DEVELOPMENT OF V-Ti-Cr-Si TYPE LOW-ACTIVATION VANADIUM ALLOYS FOR FUSION STRUCTURAL MATERIAL

M.Satou[1], K.Abe[1], A.Hasegawa[1], H.Kayano[2], T.Shibayama[3] and H.Matsui[4]
1 Department of Quantum Science and Energy Engineering, Tohoku University, Sendai 980-8579 JAPAN
2 Emeritus professor, Tohoku University, Sendai 980-8577 JAPAN
3 Center for Advanced Research of Energy Technology, Hokkaido University, Sapporo 060-8628 JAPAN
4 Institute for Materials Research, Tohoku University, Sendai 980-8577 JAPAN

Abstract

Development of V-Ti-Cr type alloy containing Si, Al and Y was described including material preparation, baseline properties, irradiation performance and coating with ceramics. The loss of elongation, which may restrict lower temperature limit of the design windows for vanadium alloy, had correlation with the concentration of interstitial impurities, especially oxygen. Therefore, purification of the alloy is one of the ways to keep the uniform elongation. Since the addition of Al and Y made the oxygen concentration in solution low, modification by the addition of Si, Al and Y is the promising way for development of vanadium alloy for fusion structural material.

1.INTRODUCTION

Vanadium alloy is considered as a fusion reactor material concerning low radioactivity, high thermal stress factor, and irradiation resistance properties. Research on V-4Cr-4Ti type alloy as a reference has been carried out. Affinity with interstitial impurity elements is strong for vanadium, so these impurities affect mechanical property and irradiation behavior. It is possible that such impurities are introduced into material by contamination under thermomechanical treatment, mass transfer from coolant materials, loss of vacuum in a reactor accident. Therefore, improvement of the oxidation resistance is one of the important issues in the alloy development. In order to use appropriately the V-4Cr-4Ti type alloy with the possibility of the oxidation, developments in following three points are needed. First is improvement in oxidation resistance of base metal. Second is prevention of oxidation by surface coating. And third is control of using atmosphere. The research and development on first two points is important from the viewpoint of material development, and third one must be considered for the reactor system. In this paper, material development of modified V-Ti-Cr type alloy is described from the first two points including effects of neutron radiation and transmutation helium.

2. MATERIAL PREPARATION

When low-activation and oxidation resistance were taken into consideration, alloying elements was limited to Ti, Cr, Al, Si, W and rare earth. Among 100 kinds of Vanadium alloys prepared by arc melting, compositions which were able to be hot-forged and hot-rolled were selected. Two of the alloys with excellent oxidation resistance and good forgeability were chosen for further investigation as candidates for the fusion structural material [1-3]. The alloy of V-5Ti-5Cr-1Si-1Al-1Y showed its superior characteristics of irradiation behavior. Modification by Si, Al and Y addition to V-Ti-Cr alloy was carried out. Seven alloys of V-Ti-Cr-Si-Al-Y type were prepared. Buttons with a couple of grams in weight were obtained by arc-melt. Table 1 shows chemical analysis of selected vanadium alloys. The sheets with thickness from 0.25mm to 3mm were obtained by hot-press followed by cold rolling. Detailed procedures were reported in ref [2,4]. An attempt production of larger heat is planed.

3. BASELINE PROPERTIES

Tensile tests were carried out using miniature size specimens, which have gauge section of 5x1.2x0.25mm. Yield stress of the V-Ti-Cr-Si-Al-Y alloys showed no significant effect depending on

TABLE 1. CHEMICAL ANALYSIS OF SELECTED VANADIUM ALLOYS
(IN WEIGHT PERCENTAGE)

Alloy	Heat#	V	Ti	Cr	Si	Al	Y	C	O	N	H
V4Ti4Cr 0.5Si0.5Al0.5Y	KAV9601	Bal.	3.99	3.96	0.46	0.49	0.20	0.0173	0.029	0.013	0.0040
V4Ti4Cr 0.3Si0.3Al0.3Y	KAV9603	Bal.	4.07	3.96	0.34	0.29	0.10	0.0142	0.034	0.013	0.0038
V4Ti4Cr 0.1Si0.1Al0.1Y	KAV9605	Bal.	4.08	3.96	0.14	0.08	0.05	0.0165	0.071	0.013	0.0038
V4Ti4Cr 0.5Si0.5Y	KAV9607	Bal.	4.10	4.00	0.46	-	0.22	0.0164	0.026	0.012	0.0034
V4Ti4Cr 0.1Si0.1Y	KAV9610	Bal.	4.09	3.92	0.14	-	0.05	0.0146	0.078	0.012	0.0029
V4Ti4Cr	KAV9611	Bal.	4.04	3.95	-	-	-	0.0224	0.115	0.012	
V5Ti5Cr 1Si1Al1Y	KAV9612	Bal.	5.12	4.92	1.04	1.03	0.72	0.0273	0.026	0.013	0.0040
V5Ti5Cr 1Si1Al1Y	KAV6	Bal.	4.79	4.01	0.85	0.95	0.77	0.0126	0.014	0.005	

concentration of alloying elements. The yield stress had a tendency to become larger slightly as the concentration of additional elements higher. Deformation mode changed into a high temperature type as the concentration of the additional elements was higher. The ultimate tensile strength decreased and total elongation increased at 900 °C[2,4]. Charpy impact properties were examined[5]. Dimension of a miniature size charpy specimen was 1.5x1.5x20mm with a 30° notch angle and a 0.3mm notch depth and a 0.08mm root radius. Ductile-Brittle Transition Temperature(DBTT) was measured to be below –50 °C for all of the V-Ti-Cr-Si-Al-Y alloys. Addition of Al was decreased its DBTT. The upper shelf energy (USE) of all alloys was kept over 0.3J/m^3. The alloy of V-4Ti-4Cr-0.3Si-0.3Al-0.3Y had the highest USE among the alloys.

4. IRRADIATION PERFORMANCE

4.1. Ductility after neutron irradiation

Recently loss of uniform elongation that might restrict lower temperature limit of design windows for vanadium alloy was reported [6]. Some V-Cr-Ti type alloys showed little uniform elongation after irradiation at temperature lower than 300 °C. Possible improvement was observed in

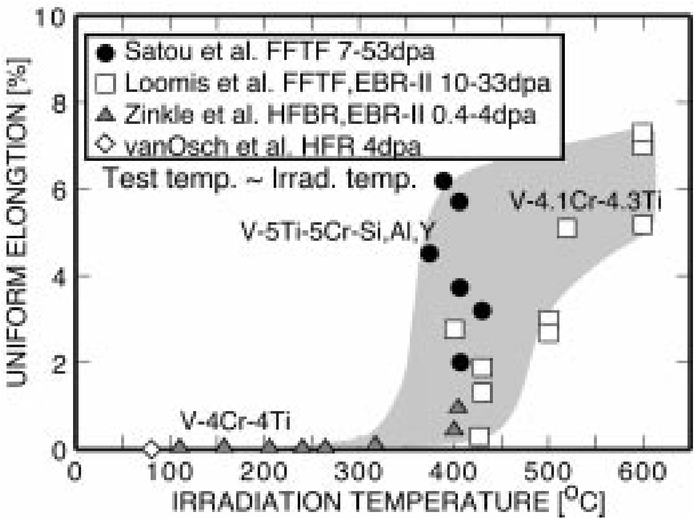

FIG. 1. Dependence on irradiation and test temperature of uniform elongation for V-4Cr-4Ti and modified V-Ti-Cr type alloy after neutron irradiation.

the Si, Al and Y modified V-Ti-Cr alloys. Fig. 1 shows irradiation and test temperature dependence of uniform elongation of some V-Ti-Cr type alloys [6-9]. The uniform elongations at the temperature above 450 ^oC are several percents for the alloys. At the temperatures lower than 350 ^oC, the V-4Cr-4Ti reference alloy shows complete loss of uniform elongation. The uniform elongation around 400 ^oC depends on alloy composition. The alloy containing Si, Al and Y shows larger elongation. The mechanism of the loss of elongation suggested by L.L.Snead et al. was that formation of small and dense complexes of irradiation defects cluster and interstitial impurities made large hardening causing loss of uniform elongation [6]. The correlation between concentration of interstitial impurities and uniform elongation of the V-Ti-Cr type alloys after neutron irradiation around 400 ^oC is shown in Fig. 2. The uniform elongation of the alloys does not depend on carbon and nitrogen concentration, but clear dependence on oxygen concentration is shown. The arrows in Fig. 2 indicate possible reduction of oxygen concentration in solution due to the formation of yttrium oxides. The yttrium oxide was identified by electron microscopy using energy dispersive spectroscopy. The oxygen concentration was reduced by formation of yttria slag during arc-melting process.

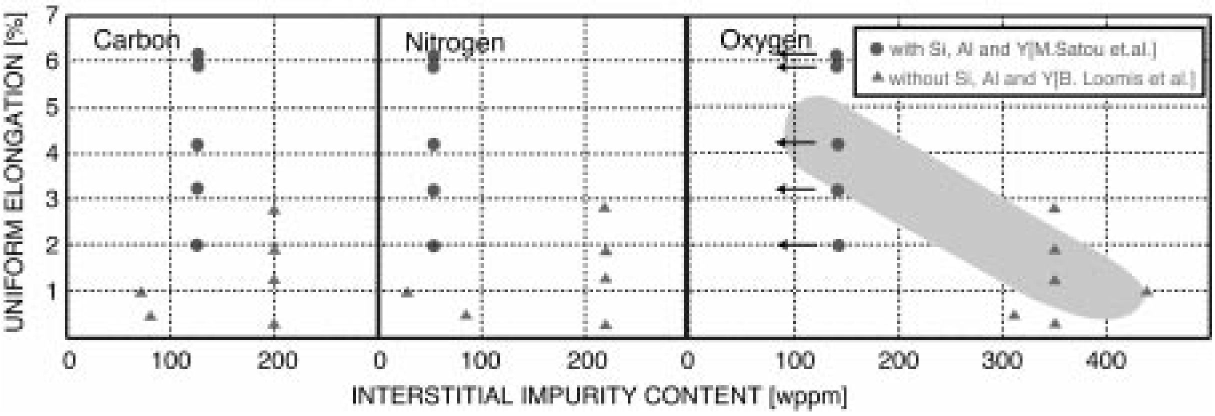

FIG. 2. Dependence of impurity content on uniform elongation of V-Ti-Cr type alloys after neutron irradiation around 400 ^oC *up to 50dpa. Arrows indicate possible reduction of oxygen concentration in solution due to the formation of yttrium oxides.*

4.2. Helium effect on tensile properties

Mechanical properties and microstructural evolution were examined by combining helium ion implantation by accelerator and methods using beta decay of tritium to helium with neutron irradiation. The neutron irradiation was carried out up to 50dpa (displacement per atom) of equivalent wall loading about 5MWy/m^2. The results showed that the helium embrittlement at elevated temperature was moderate, when the displacement damage introduced with helium generation [10,11]. Fig.3 shows summary of uniform elongation of V-4Cr-4Ti alloy and V-5Ti-5Cr-1Si-1Al-1Y alloy tested around 400 ^oC[9,10,14]. Remarkable improvement in elongation by the addition of Si, Al and Y after neutron irradiation is shown. Helium was charged to selected specimens by DHCE, which was utilizing tritium beta decay during neutron irradiation. Although helium concentration of V-5Ti-5Cr-1Si-1Al-1Y alloy much larger than that of V-4Cr-4Ti alloy, the modification seems still effective.

5. COATING AND BONDING WITH CERAMICS

From the viewpoint of prevention of oxidation, joining and coating with ceramics experiments were carried out. Selected oxide ceramics were jointed with vanadium alloys by solid-state diffusion[12] or coated by conventional RF sputtering method[13]. Integrity of the joining was examined after neutron or helium ion irradiation. The joints of V/Al_2O_3 and V/MgO after neutron irradiation were evaluated by bending test. The soundness of the interfaces between vanadium and ceramics were kept. Although bend strength of the V/Al_2O_3 joints decreased by neutron irradiation, the bend strength of the V/MgO joints did not change. Since thermal expansion rate of MgO is larger than that of vanadium, cracks caused by residual stress during irradiation formed to the direction normal to the interface. The control of residual stress is an important factor for the joints of vanadium and ceramics. The influence of adding elements on the integrity of the coating were examined by micro indentation and bending tests. Preliminary results indicated that alumina coating using RF sputtering on V-4Ti-4Cr-0.1Si-0.1Al-0.1Y alloy was harder than that on alloys without Al addition. It was indicated that adhering alumina coating on the alloy was affected by Al addition.

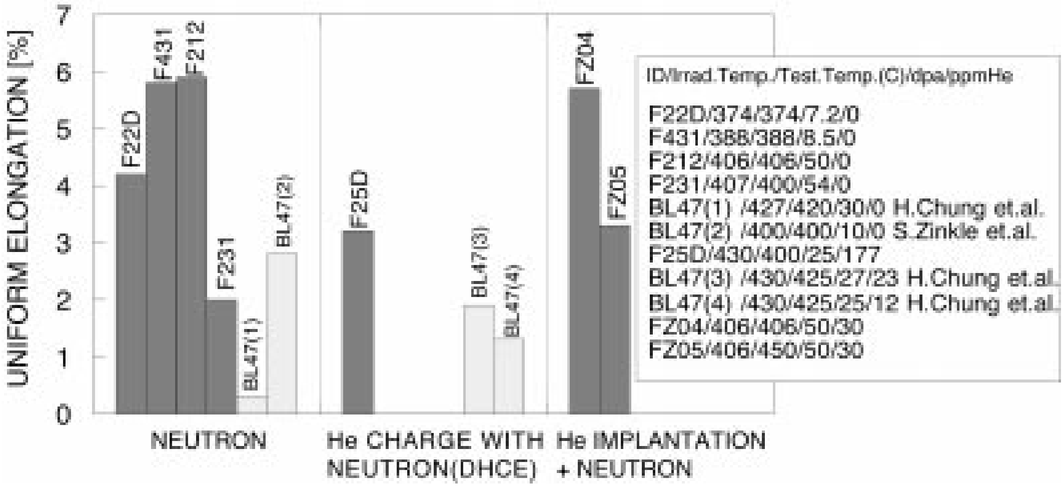

FIG. 3. Comparison of uniform elongation of V-4Cr-4Ti and modified V-Ti-Cr type alloy after neutron irradiation and He charging.

6. SUMMARY

Development of V-Ti-Cr type alloy containing Si, Al and Y was described. The loss of elongation, which may restrict lower temperature limit of the design windows for vanadium alloy, had correlation with the concentration of interstitial impurities, especially oxygen. Therefore, purification of the alloy is one of the ways to keep the uniform elongation. Since the addition of Al and Y made the oxygen concentration in solution low, modification by the addition of Si, Al and Y is the promising way for development of vanadium alloy for fusion structural material.

References

[1] KAYANO, H., “Material Development for Nuclear Fusion and Energy Development Using Actinides”, Sci. Rep. RITU **A40** (1994) 105-109.

[2] SATOU, M., et al., “High-Temperature Deformation of Modified V-Ti-Cr-Si Type Alloys”, J. Nucl. Mater., **179-181** (1991) 757 -761.

[3] SATOU, M., et al., “Tensile Properties and Microstructures of Neutron Irradiated V-Ti-Cr-Si-type Alloys”, J. Nucl. Mater., **212-215** (1994) 794 - 798.

[4] MATSUSHIMA, T., et al., “Tensile Properties of a Series of V-4Ti-4Cr Alloys Containing Small Amount of Si, Al and Y and the Influence of Helium Implantation”, J. Nucl. Mater., **258-263** (1998).

[5] SHIBAYAMA, T., et al., “Effect of small additional elements on DBTT of V-4Cr-4Ti Irradiated at Low Temperature”, J. Nucl. Mater., **258-263** (1998).

[6] SNEAD, L.L., et al., Fusion Materials, DOE/ER-0313/23 (1998) 81-98.

[7] RICE, P.M., et al., MRS Symp. Proc., **439** (1997) 343-348.

[8] VANOSCH, E.V., Proc. 2nd Workshop on Vanadium Alloy Development for Fusion, ECN-R-96-012 (1996) 417.

[9] BILLONE, M.C., Fusion Materials, DOE-ER-0313/23 (1998) 3-61.

[10] SATOU, M., et al., “Tensile Behavior of Helium Charged V-Ti-Cr-Si Type Alloys”, J. Nucl. Mater., **233-237** (1996) 447 - 451.

[11] SATOU, M., et al., “Effect of Helium Implantation on Tensile Properties of V-Ti-Cr-Si Type Alloy”, Sci. Rep. RITU **A45** (1997) 157 -161.

[12] YASUDA, R., et al., “Influence of Neutron Irradiation on Mechanical Properties of Vanadium/Ceramics Joints”, J. Nucl. Mater., **258-263** (1998) 1528-1532.

[13] SATOU, M., et al., to be published.

[14] CHUTO, T., et al., to be published.