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Introduction

Vanadium alloys are considered to be one of the candidate structural materials for fusion reactor[1]. Because they have several advantages, such as high-heat loading capability, good mechanical properties at high temperatures, low swelling under irradiation at high-neutron fluence, low induced radio-activity, good compatibility with liquid lithium. In fusion reactor environment, helium generation by (n,α) reaction is considered to be about 500appmHe for vanadium after 10MWy/m^2 operation. Helium may segregate to grain boundary and weaken the boundary. It is one of the important issue to understand the helium effects on the mechanical properties of the vanadium alloy. V-Ti-Cr-Si type alloys containing Al and Y were studied as proof-oxidation and irradiation resistant materials for fusion reactor applications[2]. Various techniques have been adopted to study helium effects on mechanical properties of the alloy[3]. In this paper, the results of implantation experiment introduced relatively high amount of helium compared to displacement damage are described in order to study the resistance against helium embrittlement of the alloy in relatively severe condition.

Experimental

The chemical composition of the V-5Ti-5Cr-1Si-Al-Y alloy is given in table 1. The preparation procedure of the alloy was described earlier[4]. Tensile specimens or disks for transmission electron microscopy were punched out from 0.25mm thick sheets. These specimens were annealed at 1100°C for 3.6ks in a vacuum of 5×10^{-3}Pa to obtain a fully recrystallized and grain size of about 20μm. The tensile specimen had a gauge section of 5mm long and 1.2mm wide. The disks had a diameter of 3mm. Helium ion of 36MeV was implanted by Tohoku University cyclotron accelerator using tandem-type energy degrader wheels. To obtain uniform helium distribution along the implanted direction, the energy degrader foil had 525 equivalent thickness. Total amount of helium in the specimen was evaluated about 50 appmHe with displacement of about 0.02 dpa. The helium ion beam was scanned by 1Hz in horizontally and 10 Hz in vertically. Specimens of 8 tensile and 14 disks were fix on water-cooled holder by indium solder, therefore, the specimen temperature during implantation kept below melting point of the solder 156°C. Tensile tests were carried out at temperature ranging from room temperature to 850°C and at strain rates from 6.7×10^{-5} to 6.7×10^{-3}/s in a vacuum (less than 2×10^{-3}Pa) after implantation. Fracture mode was characterized by scanning electron microscopy. Microstructures of the specimens as-implanted condition or post-implanted annealing conditions (650 or 850°C for 3.6ks) were observed by transmission electron microscopy. Specimens of pure vanadium were also examined for comparison.

Results

Stress-strain curves

Both of helium-implanted and un-implanted conditions, serrated portion was observed in the curves of the alloy tested at 450 or at 650°C. In un-implanted pure-vanadium, serrated portion of the curve was observed in at 350 and at 450°C. After implantation, serrated portion was disappeared at 450°C. The serrated strain-stress curves were corresponding to dynamic strain aging, so impurity atom such as oxygen or nitrogen might be trapped by the defects by helium implantation.

Tensile properties

Results of yield stress, tensile strength and elongation of unimplanted and helium implanted specimens are shown in Fig. 1. Increase of yield stress is not observed in helium-implanted alloy except for 450°C testing. Increase of yield stress is observed in pure-vanadium. The level of the hardening is decrease with testing temperatures. Tensile strength of the implanted alloy is same as unimplanted alloy except for 650°C testing. The decrease of tensile strength at 650°C is corresponding to decrease of elongation. Tensile strength of unimplanted vanadium shows the maximum at 350°C, that is corresponding to dynamic strain aging. Helium implanted vanadium shows increase of strength at room temperature, decrease at 350 and 450°C. Total elongation of the helium implanted alloy decrease with temperature from 15% at room temperature to 6.2% at 650°C. At 850°C, elongation becomes to 16%. Total elongation of unimplanted vanadium is 40% at room temperature. At 350 or 450°C, elongation decreases to about 25%. Helium implanted vanadium shows decrease of elongation at room temperature. At higher temperature than 450°C, elongation is recovered.

Fractography

Fracture mode of unimplanted alloy was ductile at the testing temperature range. Helium implanted alloy tested at room temperature showed ductile mode. At higher temperature than 450°C, mixed fracture mode was observed. Intergranular fracture mode was only observed in small part. Segregation of helium atoms could decrease the grain boundary strength, so that intergranular mode was observed. In case of pure vanadium, reduction in area was large, almost 100%, even after helium implantation.

Microstructural observation

Microstructure of helium implanted alloy shows in Fig. 2. In as-implanted specimen, fine black dots are observed. After 650°C annealing, the size of the defects become large. Defects free zone was observed along grain boundaries, but no bubbles was observed. Dislocation loops of about 200nm diameter were observed in the specimen annealed at 850°C. Helium bubbles were observed both on grain boundary and in the matrix. The size of bubble on the grain boundary was larger than that in the matrix. Intergranular fracture was observed in the specimen tested at 450°C or higher. After testing at 850°C, helium bubbles were observed both in the grain boundary and in the matrix.

Dependence on strain rate of tensile properties

Yield stress at 450 or 850 °C did not varied with strain rate of the ranging from 6.7×10^{-5} to 6.7×10^{-3}/s. Tensile strength was increased with the strain rate increase. The increase was correspond to increase of uniform elongation with the strain rate. Total elongation of the specimen tested at 450°C decreased with the strain rate. It is possible that He atoms are swept to grain boundary by moving dislocations more effectively at low strain rate.

Discussion

At 450 °C, intergranular fracture mode was observed in V-5Ti-5Cr-Si-Al-Y alloy. It is possible that segregation of implanted helium caused the degradation of grain boundary strength. After 850°C annealing or deformation, helium bubbles were observed on grain boundary, however, no bubbles was observed in the specimen annealed at 650°C. These observations indicate that invisible helium atoms may affect grain boundary strength below 650 °C testing. Segregation of helium atom on grain boundary was larger at 850°C than at 650 or 450°C. Decrease of elongation was smaller at 850°C than at 650 or 450°C. Therefore, lower concentration of helium on grain boundary caused intergranular fracture at lower testing temperature. When intergranular fracture occurs, fracture stress of grain boundary must be smaller than that of matrix and at same time deformation stress must be larger than the grain boundary strength. At 850°C testing, grain boundary strength became weaken by helium atom, which could defused from matrix and swept by moving dislocation, however, deformation stress was too small to make fracture on grain boundary. On the other hand, at 450°C testing, helium concentration on grain boundary was small but deformation strength was larger than grain boundary strength, so that intergranular fracture mode was observed. The level of tensile strength of the alloy showed almost same at temperatures from 200 to 650°C. The testing temperature became higher, helium segregation on grain boundary became higher. Therefore, the specimen tested at 650°C showed the lowest elongation of them.

Summary

Effects of helium implantation of V-5Ti-5Cr-Si-Al-Y alloy were studied.

- Intergranular fracture mode was observed at 450, 650, 850°C testing after about 50appmHe implantation.
- Decrease of elongation was observed at all testing temperatures. The lowest elongation was observed in the specimen tested at 650°C.
- Helium bubbles were observed in grain boundary and matrix in the specimen tested at 850°C.
- Elongation became lower with the strain rate at ranging from 6.7×10^{-3} to 6.7×10^{-5}/s.
- Relationship between tensile strength and decrease of elongation was discussed.

References

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2) Satou M., Abe K. and Kayano H., J. Nucl. Mater. **212-215** (1994) 794.
3) Satou M., Koide H.,Hasegawa A., et al., J. Nucl. Mater. **233-237** (1996) 447.
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Table1. Chemical analysis of vanadium alloy.

V	Ti	Cr	Si	Al	Y	C	O	N
Balance	4.79	4.01	0.85	0.95	0.77	0.0126	0.014	0.0054
	(5.0)	(5.0)	(1.0)	(1.0)	(1.0)			

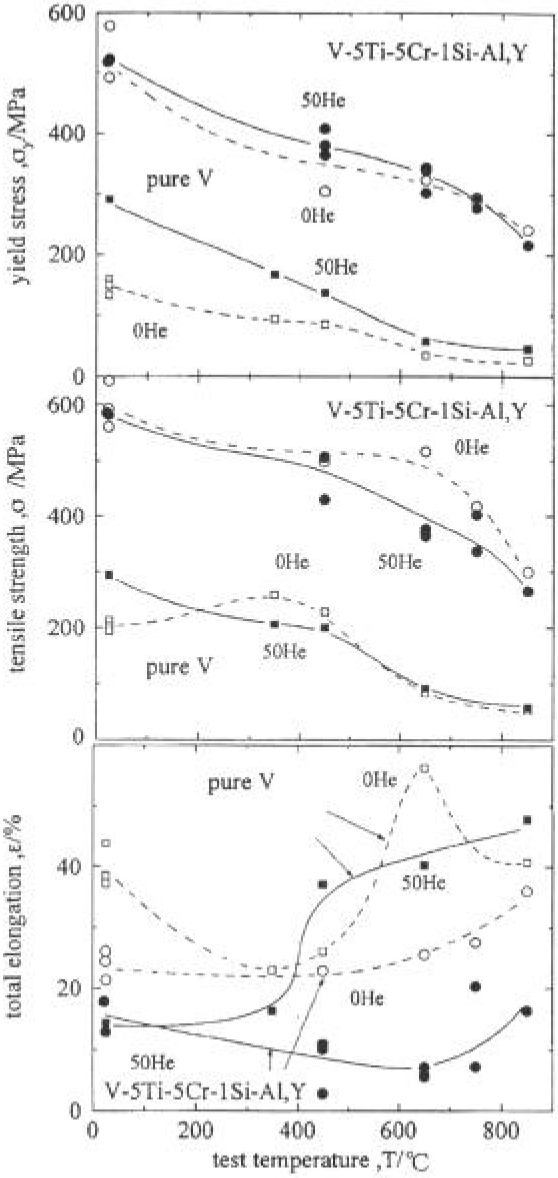

Fig. 1. Tensile properties of helium-implanted V-5Ti-5Cr-Si-Al-Y alloy and pure vanadium at temperatures from room temperature to 850°C.

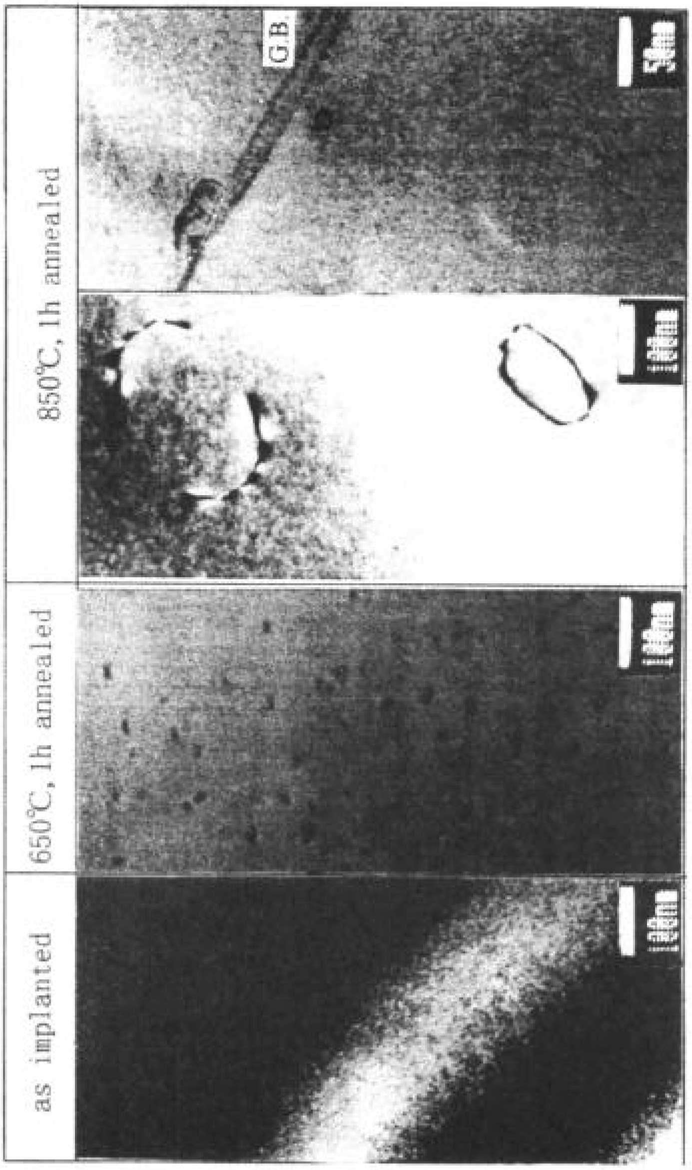

Fig. 2. Transmission electron microscopy of helium-implanted V-5Ti-5Cr-Si-Al-Y alloy as implanted and post-implanted annealing at 650 and 850°C.