ELECTRICAL RESISTIVITY DATA OF VANADIUM ALLOYS IN THE RB-17J EXPERIMENT — M. Li, D.T. Hoelzer and S.J. Zinkle (Oak Ridge National Laboratory)

OBJECTIVE

The objective of this report is to summarize the room temperature electrical resistivity measurements on several vanadium alloys, which will be included in the RB-17J neutron irradiation experiment.

SUMMARY

The room temperature electrical resistivity was measured for tensile specimens of vanadium alloys containing 4-15% Cr and 0.2-15% Ti, V-4Cr-0.38Zr, V-4Cr-0.57Ti-0.1C, and V-4Cr-4Ti weld material. The influence of 100ppm boron on the resistivity of unalloyed vanadium and V-4Cr-4Ti alloy with different thermal-mechanical treatment (TMT) was also examined. It was found that Ti has the strongest effect on the resistivity of vanadium alloys among solute species of Ti, Cr and Zr. Carbon significantly increases the resistivity of the alloys. The resistivity of unalloyed vanadium increases with the addition of 100ppm boron, but the influence of the same amount of boron on the resistivity of vanadium alloys is minimal. The resistivity of vanadium alloys also depends on the final annealing temperature.

PROGRESS AND STATUS

Experimental Procedure

The electrical resistivity was measured on several vanadium alloys including V-4Cr-4Ti (U.S. 832665 heat and Japanese NIFS-2 heat) and a series of model alloys (designated HR heats) of V-10Cr-4Ti, V-15Cr-4Ti, V-4Cr-0.2Ti, V-4Cr-0.5Ti, V-4Cr-10Ti, V-4Cr-15Ti, V + 100ppmB, V-4Cr-4Ti +100ppmB, V-4Cr-0.38Zr, and V-4Cr-0.57Ti-0.1C. The electrical resistivity measurements were also carried out on V-4Cr-4Ti weld (Heat GTA25). All materials received a final annealing treatment for 2 hours between 950 and 1300°C. The GTA25 V-4Cr-4Ti weld was further annealed at 400°C for 2 hours to remove the hydrogen contamination. The electrical resistivity measurements were performed on types SS-J1 and SS-J2 sheet tensile specimens. The SS-J1 specimens had nominal gauge dimensions of 0.25×1.2×5 mm and total length of 16 mm, and the SS-J2 specimens had nominal gauge dimensions of 0.5×1.2×5 mm and total length of 16 mm. Table 1 lists alloy classes, heat number and final heat treatment of the materials examined in this study, and specimen identification and specimen type.

A four-point probe technique was used for electrical resistivity measurements following the guidelines in ASTM Standard Test Method for Resistivity of Electrical Conductor Materials, ASTM B 193-87 (reapproved 1992). A constant electrical current of 100 mA was supplied by a Keithley 237 High Voltage Source Measure Unit through electrical contacts located in the grip region of the tensile specimens. The voltage drop in the gauge section was measured using a Keithley 182 Sensitive Digital Voltmeter. The distance between the spring-loaded voltage contacts was 4.42 mm. Thermal emf offset potentials were subtracted using the “relative reading” offset function of the Keithley 182 voltmeter. Multiple specimens (between 6 and 19 specimens) were measured for each material and heat treatment condition. Five electrical measurements were made on each specimen and were averaged. The specimen thickness and width were measured to an accuracy of 1 μm using a Mitutoyo digital micrometer. The resistance data were converted to resistivity values with the measured specimen dimensions. The temperature was recorded at the beginning and end of the measurement period. The temperatures were between 26 and 27°C. Further details on the alloy processing and measured chemical composition will be reported separately.

Table 1. Alloy classes, annealing condition and specimen identification and type.

Alloy	Heat	Final Anneal (ºC)	Specimen I.D. (Start)	Specimen I.D. (End)	Specimen Type
V-4Cr-4Ti	832665	1000ºC/2h	UB30	UB48	SS-J1
V-4Cr-4Ti	GTA25	1000ºC/2h + 400ºC/2h	UW00	UW05	SS-J1
V-4Cr-4Ti	HR-1	1000ºC/2h	UE00	UE11	SS-J1
V-10Cr-4Ti	HR-2	1000ºC/2h	UF00	UF11	SS-J1
V-15Cr-4Ti	HR-3	1000ºC/2h	UV00	UV14	SS-J2
V-15Cr-4Ti	HR-3	1300ºC/2h	UV15	UV29	SS-J2
V-4Cr-10Ti	HR-4	1000ºC/2h	UH00	UH11	SS-J1
V-4Cr-15Ti	HR-5	1000ºC/2h	UM00	UM11	SS-J1
V-4Cr-4Ti + 100ppmB	HR-11	950ºC/2h	UP00	UP11	SS-J1
V-4Cr-4Ti + 100ppmB	HR-11	1000ºC/2h	UP12	UP23	SS-J1
V-4Cr-4Ti + 100ppmB	HR-11	1300ºC/2h	UP24	UP35	SS-J1
V + 100 ppm B	HR-12	1000ºC/2h	UR00	UR11	SS-J1
V + 100 ppm B	HR-12	1300ºC/2h	UR12	UR23	SS-J1
V-4Cr-4Ti	NIFS-2	1000ºC/2h	UN00	UN18	SS-J2
V-4Cr-0.20Ti	HR-6	1000ºC/2h	US00	US14	SS-J2
V-4Cr-0.20Ti	HR-6	1300ºC/2h	US15	US29	SS-J2
V-4Cr-0.38Zr	HR-7	1000ºC/2h	UT00	UT14	SS-J2
V-4Cr-0.38Zr	HR-7	1300ºC/2h	UT15	UT29	SS-J2
V-4Cr-0.57Ti-0.1C	HR-8	1000ºC/2h	UG00	UG11	SS-J1
V-4Cr-0.50Ti	HR-10	1000ºC/2h	UY00	UY14	SS-J2
V-4Cr-0.50Ti	HR-10	1300ºC/2h	UY15	UY29	SS-J2

Results and Discussion

Table 2 summarizes the results of the electrical resistivity measurements on annealed vanadium alloys and the weld. The resistivity data were corrected to a reference temperature of 20°C using the V-Cr-Ti temperature coefficient for resistivity of $d\rho/dT = 0.75$ nΩ-m/K [1]. The values of electrical resistivity in table 2 are the averages for multiple specimens of each material and heat treatment condition. The standard error of the mean ranged from ±0.6 nΩ-m to ±2.4 nΩ-m for the SS-J1 tensile specimens and ranged from ±0.3 to ±0.9 nΩ-m for the SS-J2 tensile specimens. A large portion of the experimental error in the resistivity measurements was caused by the uncertainties in the gauge section thickness of tensile specimens [1]. It is noted that the standard error of the mean is generally smaller for the SS-J2 specimens than for the SS-J1 specimens. Since the thickness of the SS-J1 specimens is half the thickness of the SS-J2 specimens, the uncertainties in the specimen dimensions in the tensile gauge section of the SS-J1 specimens gave a larger error in the resistivity measurements for the SS-J1 specimens than for the SS-J2 specimens.

Figure 1 compares the electrical resistivity at 20°C for the various classes of vanadium alloys and the weld in annealed condition. The experimental results showed that the resistivity of vanadium alloys increases with increasing Ti solute content. Ti showed a strong effect on the resistivity. In contrast, a nonmonotonic effect was observed for the influence of Cr solute content on the resistivity of vanadium.

Table 2. Results of electrical resistivity measurements.

Alloy	Heat	Final Anneal (ºC)	Electrical Resistivity at 26-27°C (nΩ-m)	Corrected Electrical Resistivity at 20°C (nΩ-m)	No. of Specimens
V-4Cr-4Ti	832665	1000ºC/2h	312.3 ± 1.5	307.1	19
V-4Cr-4Ti	GTA25	1000ºC/2h	314.7 ± 1.6	310.2	6
V-4Cr-4Ti	GTA25	1000ºC/2h +400ºC/2h	307.8 ± 1.7	302.6	6
V-4Cr-4Ti	HR-1	1000ºC/2h	293.5 ± 1.7	289.0	12
V-10Cr-4Ti	HR-2	1000ºC/2h	303.7 ± 1.0	298.5	12
V-15Cr-4Ti	HR-3	1000ºC/2h	298.0 ± 0.4	292.8	15
V-15Cr-4Ti	HR-3	1300ºC/2h	304.9 ± 0.4	299.7	15
V-4Cr-10Ti	HR-4	1000ºC/2h	378.6 ± 1.8	373.4	12
V-4Cr-15Ti	HR-5	1000ºC/2h	443.3 ± 1.7	438.1	12
V-4Cr-4Ti + 100ppmB	HR-11	950ºC/2h	297.7 ± 1.7	293.2	12
V-4Cr-4Ti + 100ppmB	HR-11	1000ºC/2h	296.7 ± 1.4	292.2	12
V-4Cr-4Ti + 100ppmB	HR-11	1300ºC/2h	304.3 ± 2.1	299.8	12
V + 100 ppm B	HR-12	1000ºC/2h	239.3 ± 1.1	234.8	12
V + 100 ppm B	HR-12	1300ºC/2h	252.2 ± 2.4	247.0	12
V-4Cr-4Ti	NIFS-2	1000ºC/2h	297.0 ± 0.9	292.5	18
V-4Cr-0.20Ti	HR-6	1000ºC/2h	239.7 ± 0.6	234.5	15
V-4Cr-0.20Ti	HR-6	1300ºC/2h	243.0 ± 0.3	237.8	15
V-4Cr-0.38Zr	HR-7	1000ºC/2h	228.1 ± 0.4	222.9	15
V-4Cr-0.38Zr	HR-7	1300ºC/2h	232.9 ± 0.4	227.7	15
V-4Cr-0.57Ti-0.1C	HR-8	1000ºC/2h	251.5 ± 0.6	246.3	12
V-4Cr-0.50Ti	HR-10	1000ºC/2h	241.8 ± 0.5	236.6	15
V-4Cr-0.50Ti	HR-10	1300ºC/2h	248.2 ± 0.4	243.0	15

According to the literature [2,3], the specific resistivity (resistivity per atomic percent, nΩ-m/at%) of Ti solute atoms is $\geq$15.5 nΩ-m/at%, and the specific resistivity of Cr solute atoms is 4.0 nΩ-m/at%. Based on Matthiessen's rule, a larger contribution to the resistivity for Ti than for Cr is expected on an atomic percent basis. Zr solute atoms were observed to have a smaller influence on the resistivity compared with Ti. The weld material (GTA25) showed higher resistivity compared to the base V-4Cr-4Ti alloy, as expected. The further annealing treatment at 400ºC for 2 hours on the GTA25 V-4Cr-4Ti decreased its electrical resistivity due to the elimination of hydrogen contamination.

The addition of 100 ppm boron significantly increased the resistivity of unalloyed vanadium (the resistivity of pure vanadium is 196 nΩ-m [1]), but the influence on resistivity of the same amount of boron in V-4Cr-4Ti alloy is trivial. The addition of carbon increased the resistivity of a vanadium alloy. The resistivity of V-4Cr-0.57Ti-0.1C is 10 nΩ-m higher than the resistivity of V-4Cr-0.5Ti. The increase in resistivity due to carbon solute atoms is lower than the reported specific resistivity of 90 nΩ-m/at% [4]. It implies that the matrix concentration of free carbon interstitial solutes is low due to precipitation.

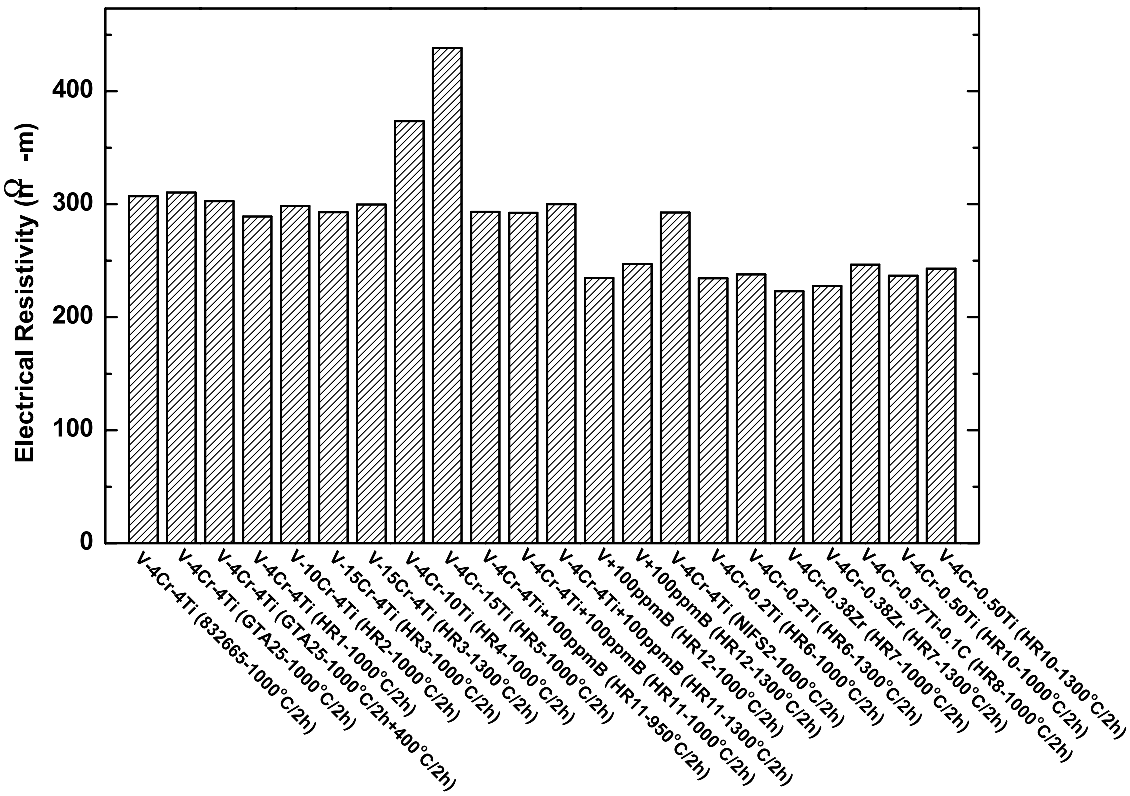

Figure 1. Comparison of the electrical resistivity of various classes of vanadium alloys.

The electrical resistivity results showed a small dependence on the final annealing temperature in the model HR6-8, and HR10-12 alloys. A slight increase of electrical resistivity was observed in all of the specimens annealed at 1300°C for 2 hours compared with the resistivity of the specimens annealed at 1000°C for 2 hours. This is likely attributed to interstitials dissolving back into the matrix during the annealing of the specimens at 1300°C. For V-4Cr-4Ti +100ppmB alloy, the resistivity of the specimens annealed at 950°C is the same as those annealed at 1000°C. The annealing temperature has a stronger effect on the resistivity of unalloyed vanadium (HR12) with 100ppmB. It is interesting to note that the measured resistivity in the V-4Cr-4Ti specimens (heat 832665) was somewhat higher than that measured on the same heat of material in a previous study [1]. The cause of this difference in electrical resistivity is uncertain.

Rererences

[1] S.J. Zinkle, A.N. Gubbi and W.S. Eatherly, Fusion Materials Semiannual Progress Report for Period Ending December 31, 1996, DOE/ER-0313/21, p.15.
[2] E.W. Collings, Phys. Rev. B9 (1970), p.3989.
[3] A. Giannuzzi, H. Tomaschke and K. Schroeder, Philos. Mag., 21(1970), p.479.
[4] J.T. Stanley, J.M. Williams, W.E. Brundage and M.S. Wechsler, Acta Metall., 20(1972), p.191.