6b). In addition to the profuse cavity population, dual-ion irradiation using $^3\text{He}^+$ ions with "degraded" energy resulted in the formation of an aligned precipitate structure with a {110} habit plane (Fig. 6c). This aligned precipitate structure was a notable difference from the precipitate distribution in single-ion irradiated specimens where the precipitates were generally sited on the dislocation network as shown, for example, in Fig. 3. The microstructure for the V-15Cr-5Ti alloy after dual-ion irradiation at 675°C with 3.0-MeV $^{51}\text{V}^{++}$ ions and 0.25-MeV $^3\text{He}^+$ ions to 200 dpa (5 appm He/dpa) is shown in Fig. 7. This microstructure contained a high number density ($\sim 10^{23} \text{m}^{-3}$) of cavities with a diameter of ~ 5 nm. A bi-modal distribution of cavities sizes was not evident in this microstructure. The microstructure for the alloy after dual-ion irradiation at 725°C with 3.0-MeV $^{58}\text{Ni}^{++}$ ions and 0.25-MeV $^3\text{He}^+$ ions to 125 dpa (9 appm He/dpa) is shown in Fig. 8. Cavities with diameters ranging from 4 nm to 8 nm (cavities with the largest diameter at the arrow in Fig. 8) and number density of 10^{21}m^{-3} were discernible in this microstructure. In addition to this cavity population, there appeared to be a population (10^{23}m^{-3}) of cavities with a diameter of 2-4 nm. The aligned precipitate structure with {110} habit plane was also visible in this dual-ion irradiated

microstructure.

The swelling of the V-15Cr-5Ti alloy that was attributable to the presence of cavities produced during these dual-ion irradiations was negligible ($< 0.1\%$). The evolution of the microstructure in the alloy did not appear to depend on the choice of ion for production of displacement damage, i.e., Ni or V ions. Moreover, the microstructural evolution did not appear to depend on the use of helium ions with degraded energy.

3.4. Helium pre-injection and irradiation

The TEM microstructure for the alloy specimen implanted with 780 appm He (0.50-MeV $^4\text{He}^+$ ions) at ambient room temperature prior to 4.0-MeV $^{58}\text{Ni}^{++}$ ion irradiation at 725°C to 125 dpa is shown in Fig. 9. This microstructure appeared very similar to the microstructure of the alloy specimen irradiated at 725°C with 4.0-MeV $^{51}\text{V}^{++}$ ions to 125 dpa (Fig. 3). The precipitates that formed during both of these irradiations had a $\{110\}$ habit plane and were generally associated with the dislocation network. Cavities were not discernible in the matrix of this pre-implanted-helium specimen.

3.5. AES, EDXS, and EELS analyses for RIS

The RIS of the Cr, Ti, C, and S solute atoms in single-, dual-, and helium implanted plus single-ion irradiated V-15Cr-5Ti alloy specimens after irradiation at 725°C is shown in Figs. 10-13. A comparison of the solute segregation results from the AES analyses for the single- and dual-ion irradiated alloy shows that the simultaneous production of irradiation damage and deposition of helium resulted in enhanced depletion of Cr solute in the near-surface layers (0-10 nm), and enrichment of Ti (0-25 nm), C (0-70 nm), and S (0-30 nm) solute atoms. An increase of the irradiation damage level from 0 to 169 dpa resulted, in general, in an increase of the solute concentration in the near-surface layers of the specimens. In the case of

specimens that were pre-injected with helium prior to single-ion irradiation to 103 dpa, the Cr and S concentrations in the near-surface layers were increased whereas the Ti and C concentrations were decreased relative to the concentrations for the single-ion irradiated specimens. The concentration and distribution of oxygen, silicon, and nitrogen solute atoms in the near-surface layers of the irradiated specimens were not significantly altered from the concentration and distribution of these solutes in the unirradiated specimen.

EDXS analyses on the unirradiated alloy showed in some instances an exceptionally high concentration (20 a/o) of Si in the vicinity of a grain boundary. The more typical concentration of Si in the grain boundary region was 0.5-1.0 a/o. The S concentration in the grain boundary region was typically 1-2 a/o. The EDXS analyses on the unirradiated alloy showed that the Cr and Ti concentrations were exceptionally uniform.

The EELS analyses on the precipitates in the alloy specimen irradiated at 750°C with 4.0-MeV $^{58}\text{Ni}^{++}$ ions to 200 dpa (Fig. 4d) revealed that the irradiation-produced precipitates had a composition corresponding to Ti_3O . EDXS analyses on an alloy specimen irradiated at 650°C with 4.0-MeV $^{51}\text{V}^{++}$ ions to 50 dpa revealed no significant variation of the Ti concentration in the matrix microstructure, but the intrinsic precipitates in, for example, Figs. 1 and 2, contained 26 a/o Ti. EDXS analyses on the specimen irradiated at 650°C to 50 dpa showed that the grain boundaries in the microstructure were enriched to 16 a/o in Cr concentration. The EDXS analyses also showed that the Ti_3O precipitates were surrounded with a layer that was depleted to 4 a/o Cr concentration. EDXS and EELS analyses have not been conducted on the dual-ion irradiated specimens.

4. Discussion of Results

The effect on microstructural evolution in the V-15Cr-5Ti alloy of simultaneous helium implantation and production of irradiation damage during dual-ion irradiation, in comparison with irradiation damage production without helium implantation during single-ion irradiation, was to induce the formation of a high density of small diameter cavities and to alter the precipitate morphology, e.g., compare Fig. 3 with Fig. 8 and Fig. 4b with Fig. 7. Nevertheless, the swelling of the alloy due to cavities (voids) was negligible ($< 0.1\%$) for dual-ion irradiations at temperatures to 725°C and irradiation damage levels to 200 dpa and for single-ion irradiations at temperatures to 750°C and damage levels to 300 dpa.

The TEM observations of the microstructure in the dual-ion irradiated specimens suggested that a bi-modal distribution of cavity sizes existed in specimens irradiated at 675°C to 15 dpa and at 725°C to 125 dpa and implanted simultaneously with helium at the rate of 9-10 appm He/dpa. However, the bi-modal distribution of cavity sizes was not apparent in a specimen irradiated at 675°C to 200 dpa and implanted simultaneously with helium at the rate of 5 appm/dpa. These results suggest that a helium implantation rate in the range of 5 to 9 appm/dpa causes the accelerated growth of some helium-filled cavities in the alloy to give a bi-modal distribution of cavity sizes. The formation of a bi-modal distribution of cavity sizes can result in a substantial increase in swelling [3]. Since the helium production rate in the MFR environment has been calculated to be 5.2 appm/dpa, it may be anticipated that swelling of the V-15Cr-5Ti alloy in an MFR will be negligible to higher damage levels (> 200 dpa) and to possibly higher temperatures than realized in the present study.

The irradiation-produced precipitates in the V-15Cr-5Ti alloy after single-ion irradiation were sited on {110} habit planes and were generally associated with the dislocation network, whereas these precipitates were aligned on {110} habit planes in the dual-ion irradiated alloy. We have no clear understanding for the difference in the precipitate morphology that resulted from the single- or dual-ion irradiation. The EDXS and EELS analyses of the precipitates in the single-ion irradiated alloy have shown that the precipitates have a composition of Ti_3O . Loomis, et al. [7] have postulated that this particular composition for the precipitates contributes to the remarkable stability of this alloy to irradiation-induced swelling. We have not performed similar analyses on the precipitates in the dual-ion irradiated alloy. On the basis of the AES analyses, it might be conjectured that the concentrations of Ti and C in the precipitates produced during dual-ion irradiation were significantly different from the concentrations in the precipitates produced during single-ion irradiation. The different precipitate morphology for the single- and dual-ion irradiated alloy and the presence of cavities in the dual-ion irradiated alloy suggest that the mechanical properties obtained for the alloy after neutron irradiation in a fast neutron energy spectrum may not be applicable for guidance on these properties in the MFR environment because of the different levels of helium generation.

5. Conclusions

1. The swelling of the V-15Cr-5Ti alloy from the presence of cavities (voids) is negligible ($< 0.1\%$) for dual-ion irradiations at temperatures to 725°C and irradiation damage levels to 200 dpa and for single-ion irradiations at temperatures to 750°C and irradiation damage levels to 300 dpa.
2. The morphology and distribution of irradiation-produced precipitates are distinctly different for single- and dual-ion irradiated V-15Cr-5Ti alloy.

3. A helium implantation rate in the range of 5 to 9 appm He/dpa causes the accelerated growth of some helium-filled cavities in the V-15Cr-5Ti alloy to give a bi-modal distribution of cavity sizes.
4. The resistance of the V-15Cr-5Ti alloy to irradiation-induced swelling is due to the formation of Ti_3O precipitates.
5. The mechanical properties for the V-15Cr-5Ti alloy that are derived from irradiations of the alloy in a fast neutron energy spectrum may not provide reliable data on these properties in an MFR.

Table 1. Chemical analysis for the V-15Cr-5Ti alloy

Element	Concentration (a/o)
Cr	14.1
Ti	6.6
O	0.10
C	0.14
N	0.18
S	0.03
Si	0.05

References

- [1] D. L. Smith, B. A. Loomis, and D. R. Diercks, J. Nucl. Mater. 135 (1985) 125.
- [2] M. P. Tanaka, E. E. Bloom, and J. A. Horak, J. Nucl. Mater. 103 & 104 (1981) 895.
- [3] B. A. Loomis and S. B. Gerber, J. Nucl. Mater. 103 & 104 (1981) 1193.
- [4] A. T. Santhanam, A. Taylor and S. D. Harkness, Nucl. Metall. 18 (1973) 302.
- [5] B. A. Loomis and S. B. Gerber, J. Nucl. Mater. 117 (1983) 224.
- [6] J. P. Biersack and L. G. Haggmark, Nucl. Inst. and Methods 174 (1980) 257.
- [7] B. A. Loomis, B. J. Kestel, and S. B. Gerber, to be published in: Proc. Thirteenth International Symposium on Effects of Radiation on Materials, June 23-25, 1986, Seattle.

Figure Captions

- Fig. 1. TEM microstructure for V-15Cr-5Ti alloy prior to irradiation (marker = 500 nm).
- Fig. 2. TEM microstructure for V-15Cr-5Ti alloy after an anneal at 725°C for 2.5×10^4 s (marker = 500 nm).
- Fig. 3. TEM microstructure for V-15Cr-5Ti alloy after 4.0-MeV $^{51}\text{V}^{++}$ ion irradiation to 125 dpa at 725°C for the (a) bright field and (b) dark field condition (marker = 100 nm).
- Fig. 4. TEM microstructures for V-15Cr-5Ti alloy after 4.0-MeV $^{58}\text{Ni}^{++}$ ion irradiation to 200 dpa at (a) 600°C, (b) 675°C, (c) 700°C, and (d) 750°C (marker = 500 nm).
- Fig. 5. TEM microstructure for V-15Cr-5Ti alloy after 4.0-MeV $^{58}\text{Ni}^{++}$ ion irradiation to 300 dpa at 725°C for the (a) bright field and (b) dark field condition (marker = 100 nm).
- Fig. 6. TEM microstructures for V-15Cr-5Ti alloy after dual-ion irradiation with 3.0-MeV $^{51}\text{V}^{+}$ and degraded 0.87-MeV $^3\text{He}^{+}$ ions at (a) 540°C to 30 dpa (10 appm He/dpa), (b) 675°C to 15 dpa (10 appm He/dpa) and (c) 640°C to 60 dpa (3 appm He/dpa).

Fig. 7. TEM microstructure for V-15Cr-5Ti alloy after dual-ion irradiation with 3.0-MeV $^{51}\text{Ni}^{++}$ and 0.25-MeV $^3\text{He}^{++}$ ions (5.0 appm He/dpa) at 675°C to 200 dpa (marker = 250 nm).

Fig. 8. TEM microstructure for V-15Cr-5Ti alloy after dual-ion irradiation at 725°C with 3.0-MeV $^{58}\text{Ni}^{++}$ ions and 0.25-MeV $^3\text{He}^{+}$ ions to 125 dpa (9 appm He/dpa) (marker = 250 nm).

Fig. 9. TEM microstructure for V-15Cr-5Ti alloy after 0.50-MeV $^4\text{He}^{+}$ ion implantation (780 appm) and subsequent 4.0-MeV $^{58}\text{Ni}^{++}$ ion irradiation at 725°C to 125 dpa (marker = 250 nm).

Fig. 10. RIS of Cr in ion-irradiated V-15Cr-5Ti alloy.

Fig. 11. RIS of Ti in ion-irradiated V-15Cr-5Ti alloy.

Fig. 12. RIS of C in ion-irradiated V-15Cr-5Ti alloy.

Fig. 13. RIS of S in ion-irradiated V-15Cr-5Ti alloy.

Fig. 1. TEM microstructure for V-15Cr-5Ti alloy prior to irradiation (marker = 500 nm).

Fig. 2. TEM microstructure for V-15Cr-5Ti alloy after an anneal at 725°C for 2.5×10^4 s (marker = 500 nm).

Fig. 3. TEM microstructure for V-15Cr-5Ti alloy after 4.0-MeV $^{51}\text{V}^{++}$ ion irradiation to 125 dpa at 725°C for the (a) bright field and (b) dark field condition (marker = 100 nm).

(a)

(b)

(c)

(d)

Fig. 4. TEM microstructures for V-15Cr-5Ti alloy after 4.0-MeV $^{58}\text{Ni}^{++}$ ion irradiation to 200 dpa at (a) 600°C, (b) 675°C, (c) 700°C, and (d) 750°C (marker = 500 nm).

Fig. 5. TEM microstructure for V-15Cr-5Ti alloy after 4.0-MeV $^{58}\text{Ni}^{++}$ ion irradiation to 300 dpa at 725°C for the (a) bright field and (b) dark field condition (marker = 100 nm).

Fig. 6. TEM microstructures for V-15Cr-5Ti alloy after 3.0-MeV $^{51}\text{V}^+$ and degraded 0.87-MeV $^3\text{He}^+$ ion irradiation at (a) 540°C to 30 dpa (10 appm He/dpa), (b) 675°C to 15 dpa (10 appm He/dpa) and (c) 640°C to 60 dpa (3 appm He/dpa).

Fig. 7. TEM microstructure for V-15Cr-5Ti alloy after dual-ion irradiation with 3.0-MeV $^{51}\text{Ni}^{++}$ and 0.25-MeV $^3\text{He}^{++}$ ions (5.0 appm He/dpa) at 675°C to 200 dpa (marker = 250 nm).

8

Fig. 8. TEM microstructure for V-15Cr-5Ti alloy after dual-ion irradiation at 725°C with 3.0-MeV $^{58}\text{Ni}^{++}$ ions and 0.25-MeV $^3\text{He}^+$ ions to 125 dpa (9 appm He/dpa) (marker = 250 nm).

Fig. 9. TEM microstructure for V-15Cr-5Ti alloy after 0.50-MeV $^4\text{He}^+$ ion implantation (780 appm) and subsequent 4.0-MeV $^{58}\text{Ni}^{++}$ ion irradiation at 725°C to 125 dpa (marker = 250 nm).

Fig. 10. RIS of Cr in ion-irradiated V-15Cr-5Ti alloy.

Fig. 11. RIS of Ti in ion-irradiated V-15Cr-5Ti alloy.

Fig. 12. RIS of C in ion-irradiated V-15Cr-5Ti alloy.

Fig. 13. RIS of S in ion-irradiated V-15Cr-5Ti alloy.