TENSILE PROPERTIES OF VANADIUM ALLOYS IRRADIATED AT 390°C in EBR-II*

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SUMMARY

Vanadium alloys were irradiated in Li-bonded stainless steel capsules to ≈4 dpa at ≈390°C in the EBR-II X-530 experiment. This report presents results of postirradiation tests of tensile properties of two large-scale (100 and 500 kg) heats of V-4Cr-Ti and laboratory (15-30 kg) heats of boron-doped V-4Cr-4Ti, V-8Cr-6Ti, V-5Ti, and V-3Ti-1Si alloys. Tensile specimens, divided into two groups, were irradiated in two different capsules under nominally similar conditions. The 500-kg heat (#832665) and the 100-kg heat (VX-8) of V-4Cr-4Ti irradiated in one of the subcapsules exhibited complete loss of work-hardening capability, which was manifested by very low uniform plastic strain. In contrast, the 100-kg heat of V-4Cr-4Ti irradiated in another subcapsule exhibited good tensile properties (uniform plastic strain 2.8-4.0 %). A laboratory heat of V-3Ti-1Si irradiated in the latter subcapsule also exhibited good tensile properties. These results indicate that work-hardening capability at low irradiation temperatures varies significantly from heat to heat and is influenced by nominally small differences in irradiation conditions.

INTRODUCTION

Recent attention to vanadium alloys has focused on low-temperature irradiation performance of V-4Cr-4Ti, especially the phenomenon of loss of work-hardening capability. This phenomenon, usually manifested by low uniform elongation (<1%), was not observed for irradiation temperature ≥ 500°C. Under conditions of conventional neutron irradiation (i.e., negligible helium generation), complete loss of work-hardening capability has been reported for a 500-kg heat of V-4Cr-4Ti (heat #832665) irradiated to ≈0.4 dpa at 100-275°C in the High Flux Beam Reactor (HFBR)[1] and for a 30-kg heat of V-4Cr-4Ti (BL-47) irradiated to ≈10 dpa at ≈200°C in the High Flux Isotope Reactor (HFIR).[2]

In contrast, the 30-kg laboratory heat (BL-47) has been reported to retain a significant level of work-hardening capability (uniform elongation ≈3%) after irradiation to ≈10 dpa at ≈400°C in the HFIR.[3] Despite the low uniform elongation, total elongation appears to be significant, and fracture surface morphology is typically ductile dimple fracture. This report presents results of postirradiation testing of tensile properties of large-scale and laboratory heats of several vanadium alloys irradiated in Li-bonded stainless steel subcapsules to ≈4 dpa at ≈390°C in the EBR-II X530 experiment.

MATERIALS AND TESTING PROCEDURES

The elemental composition of the alloys, determined prior to irradiation, is given in Table 1. Tensile specimens with a gauge length of 7.62 mm and a gauge width of 1.52 mm (SS-3 geometry) were machined from ≈1.0-mm-thick sheets that had been produced by rolling a ≈3.8-mm-thick plate at 25 or 400°C. Specimens from the V-Cr-Ti alloys were annealed at 950-1125°C for 1 h in an ion-pumped vacuum system, whereas specimens from V-Ti and V-Ti-Si alloys were annealed at 1050°C for 1 h. Following irradiation and specimen retrieval, the specimens were cleaned ultrasonically in alcohol and tested without the customary degassing treatment at 400°C (used to expel hydrogen). Tensile properties were measured at 390°C (same irradiation temperature) in flowing argon at a strain rate of 0.001 s^{-1}.

IRRADIATION CONDITIONS

Details of the X-530 experiments, the last irradiation experiment in EBR-II before its shutdown, are described elsewhere.[4] The tensile specimens were irradiated at ≈390-394°C to ≈4 dpa in

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Table 1. Chemical composition of vanadium alloys irradiated to ≈4 dpa at ≈390°C in lithium in the EBR-II X530 experiment

Heat ID	Irradiated in Subcapsule	Nominal Compo. (wt.%)	Impurity Concentration (wt. ppm) O	N	C	Si
BL-45	S8	2.5Ti-1Si	345	125	90	9900
BL-62	S8	3.1Ti	320	86	109	660
BL-46	S8	4.6Ti	305	53	85	160
QN74[a]	S9	4.0Cr–4.1Ti-B	480	79	54	350
BL-63	S8	4.6Cr-5.1Ti	440	28	73	310
VX-8[b]	S8 and S9	3.73Cr-3.93Ti	350	70	300	500
832665[c]	S9	3.8Cr–3.9Ti	310	85	80	783

[a]Contains ≈250 appm boron–10.

[b]100-kg heat, obtained from Russian Federation, contains (in wppm) 1120 Al, 280 Fe, 500 Co, 270 Mo, 1280 Nb, 19 Zr.

[c]500–kg heat produced by Teledyne Wah Chang Albany, OR.

[d]All others are 15– to 30–kg laboratory heats.

Li-bonded Type 304 stainless steel subcapsules. They were divided into two groups and irradiated in two different subcapsules under nominally similar conditions (see Table 1).

RESULTS AND DISCUSSION

Uniform and total plastic strains of the specimens irradiated in the Subcapsule S8 (loaded in Capsule AH-2) are shown in Figs. 1A and 1B, respectively. Similar results measured on specimens irradiated in the Subcapsule S9 (loaded in Capsule AH-1) are shown in Fig. 2. According to the original plan, all heats of V-4Cr-4Ti were irradiated in the same subcapsule, i.e., S9. Specimens from other alloys were irradiated in the S8 subcapsule under nominally the same conditions. Only the specimens from the 100-kg heat of V-4Cr-4Ti (VX-8) were irradiated in both subcapsules.

A surprising observation is the contrasting work-hardening behavior of Heat VX-8 (V-4Cr-4Ti) after irradiation and retrieval from Subcapsules S8 and S9. That is, uniform plastic strain of the heat irradiated in Subcapsule S8 was as high as 2.8-4.0 %, whereas specimens irradiated in the counterpart subcapsule S9 exhibited uniform strains of only ≈0.6-0.8 %. All four specimens were double-checked and it was confirmed that specimen identity was correct.

At this time, it is difficult to understand the contrasting behavior of the VX-8 specimens under nominally similar irradiation conditions. One factor being investigated, however, is possible contamination of Li in Subcapsule S9, either during fabrication or disassembly. In contrast to the TZM subcapsules used in the past irradiation experiments at 420-600°C in the FFTF-MOTA, Type 304 stainless steel subcapsules were used in this experiment. It cannot be unequivocally ruled out at this time that impurity (such as N) transfer from stainless steel wall was more pronounced in Subcapsule S9 than in S8.

The specimens from the 500-kg heat of V-4Cr-4Ti (#832665) that were irradiated in Subcapsule S9 exhibited minimal work-hardening capability, and uniform plastic strain was <0.6% regardless of annealing conditions. Compared to the VX-8 specimens irradiated in Subcapsule S8 (uniform elongation 2.8-4.0 %), the specimens from Heat #832665 irradiated in Subcapsule S9 (uniform elongation 0.4-0.6 %) exhibited a higher degree of localized wall thinning at the fracture tip, indicating that the latter heat suffered more from loss of work-hardening capability and strain localization than did the former heat.

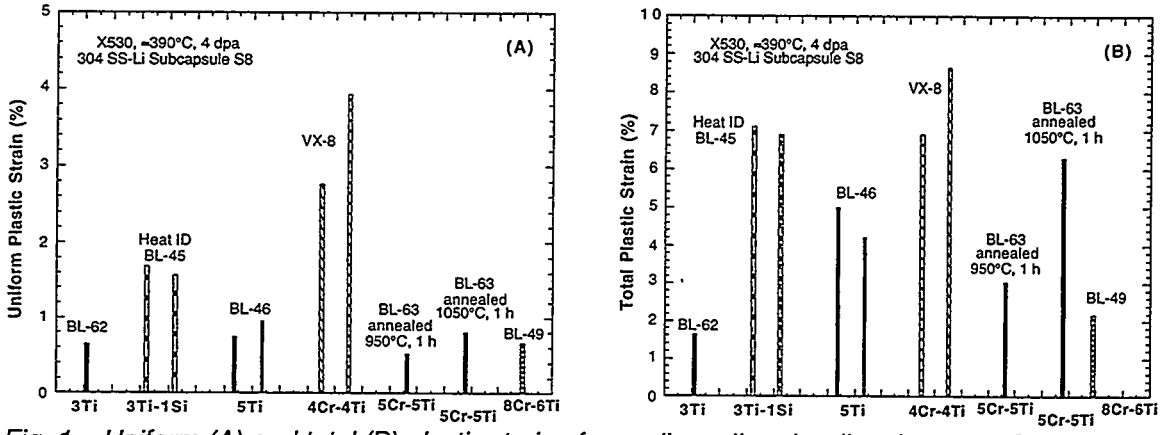

Fig. 1. Uniform (A) and total (B) plastic strain of vanadium alloys irradiated at ≈390°C to ≈4 dpa in lithium in S8 subcapsule.

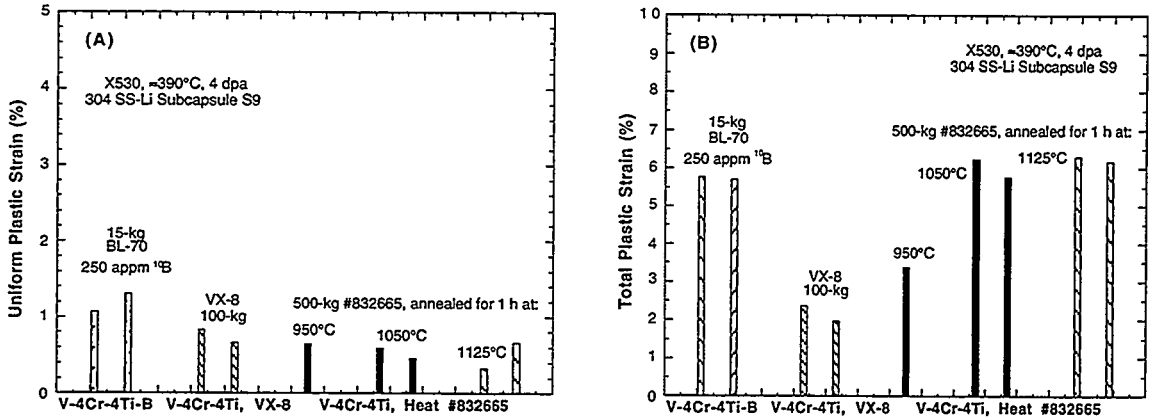

Fig. 2. Uniform (A) and total (B) plastic strain of vanadium alloys irradiated at ≈390°C to ≈4 dpa in lithium in S9 subcapsule.

However, specimens from Heat 832665 were not loaded in Subcapsule S8, nor were any tensile specimens from the 30-kg heat of V-4Cr-4Ti (BL-47), which exhibited good tensile behavior at 400°C in HFIR,[3] included in this experiment. Nevertheless, it seems that the tensile properties of V-4Cr-4Ti during conventional neutron irradiation near 400°C vary strongly from heat to heat, and possibly, due to subtle differences in irradiation conditions. This behavior was, however, not observed at irradiation temperatures ≥ 500°C.

Figure 3 shows yield and ultimate tensile strengths of BL-45 (V-3Ti-1Si) and VX-8 (V-4Cr-4Ti) irradiated in Subcapsule S8, the two heats that exhibited good tensile properties in this experiment.

CONCLUSIONS

1. Vanadium alloys were irradiated in two Li-bonded Type 304 stainless steel subcapsules to ≈4 dpa at ≈390°C in the X530 experiment in EBR-II. A 500-kg heat (Heat ID 832665) and a 100-kg heat (Heat ID VX-8) of V-4Cr-4Ti irradiated in one of the subcapsules suffered from complete loss of work-hardening capability, which was manifested by very low uniform plastic strains.

2. In contrast, the 100-kg heat (Heat VX-8) irradiated in another subcapsule exhibited good tensile properties (uniform plastic strain 2.8-4.0 %), although the irradiation conditions were

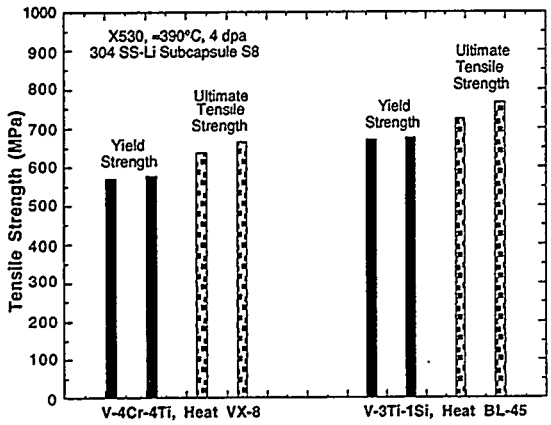

Fig. 3.
Yield and ultimate tensile strength of Heat BL-45, V-3Ti-1Si and Heat VX-8, V-4Cr-4Ti irradiated in S8 subcapsule.

nominally the same. The contrasting work-hardening behavior of this heat in the two subcapsules is not understood.

3. Susceptibility of V-4Cr-4Ti to low-temperature (<430°C) loss of work-hardening capability varies strongly from heat to heat. This phenomenon, not observed at irradiation temperatures ≥ 500°C, is probably associated with synergistic interaction between minor nonmetallic impurities and displacement damages produced at low irradiation temperatures.

4. A 15-kg heat of V-3Ti-1Si (Heat ID BL-45) irradiated in one subcapsule exhibited relatively good tensile properties (uniform plastic strain 1.6-1.7 %). Heat-to-heat sensitivity of the alloy to susceptibility to low-temperature loss of work-hardening capability, similar to that observed for V-4Cr-4Ti, is not known yet.

5. Elimination of the culprit nonmetallic impurity or impurities, or doping of an alloy (e.g., V-4Cr-4Ti and V-3Ti-1Si) with certain metallic elements, is believed to be effective in suppressing susceptibility to low-temperature loss of work-hardening capability.

FUTURE WORK

Chemical analysis and microstructural characterization will be conducted, with a focus on specimens from V-3Ti-1Si (Heat BL-45) and V-4Cr-4Ti (Heats VX-8 and #832665) to provide an understanding of the contrasting work-hardening behavior of these heats.

REFERENCES

1. D. J. Alexander, L. L. Snead, S. J. Zinkle, A. N. Gubbi, A. F. Rowcliffe, and E. E. Bloom, "Effects of Irradiation at Low Temperature on V-4Cr-4Ti," in Fusion Reactor Materials, Semiannual Prog. Rep. DOE/ER-0313/20, Oak Ridge National Laboratory, Oak Ridge, TN (1996), pp. 87-95.

2. H. M. Chung, L. Nowicki, and D. L. Smith, "Tensile Properties of Vanadium Alloys Irradiated at 200°C in the HFIR," in this report.

3. H. M. Chung, L. Nowicki, and D. L. Smith, "Tensile Properties of Vanadium Alloys Irradiated at 400°C in the HFIR," in Fusion Reactor Materials, Semiannual Prog. Rep. DOE/ER-0313/20, Oak Ridge National Laboratory, Oak Ridge, TN (1996), pp. 84-86.

4. H.-C. Tsai, R. V. Strain, A. G. Hins, H. M. Chung, L. Nowicki, and D. L. Smith, "Vanadium Alloy Irradiation Experiment X530 in EBR-II," in Fusion Reactor Materials, Semiannual Prog. Rep. DOE/ER-0313/17, Oak Ridge National Laboratory, Oak Ridge, TN (1994), pp. 8-14.