§3. Hardening of Vanadium Doped with Nitrogen by Heavy Ion Irradiation and Post-irradiation Annealing

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Influence of the interstitial impurities, such as nitrogen, oxygen and carbon, on interaction of dislocations with defects and defect clusters should be investigated for research into the impurity effects on radiation embrittlements of low activation vanadium alloys.

Radiation anneal hardening (RAH) is an additional hardening due to post-irradiation annealing. RAH is explained by interaction between interstitial impurities and dislocation loops produced by irradiation. In the previous studies, however, nitrogen, oxygen and carbon effects have not been well separated from each other.

The purpose of this study is to investigate the effects of nitrogen on irradiation hardening and RAH by heavy ion irradiation using vanadium doped with controlled levels of nitrogen.

Table I shows the contents of interstitial impurities in the vanadium specimens used in this study. All the specimens were cold-rolled into 0.2 mm-thick sheets, then annealed at 1373 K for 3 hours in a vacuum.

Table I. Interstitial impurity content in the vanadium specimens used in the present study (wppm).

Code	N	O	C
V-EB-1	12	290	33
V-LI	91	43	93
V-LI-R	94	55	70
V-N-1	170	51	79
V-N-2	400	52	72
V-N-3	540	56	74
V-HI	540	46	270
V-HI-R	610	82	210
V-HI-N-1	770	74	210

These specimens were irradiated with 2.0 or 2.4 MeV copper (Cu^{2+}) ions at room temperature (RT) and at 573 K with Tandem accelerator of Kyushu University. The damage peak for 2.0 and 2.4 MeV Cu ions calculated by TRIM code was at 460 nm and at 530 nm from the surface, respectively. The total fluence was about 1 dpa at the damage peak. Microhardness at the damaged layer was measured by a micro-indentation test machine installed in National Institute for Fusion Science. Post-irradiation

annealing was conducted at 573 K and 873 K for 1 hour.

Irradiation hardening was not strongly influenced by either nitrogen content or irradiation temperature. The microstructures consisted of the $a/2\langle 111 \rangle$ type dislocation loops. The average of irradiation hardening at RT and at 573 K is 1.2 and 1.0 GPa, respectively. This fact agrees with TEM observations indicating that the microstructures of all irradiated specimens were similar to each other.

RAH appears with 170 wppm nitrogen and above after post-irradiation annealing at 573 K. Fig. 1 shows a comparison between RAH ($\Delta M_{573\text{ K}}$) and anneal hardening of deformed vanadium ($\Delta H_{573\text{ K}}$). $\Delta M_{573\text{ K}}$ and $\Delta H_{573\text{ K}}$ are defined as the increase in microhardness due to the post-irradiation annealing at 573 K, and as the increase in Vickers hardness due to annealing at 573 K after deformation to 90 %-cold working, respectively. RAH increases with nitrogen content in stepwise manner and similar to anneal hardening of deformed vanadium. Because the microstructures were not changed either by the impurity level or irradiation-anneal histories, RAH and the anneal hardening of deformed vanadium at 573 K should be accounted for by interaction of nitrogen with dislocation loops and dislocation network, respectively.

Fig. 1. Comparison between (a) RAH and (b) anneal hardening at 573 K after 90% cold-rolling. Oxygen contents are indicated in parentheses after the material codes.