FRACTOGRAPHY RESULTS FOR V-ALLOY TENSILE SPECIMENS IRRADIATED IN THE BOR-60, ATR, AND FFTF REACTORS. T. S. Bray, H. Tsai, R. V. Strain, M. C. Billone, and D. L. Smith (Argonne National Laboratory)

Summary

Fractography studies were conducted on numerous V-alloy tensile specimens. These specimens had been irradiated in the ATR, FFTF, and BOR-60 reactors at temperatures ranging from 273 to 600°C and damage doses from 41 to 51 dpa. The results of the fractography studies show the medium dose (17 to 19 dpa), low irradiation temperature materials irradiated in BOR-60 to have mostly ductile fractures but with low areal reduction. The low dose (~4 dpa) ATR samples display a wide range of areal reductions with mostly ductile fractures. The fractography results for the FFTF samples with irradiation temperatures from 520°C to 600°C and damage doses from 41 to 51 dpa show a wide range of reductions in area and all ductile fractures. Side-view observations revealed evidence of slip bands that are typically associated with dislocation channeling.

Objective

The objective of the task was to determine the failure mode and measure the reduction in area for tensile specimens irradiated in ATR, FFTF, and BOR-60.

Background

The tensile properties of these specimens were measured and results were reported [1-4]. The compositions of the materials are presented in Table 1. The summary of the tensile results are presented in Table 2. The results of the tensile testing for the BOR-60 irradiated specimens corroborate previous findings [3-8]; a significant loss of work hardening capability in the materials exists. Fractographic examinations of samples tested at room temperature (irradiation temperatures from 318 to 323°C) show a mixture of ductile tear and brittle cleavage. Consistent with the poor elongations, the reduction in area values were low (3-4%) [2].

Table 1. Nominal composition of the alloys investigated

Heat	Nom. Composition (wt.%)	Impurity content (wppm)			
		O	N	C	Si
832665	V-3.8Cr-3.9Ti	310	85	80	780
T87	V-5.0Cr-5.0Ti	380	90	110	550
VX8[a]	V-3.7Cr-3.9Ti	350	70	300	500
BL-42[b]	V-3.1Ti-0.5Si	580	190	140	n/a
BL-47	V-4.1Cr-4.3Ti	350	220	200	870

[a] From Russia. Contains (in wppm) 1120 Al, 280 Fe, 500 Co, 270 Mo, 1280 Nb, and 19 Zr.
[b] Contains 0.02 wt% Fe.

Table 2. Tensile data summary for specimens subject to fractography studies in this report [1,2,7,8].

Reactor Exp.	Specimen ID No.	Material/Heat	Irrad. Temp. (°C)	Tensile Test Temp. (°C)	dpa	0.2% YS (MPa)	UTS (MPa)	UE (%)	TE (%)
BOR-60 Fusion-1	71-2	V-4Cr-4Ti/832665	318	23	17	1115	1120	0.3	0.4
	71-2H-1	V-4Cr-4Ti/832665	318	318	17	892	926	0.4	2.2
	71-2H-2	V-4Cr-4Ti/832665	318	23	17	1100	1115	0.3	0.5
	71-A	V-4Cr-4Ti/832665	318	318	17	953	962	0.4	1.3
	71-B	V-4Cr-4Ti/832665	318	23	17	1120	1125	0.5	0.8
	69-1	V-4Cr-4Ti/VX8	323	323	19	909	936	0.5	2.3
	69-2	V-4Cr-4Ti/VX8	323	23	19	1135	1170	1.4	2.8
	72-1	V-5Cr-5Ti/T87	323	323	19	953	955	0.1	1.8
	72-2	V-5Cr-5Ti/T87	323	23	19	1145	1150	0.4	0.4
	71-LZ-1	832665/Laser	320	320	18	a	782	0.0	0.0
ATR ATR-A1	71-F	V-4Cr-4Ti/832665	273/280	290	4.3	945	983	0.7	2.1
	47-E	V-4Cr-4Ti/BL-47	288/302	290	4.6	844	866	0.5	4.9
	72-D	V-5Cr-5Ti/T87	284/300	290	4.1	880	941	1.1	4.1
	71-LZ-B	832665/Laser	288/302	290	4.6	a	607	0.0	0.0
FFTF MOTA 11	143	V-3.1Ti-0.5Si/BL42	520	520	41	525	624	4.2	8.1
	144	V-3.1Ti-0.5Si/BL42	520	520	46	453	559	7.7	16.4
	146	V-3.1Ti-0.5Si/BL42	600	600	47	373	541	11.0	15.9
	147	V-3.1Ti-0.5Si/BL42	600	600	51	368	566	10.4	14.4
	148	V-3.1Ti-0.5Si/BL42	600	600	51	380	539	11.7	17.2
	149	V-3.1Ti-0.5Si/BL42	600	22	51	424	615	11.7	15.0

[a] No measurable plastic deformation; offset yield strength could not be determined.

Results

Fractographic examinations were conducted with a scanning electron microscope (SEM). The objective of the examination was to determine the mode of fracture and the reduction of gauge cross-sectional area. All fractures except for 71-LZ-1 and 71-LZ-B (laser weld samples) were ductile fractures as shown in Figures 1 and 2. Sample 71-LZ-1, irradiated in BOR-60 at 320°C to a damage dose of 18 dpa, shows brittle cleavage except for a small corner that displays ductile tear (Figures 3 and 4). This ductile tear corner could be the result of the fracture not following the plane of the weld. Sample 71-LZ-B, irradiated in the ATR-A1 experiment at 288/302°C to a damage dose of 4.6 dpa, shows brittle cleavage.

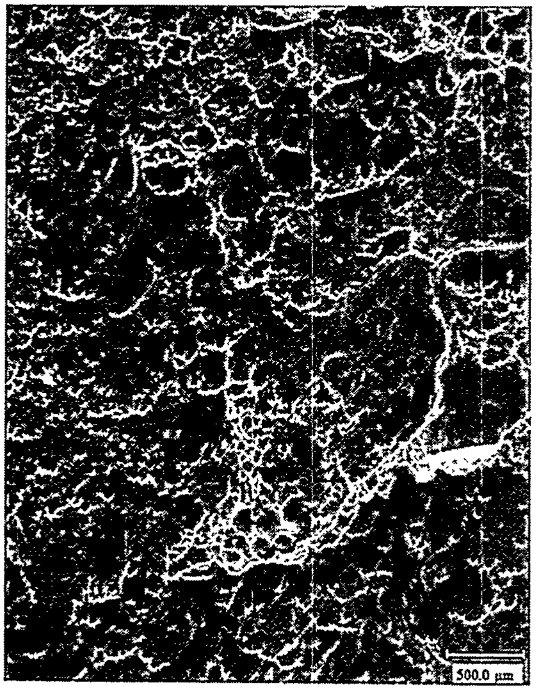

Figure 1: Sample 146 ductile fracture (ET 325643).

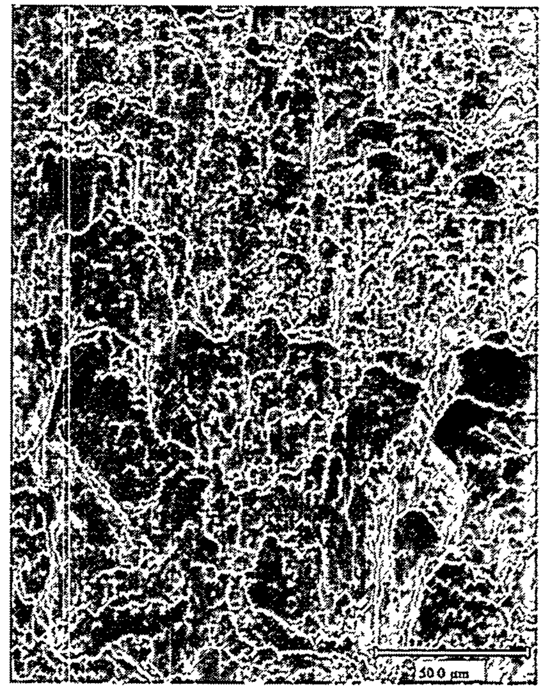

Figure 2: Sample 72-1 ductile fracture (ET 325623).

Figure 3: Sample 71-LZ-1 brittle fracture (ET 325627).

Figure 4: Sample 71-LZ-1 corner showing both ductile and brittle fracture (ET 325630).

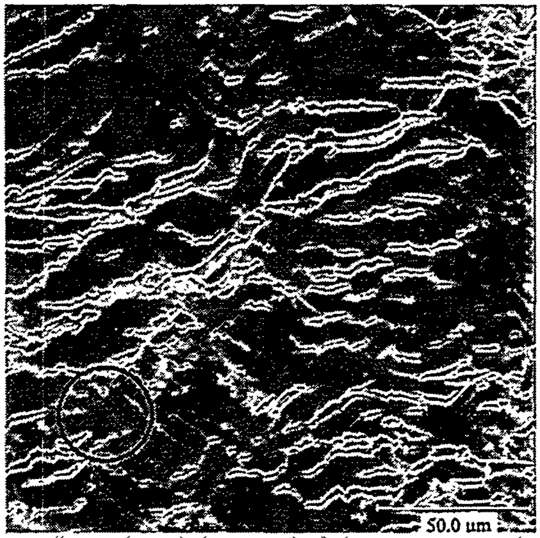

Figure 5: Example of surface steps from Sample 69-1 indicating dislocation channeling. (ET 325620)

Side surface examinations were conducted to determine if slip bands that are characteristic of dislocation channeling were formed during testing. Slip bands were apparent in most samples examined. A typical example of slip bands is shown in Figure 5. Side surface examinations also revealed short transverse cracks initiated at the surface. These transverse cracks, observed in necked regions, grew perpendicular to the direction of the applied tensile load.

Reduction-in-area measurements completed are reported in Table 3. The low reduction in area results (0 to 17%) for the BOR-60 specimens were consistent with previously reported reduction in area and elongation data. The laser weld sample (71-LZ-1) fracture was brittle, and as expected did not have a measurable reduction-in-area. This fractography data supports findings that the V-4Cr-4Ti alloys may be susceptible to significant low-temperature embrittlement [3,5,6,7].

The low damage dose samples irradiated in ATR displayed a higher reductions-in-area than the majority of the samples irradiated in BOR-60. These differing results are consistent with the tensile test data and can be explained by saturation effects. The laser weld sample (71-LZ-B) fracture was brittle, and as expected did not have a measurable reduction-in-area.

Reduction in area measurements for the BL-42 heat, irradiated at higher temperatures in FFTF, showed good reductions-in-area even at high damage doses of 41 to 51 dpa (13 to 41%). The only exception is sample 147. This sample displays a ductile fracture through SEM analysis, but did not have a measurable areal reduction. This result is currently under further investigation.

The variability in these results can be attributed to saturation effects and impurity content variations in the samples.

Table 3. Reduction in area measurement results.

Reactor	Specimen ID No.	Material/Heat	Irrad. Temp. (°C)	Tensile Test Temp. (°C)	dpa	%RA
BOR-60	71-2[a]	V-4Cr-4Ti/832665	318	23	17	1
	71-2H-1	V-4Cr-4Ti/832665	318	318	17	0
	71-2H-2[a]	V-4Cr-4Ti/832665	318	23	17	1
	71-A	V-4Cr-4Ti/832665	318	318	17	0
	71-B[a]	V-4Cr-4Ti/832665	318	23	17	1
	69-1	V-4Cr-4Ti/VX8	323	323	19	17
	69-2[a]	V-4Cr-4Ti/VX8	323	23	19	4
	72-1	V-5Cr-5Ti/T87	323	323	19	10
	72-2[a]	V-5Cr-5Ti/T87	323	23	19	1
	71-LZ-1	832665/Laser	320	320	18	0
ATR	71-F	V-4Cr-4Ti/832665	273/280	290	4.3	16
	47-E	V-4Cr-4Ti/BL-47	288/302	290	4.6	12
	72-D	V-5Cr-5Ti/T87	284/300	290	4.1	32
	71-LZ-B	V-4Cr-4Ti/Laser	288/302	290	4.6	0
FFTF	143	V-3.1Ti-0.5Si/BL42	520	520	41	35
	144	V-3.1Ti-0.5Si/BL42	520	520	46	41
	146	V-3.1Ti-0.5Si/BL42	600	600	47	34
	147	V-3.1Ti-0.5Si/BL42	600	600	51	0
	148	V-3.1Ti-0.5Si/BL42	600	600	51	13
	149	V-3.1Ti-0.5Si/BL42	600	22	51	17

[a] Results originally reported in Reference 3, included here for completeness.

References

1. H. Tsai, L. J. Nowicki, T. S. Bray, M. C. Billone, and D. L. Smith, "Tensile and Impact Properties of a V-3.1Ti-0.5Si Alloy After Irradiation in the Fast Flux Test Facility," Fusion Materials Semiannual Progress Report for Period Ending December 31, 1998, DOE/ER-0313/25, pp. 25-31.

2. H. Tsai, J. Gazda, L. J. Nowicki, M. C. Billone, and D. L. Smith, "Tensile Properties of Vanadium-Base Alloys Irradiated in the Fusion-1 Low-Temperature Experiment in the BOR-60 Reactor," Fusion Materials Semiannual Progress Report for Period Ending June 30, 1998, DOE/ER-0313/24, pp. 15-19.

3. J. Gazda et. al., "Room-Temperature Fracture in V-(4-5)Cr-(4-5)Ti Tensile Specimens Irradiated in Fusion-1 BOR-60 Experiment," Fusion Materials Semiannual Progress Report for Period Ending June 30, 1998, DOE/ER-0313/24, pp. 20-27.

4. H. Tsai et al., "Tensile and Impact Properties of Vanadium-Base Alloys Irradiated at Low Temperatures in the ATR-A1 Experiment," Fusion Materials Semiannual Progress Report for Period Ending December 31, 1997, DOE/ER-0313/23, pp. 70-76.

5. H. Chung, H. Tsai, L. J. Nowicki, and D. L. Smith, "Tensile Properties of Vanadium Alloys Irradiated at 390°C in EBR-II," Fusion Material Semiannual Progress Report for Period Ending June 30, 1997, DOE/ER-0313/22, pp. 18-21.

6. S. J. Zinkle et al., "Effects of Fast Neutron Irradiation to 4 dpa at 400°C on the Properties of V-(4-5)Cr-(4-5)Ti Alloys," Fusion Materials Semiannual Progress Report for Period Ending December 31, 1996, DOE/ER-0313/21, pp. 73-78.

7. D. J. Alexander et al., "Effects of Irradiation at Low Temperature on V-4Cr-4Ti," Fusion Materials Semiannual Progress Report for Period Ending June 30, 1996, DOE/ER-0313/20, pp. 87-95.

8. H. Tsai et al., "Tensile and Impact Properties of Vanadium-Base Alloys Irradiated at Low Temperatures in the ATR-A1 Experiment," Fusion Materials Semiannual Progress Report for Period Ending December 31, 1997, DOE/ER-0313/23, pp. 70-76.