TENSILE PROPERTIES OF VANADIUM ALLOYS IRRADIATED AT <430°C*

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SUMMARY

Recent attention to vanadium alloys has focused on significant susceptibility to loss of work-hardening capability in irradiation experiments at <430°C. An evaluation of this phenomenon was conducted on V-Ti, V-Cr-Ti, and V-Ti-Si alloys irradiated in several conventional and helium-charging irradiation experiments in the FFTF-MOTA, HFIR, and EBR-II. Work-hardening capability and uniform tensile elongation appear to vary strongly from alloy to alloy and heat to heat. A strong heat-to-heat variation has been observed in V-4Cr-4Ti alloys tested, i.e., a 500-kg heat (#832665), a 100-kg heat (VX-8), and a 30-kg heat (BL-47). The significant differences in susceptibility to loss of work-hardening capability from one heat to another are estimated to correspond to a difference of ≈100°C or more in minimum allowable operating temperature (e.g., 450 versus 350°C).

INTRODUCTION

Recent attention to vanadium alloys has focused on low-temperature irradiation performance of V-4Cr-4Ti, especially tensile and fracture behavior after irradiation at <450°C. From several irradiation experiments at 80-430°C, it has been reported that some heats of V-4Cr-4Ti exhibited low uniform elongation as a result of complete loss of work-hardening capability.[1-4] Significant susceptibility to loss of work-hardening capability (LWHC) has been not observed at irradiation temperatures ≥500°C, however. Initial assessment indicates that the LWHC phenomenon in V-4Cr-4Ti is strongly dependent not only on heat but also on irradiation variables at <430°C.[2-4] This is important in understanding the phenomenon because susceptibility to LWHC at low temperatures under fusion-relevant conditions is considered to be a major factor in governing the minimum operating temperature of a fusion reactor. Therefore, a systematic evaluation of the phenomenon was conducted on a wider variety of alloys. This report presents results of an analysis of work-hardening behavior and uniform elongation of V-Ti, V-Cr-Ti, and V-Ti-Si alloys irradiated at <430°C in several conventional and helium-charging irradiation experiments in FFTF-MOTA, HFIR, and EBR-II.

MATERIALS AND TESTING PROCEDURES

The elemental composition of the alloys analyzed in this study, 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 1000-1050°C for 1 h. Following irradiation, retrieved 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 the irradiation temperature in flowing argon at a strain rate of 0.0011 s^{-1}.

IRRADIATION CONDITIONS

Details of the conventional and helium-charging irradiation experiments at <430°C in the FFTF-MOTA, HFIR, and EBR-II are summarized in Table 2. In the latter type of experiment (i.e., the Dynamic Helium Charging Experiment, or DHCE), helium atoms were produced during irradiation in the range of 14-76 appm He,[4] whereas in the former type of experiments (referred to as "non-DHCE") helium generation was negligible except for the boron-doped heat QN74 (irradiated in the X530 experiment in EBR-II).

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Table 1. Chemical composition of vanadium alloys

Heat ID	Nominal Comp. (wt.%)	Impurity Concentration (wt. ppm) O	N	C	Si
BL-50	1.0Ti	230	130	235	1050
BL-62	3.1Ti	320	86	109	660
BL-52	3.1Ti	210	310	300	500
BL-46	4.6Ti	305	53	85	160
BL-12	9.8Ti	1670	390	450	245
BL-15	17.7Ti	830	160	380	480
BL-10	7.2Cr-14.5Ti	1110	250	400	400
BL-24	13.5Cr–5.2Ti	1190	360	500	390
BL-40	10.9Cr-5.0Ti	470	80	90	270
BL-41	14.5Cr-5.0Ti	450	120	93	390
BL-43	9.2Cr-4.9Ti	230	31	100	340
BL-49	7.9Cr-5.7Ti	400	150	127	360
BL-63[a]	4.6Cr-5.1Ti	440	28	73	310
BL-27	3.1Ti–0.25Si	210	310	310	2500
BL-45	2.5Ti-1Si	345	125	90	9900
QN74[b]	4.0Cr–4.1Ti	480	79	54	350
BL-47	4.1Cr-4.3Ti	350	220	200	870
VX-8[c]	3.73Cr–3.93Ti	350	70	300	500
832665[d]	3.8Cr–3.9Ti	310	85	80	783

[a]80-kg heat fabricated with sponge Ti.
[b]Contains ≈250 appm boron–10.
[c]100-kg heat, obtained from Russian Federation, contains (in wppm) 1120 Al, 280 Fe, 500 Co, 270 Mo, 1280 Nb, 19 Zr.
[d]500–kg heat produced in Teledyne Wah Chang Albany, OR.
[e]All others 15– to 30–kg laboratory heats.

Table 2. Summary of irradiation experiments

Experiment ID	Subcapsule	Environment	Temperature (°C)	dpa	He/dpa Ratio
HFIR	200J	He	200	10	-
	400J	He	400	10	-
COBRA-1A2	V499	Li	395	36	-
	V495	Li	379	31	-
EBR-II X530	S8	Li	394	4	-
	S9	Li	390	4	-
FFTF-nonDHCE	many	Li	427-600	14-46	-
FFTF-DHCE	many	Li	430-600	14-27	0.4-4.2

The 30-kg heat BL-47 showed uniform elongation of 1-3% in the temperature range of 380-430°C. This heat appears to exhibit uniform elongation higher than that of #832665, but not as good as that of VX-8, although data that will allow a direct comparison are not available. Understanding the cause of the large heat-to-heat variation of work-hardening capability at <430°C is therefore of major importance. Based on the observation that work-hardening behavior is sensitive to not only heat but also subtle irradiation variations, it is likely that one or more minor impurities are involved. One heat of V-3Ti-1Si (Heat BL-45) exhibited excellent resistance to loss of work-hardening behavior when irradiated at 390-430°C. This heat, like BL-47 of V-4Cr-4Ti, retained a very low ductile-brittle transition temperature (DBTT<-190°C) after conventional irradiation at 420-600°C to 14-33 dpa.

RESULTS AND DISCUSSION

Uniform plastic strains of the alloy specimens irradiated at <430°C are summarized in Table 3. Similar results measured on specimens irradiated at 500-600 were also obtained and compared with those from the low-temperature irradiation. Uniform elongations of four heats of V-4Cr-4Ti and one heat of V-3Ti-1Si determined from the irradiation experiments at 200-430°C are plotted in Fig. 1. For a similar temperature range of 380-425°C, the effect of dpa level appears to be secondary.

It seems from Fig. 1 that work-hardening capability, and hence uniform elongation, of V-4Cr-4Ti class alloys varies strongly from heat to heat and is also influenced significantly by irradiation variations. The 500-kg heat #832665 exhibited the lowest work-hardening capability after irradiation in the X-530 experiment in EBR-II, whereas Heat VX-8 (irradiated in one of the subcapsules) showed excellent work-hardening capability.

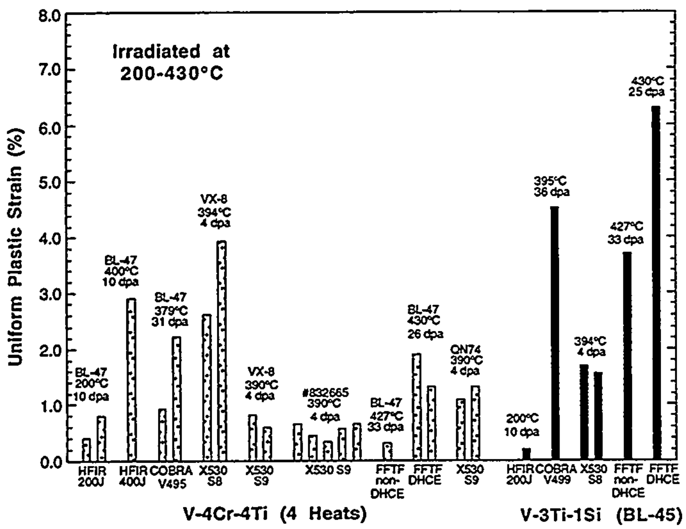

Fig. 1.
Uniform plastic strain of four heats of V-4Cr-4Ti and one heat of V-3Ti-1Si irradiated at 200-430°C to 4-46 dpa in several experiments.

Uniform elongation of all V-Ti, V-Cr-Ti, and V-Ti-Si alloys examined in this study has been plotted in Fig. 2 as a function of irradiation/test temperature. Significant scattering is obvious in this type of plot, probably reflecting the effects of many other factors such as dpa and helium levels and heat-to-heat and alloy-to-alloy variations. However, the plot also serves as an estimate of the approximate threshold temperature above which uniform elongation of these alloys is higher than a threshold level, e.g., 2%. The threshold temperature is considered to be an important consideration in governing the minimum operating temperature of a fusion reactor.

A similar plot for V-Cr-Ti alloys (see Table 3) is shown in Fig. 3. It appears that the threshold temperature to meet a minimum uniform elongation of 2% ($T_{2\%}$) could be anywhere between

Table 3. Uniform plastic strain of vanadium-base alloys irradiated at <430C

	Nominal	Irradiation Experiment							
	Composition	HFIR-200J	HFIR-400J	COBRA-1A2/V499	COBRA-1A2/V495	EBRII-X530-S8	EBRII-X530-S9	FFTF-nonDHCE	FFTF-DHCE
Heat ID	(wt.%)	200°C, 10 dpa	400°C, 10 dpa	395°C, 36 dpa	379°C, 31 dpa	394, 4 dpa	390, 4 dpa	427°C, dpa in (46)	430°C, dpa in (25)
BL-50	1.0Ti	0.56							
BL-62	3.1TI	.				0.65			
BL-46	4.6Ti	0.66		1.44		0.75, 0.95			1.8, 5.1, 1.4, 1.4 (14-27)
BL-12	9.8Ti	0.79							
BL-15	17.7Ti	2.42						3.7 (46)	
BL-10	7.2Cr-14.5Ti							2.8, 3.0 (46)	
BL-24	13.5Cr-5.2Ti							2.8, 5.0, 3.54, 1.8 (46)	
BL-40	10.9Cr-5.0Ti			1.44					
BL-41	14.5Cr-5.0Ti		0.99						
BL-43	9.2Cr-4.9Ti	0.66	1.18					1.2 (44)	1.0 (25)
BL-49	7.9Cr-5.7Ti	0.52	1.18	1.64		0.65		1.31 (33)	1.8, 1.0 (14-25)
BL-63[a]	4.6Cr-5.1Ti					0.80, 0.52			
BL-27	3.1Ti-0.25Si							1.8, 1.5 (38-46)	
BL-45	2.5Ti-1Si	0.2		4.53		1.68, 1.56		3.7 (33)	6.3 (25)
QN74[b]	4.0Cr-4.1Ti-B						1.07, 1.31		
BL-47	4.1Cr-4.3Ti	0.4, 0.79	2.91		0.92, 2.23 (CW)[c]			0.3 (33)	1.9, 1.3 (25-27)
VX-8[d]	3.7Cr-3.9Ti					2.62, 3.93	0.82, 0.59		
832665[e]	3.8Cr-3.9Ti						0.65, 0.45, 0.34, 0.57, 0.65		

[a]80–kg heat
[b]Contains ≈250 appm boron–10
[c]Coldworked material
[d]100–kg heat obtained from RF
[e]500–kg production–scale heat; all others, 15– to 30–kg laboratory heats unless otherwise noted

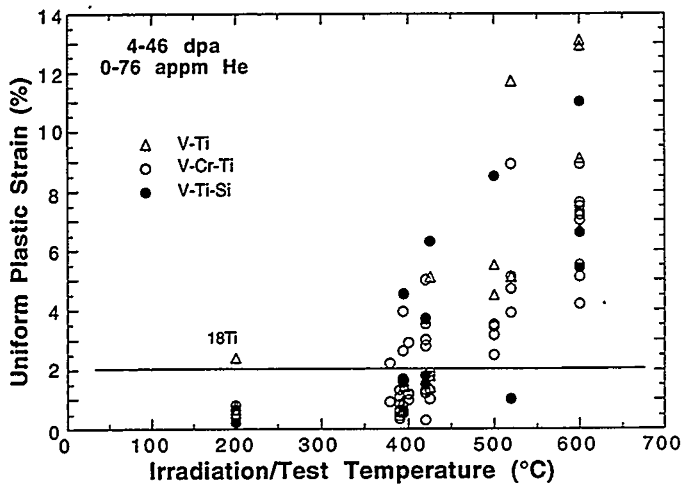

Fig. 2.
Uniform plastic strain of V-Ti, V-Cr-Ti, and V-Ti-Si alloys as function of irradiation temperature (same as test temperature).

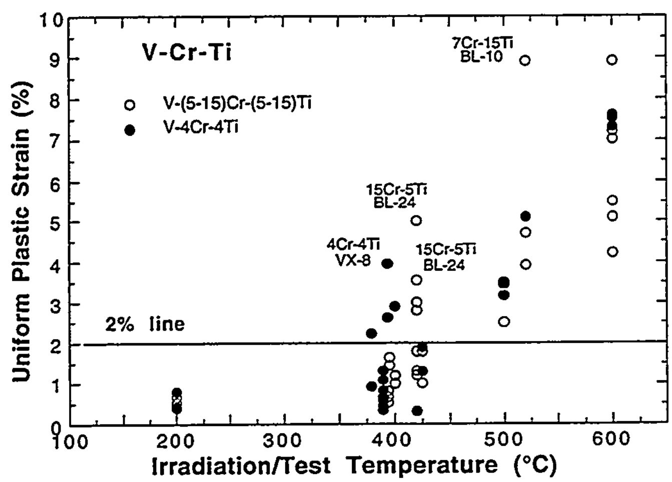

Fig. 3.
Uniform plastic strain of V-Cr-Ti alloys as function of irradiation temperature (same as test temperature).

≈320 and ≈470°C, depending on alloy type, heat, and basis of extrapolation. Interestingly, one heat of V-15Cr-5Ti (BL-24) showed high uniform elongation after irradiation at ≈420°C in the FFTF-MOTA. Similar data limited to V-4Cr-4Ti are shown in Fig. 4. A possible advantage with a resistant heat such as VX-8 is indicated in this figure.

Results in Fig. 5 show that one heat of V-3Ti-1Si (BL-45) exhibits good work-hardening capability at <430°C, whereas one heat of V-3Ti-0.25Si (BL-27) does not. From these data alone, one cannot predict if the heat-to-heat sensitivity of the V-3Ti-1Si class alloys to low-temperature work-hardening capability is inherently less than or similar to that of the V-4Cr-4Ti class.

CONCLUSIONS

1. Work-hardening capability and uniform tensile elongation of V-Ti, V-Cr-Ti, V-Ti-Si alloys during irradiation at 380-430°C appear to vary strongly from alloy to alloy and heat to heat. A strong heat-to-heat variation has been observed in three heats of V-4Cr-4Ti tested, a 500-kg heat (#832665), a 100-kg heat (VX-8), and a 30-kg heat (BL-47).

2. Work-hardening capability of V-4Cr-4Ti alloys appears also to be influenced significantly by variations in irradiation conditions. Based on the observation that work-hardening behavior is sensitive to not only heat but also subtle irradiation variations, it is likely that one or more minor impurities are involved in the process.

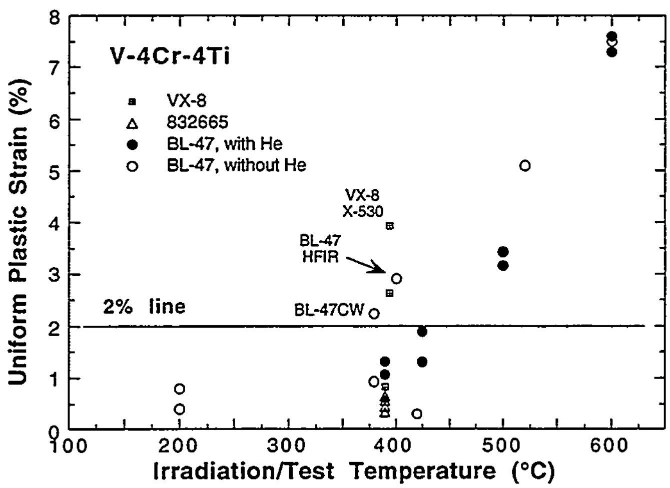

Fig. 4.
Uniform plastic strain of three heats of V-4Cr-4Ti as function of irradiation temperature (same as test temperature).

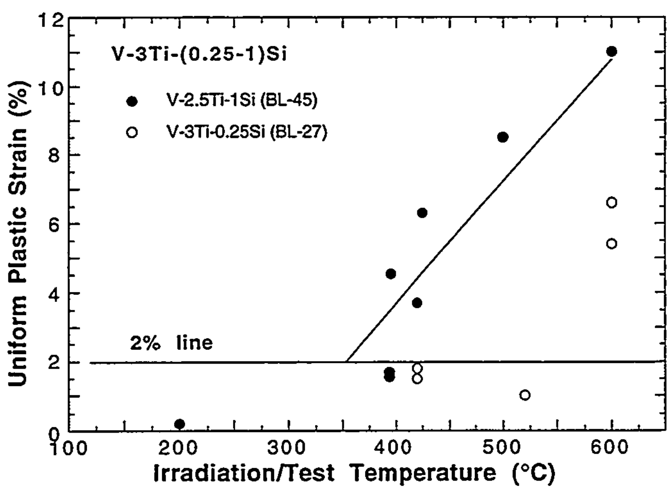

Fig. 5.
Uniform plastic strain of V-Ti-Si alloys as function of irradiation temperature (same as test temperature).

3. Significant differences in susceptibility to loss of work-hardening capability from one heat to another are estimated to correspond to a difference of ≈100°C or more in minimum allowable operating temperature (e.g., 450 vs. 350°C).

REFERENCES

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