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Microstructural Evolution of Vanadium Alloys by Heavy-ion Bombardment and Irradiation Correlation

重イオン照射によるバナジウム合金の組織発達と照射相関

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TEM observation and analysis of dislocation loops were carried out for V-4Cr-4Ti by heavy ion and neutron irradiation at ~403K to 573K, and fundamental defect migration and interaction properties were extracted. The data were compared with those obtained with electron irradiations for irradiation correlation. The loop density as a function of temperature and damage rate were similar to those obtained for V-20Ti and V-3Ti-1Si by electron irradiation. Thus the loop evolution and resulting mechanical property change are to some extent predictable based on the available models established by electron irradiations.

1. Introduction

Vanadium alloys are promising candidate low activation structural materials for fusion blankets. According to large amount of researches, V-4Cr-4Ti was selected as a leading candidate. For this material, it is known that the factor determining its low temperature operation limit is hardening and loss of elongation by irradiation.

Previous studies showed that addition of Y (and Si, Al) can improve the elongation after irradiation at temperature ranging from 573 to 673K. In the temperature range, Ti-CON precipitates are formed in initial stage of irradiation causing hardening. Thus the addition of Y, which can scavenge interstitial impurities of C, O and N, would suppress the precipitate formation retarding hardening and loss of elongation. However, at temperature lower than 573K, effects of the minor element addition is small because initial defects formed by irradiation are interstitial dislocation loops, on which the impurities are thought to have only small effects.

Thus, for the purpose of predicting radiation hardening at temperature below 573K, dislocation loop evolution kinetics needs to be investigated.

The kinetics of dislocation loop evolution have been investigated extensively for many metals and alloys by High Voltage Electron Microscopy (HVEM) including some vanadium alloys[1]. However V-4Cr-4Ti was not investigated. The objectives of this study are to investigate the dislocation loop kinetics of V-4Cr-4Ti by ion and neutron irradiations comparing with past HVEM irradiations on vanadium alloys. Efforts are being made to extract fusion relevant effects such as cascade damage effects and damage rate effects.

2. Experimental

The ion irradiations were carried out with 2.4 MeV Cu^{2+} ions at 403-413K (varied during irradiation), 473K and 573K to 1 dpa and at $4.5x10^{-3}$ dpa/s at the damage peak depth (800nm from surface) using Tandem accelerator of Kyushu University. Microstructure at the damage peak was observed by TEM following electropolishing.

Neutron irradiations were carried out at BR2 reactor at 363K and 563K to 0.2 dpa and at JMTR at 563K to 0.08 dpa. The irradiation conditions are listed in Table I. Some of the data obtained by JMTR irradiation was published elsewhere[2].

Table I. Irradiation conditions

Irradiation	Temperature	dpa	dpa/s
2.4MeV Cu^{2+} ions	403-413K	1.0	4.5×10^{-3}
	473K	1.0	4.5×10^{-3}
	573K	1.0	4.5×10^{-3}
Fission Neutrons (BR2)	363K	0.20	$1.10x10^{-7}$
	563K	0.20	$1.10x10^{-7}$
Fission Neutrons (JMTR)	563K	0.08	$4.4x10^{-8}$

3. Results

Figure 1 shows microstructure by ion irradiations. High density dislocation loops are observed. At 403-413K and 473K, very small defect clusters which are clearly visible only by Weak-Beam Dark-Field (WBDF) conditions were formed. Such very small clusters were not formed at 573K.

Figure 2 shows microstructure after neutron irradiation at BR2 at 363K and 563K. Similar to ion irradiations, high density of dislocation loops were observed. Very small defect cluster which are clearly visible only WBDF conditions were formed only at 363K.

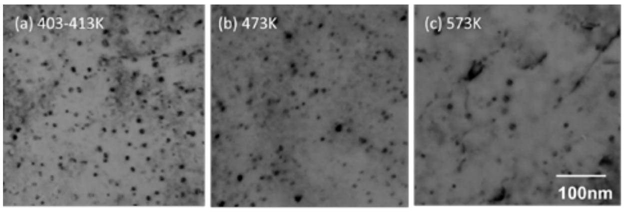

Fig. 1 Microstructure by heavy ion irradiation.

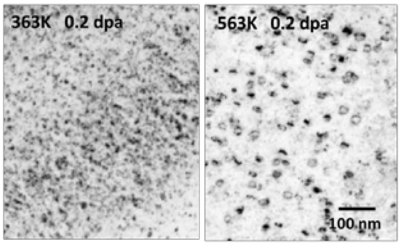

Fig. 2 Microstructure by neutron irradiation at BR2.

4. Discussion

Dislocation loop evolution was investigated with HVEM for V-20Ti and V-3Ti-1Si[1]. The saturated loop density was categorized into two regimes, namely, lower temperature regime (<473K) where both temperature and damage rate dependence of the density is very small, implying that the loops nucleated at trapping positions, and higher temperature regime (>473K) where the loop density has distinct temperature and damage rate dependence suggesting that loop nucleation took place as a result of trapping/detrapping balances.

Figures 3 and 4 shows the loop number density as a function of reciprocal temperature and damage rate for the present ion and neutron irradiations on V-4Cr-4Ti comparing with the HVEM irradiation on V-10Ti and V-3Ti-1Si. The HVEM data showed that the loop density of V-20Ti and V-3Ti-1Si are similar with each other. Fig. 3 shows that ion irradiation data are close to that of electron irradiations, showing the two temperature regimes. The densities by neutron irradiation is lower than electron and ion irradiations. This is mostly due to the effect of damage rate as can be seen in Fig.3.

Figure 4 shows that all data at 473K and below are in the range of $1x10^{22}$-$2x10^{23}/m^3$, showing small effects of damage rate. This is consistent with the model obtained by electron irradiations. At 563K and 573K, the density has a distinct temperature dependence. This is again consistent with the model. However, the density by electrons and ions and neutrons are very different, the neutron irradiation showing almost one order higher density than that predicted by electron and ion irradiations.

Similar enhanced loop density by neutron irradiations were reported for Fe-Cr-Ni austenitic model alloys[3]. The mechanism of the difference is remaining to be explored further.

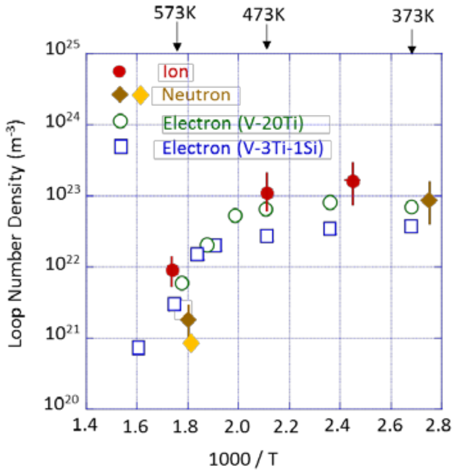

Fig. 3 Loop number density as a function of reciprocal temperature for ion and neutron irradiated V-4Cr-4Ti in comparison with electron irradiation data for V-20Ti and V-3Ti-1Si.

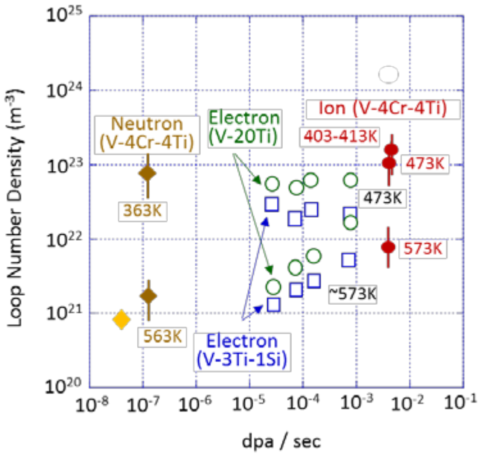

Fig. 4 Loop number density as a function of damage rate for ion and neutron irradiated V-4Cr-4Ti in comparison with electron irradiation data for V-20Ti and V-3Ti-1Si.

5. Conclusions

V-4Cr-4Ti showed similar loop formation kinetics to those for V-20Ti and V-3Ti-1Si at 360K~600K, showing nucleation by interstitial trapping at 360K~500K and nucleation by balance of trapping-detrapping at 500K~600K. The loop evolution and mechanical property change are to some extent predictable based on the available models in the relatively low temperature regime.

References

[1] T. Muroga et al., ASTM STP 1047 (1990) 199-209
[2] T. Nagasaka et al., Mat. Trans. 46 (2005) 498-502
[3] T. Muroga et al., J. Nucl. Mat. 174 (1990) 282-288