Performance of V-4Cr-4Ti Material
Exposed to the DIII-D Tokamak Environment

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Abstract

As a first step to demonstrate the viability of using vanadium-base alloys for structural applications in fusion devices, six welded upper radiative divertor baffle support brackets made from a V-4Cr-4Ti alloy were installed in the DIII-D tokamak. To determine the effects of exposure to the tokamak environment, lead tests are being conducted on parent metal and weldment specimens. One of the issues to be addressed is whether excessive hydrogen uptake may occur to cause material embrittlement. Some of the lead tests have been completed. Data from samples exposed to up to four DIII-D operating cycles (≈4 years) indicate that the performance of the V-4Cr-4Ti alloy would not be significantly affected by the exposure. Brittle cleavage fractures are noted near the surface of some of the impact specimens, but only at very low (<-150°C) test temperatures. Above -150°C, all fractures are ductile.

Introduction

Vanadium-base alloys are attractive candidates for structural applications in fusion devices because they possess good thermal and mechanical properties, particularly at elevated temperatures, required for high system performance [1,2]. When compared with many other candidate materials, they also exhibit benign irradiation effects in terms of swelling, hardening, and activation [2,3].

As a first step to demonstrate the viability of vanadium-base alloys as a structural material for tokamaks, six upper radiative divertor baffle support brackets made with a V-4Cr-4Ti alloy were installed in the DIII-D tokamak [4]. These brackets, which support carbon-carbon armor tiles, represent the first functional components of a vanadium-base alloy in a tokamak device (Figure 1). The brackets are exposed to a wide range of environmental conditions, including alternating vacuum/low-pressure deuterium plasma operation, thermal-cycle and periodic bakeouts, glow discharge cleaning with helium, periodic boronization coating of armor tiles, and occasional re-exposure to air during vents for maintenance. Because the exposure may degrade the properties of the bracket material, mainly from the uptake of interstitial impurities, lead tests with coupon-size parent metal and weldment specimens are being conducted in the DIII-D to obtain early performance data.

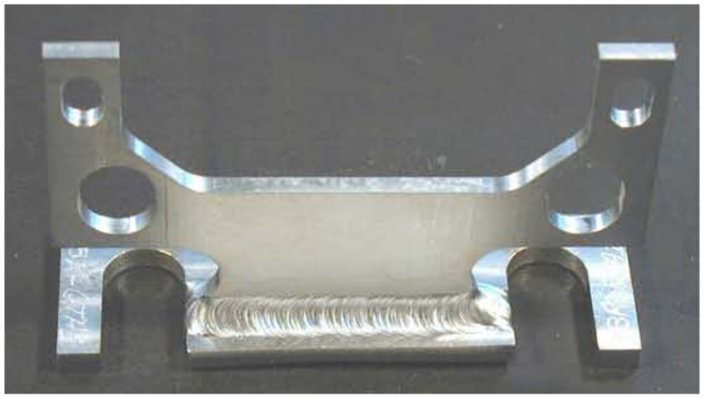


Fig. 1. Baffle support brackets made with a V-4Cr-4Ti alloy for the DIII-D upper radiative divertor

Two large heats of V-4Cr-4Ti alloys have been produced by the U.S. fusion program for research and the DIII-D demonstration tests: 832665 (500 kg) [5] and 832864 (1200 kg) [6]. The coupon-size specimens described in this paper were prepared from both heats whereas the baffle support brackets were made from the 832864 material. The two heats were produced by the same industrial vendor and exhibit comparable mechanical properties [7].

Objective

In service, the V-4Cr-4Ti divertor components in the DIII-D will be exposed to a range of temperature and impurity conditions typical of today's tokamak plasma physics experiments. The objective of the lead tests is to determine the effects of these environmental exposures on the performance of the vanadium alloy material. Of particular importance is the determination of whether interstitial impurities (mainly H and possibly O, C, and N) are absorbed in quantities sufficient to cause material embrittlement.

Experiment and Specimen Description

Three tests, denoted W1, W2, and B1, to assess composite effects of long-term exposures in the DIII-D have been recently concluded and are the subject of this paper. Two earlier tests, which utilized the DIII-D Divertor Materials Evaluation System (DiMES) [8] to investigate the effects of specific exposure events, have been reported [9]. Four additional long-exposure tests, W3, B2, B3, and B4 are still ongoing in the DIII-D.

Each of the W1, W2 and B1 tests consisted of a number of miniature Charpy impact and tensile specimens held in a frame mounted on the vessel wall. The W1 and W2 tests were mounted behind a lower divertor baffle whereas the B1 test was mounted behind the inner section of the upper radiative divertor (upper private flux baffle). The temperatures of the specimens were measured with thermocouples attached to the ends of the specimens. Figure 2 shows the mounting of the W2 test.

Fig. 2. Mounting of the W2 specimens in bracket on DIII-D vessel wall.

The Charpy specimens were 1/3 size (3.3 x 3.3 x 25.4 mm) and contained a 0.6-mm-deep, 30° blunt notch with a root radius of 0.08 mm. The crack plane direction was perpendicular to the rolling direction and through the thickness of the plate from which the specimens were prepared. The tensile specimens were 25.4 mm long with a gauge section of 7.62 mm long x 1.52 mm wide x 0.76 mm thick. The long direction of the gauge section was parallel to the final rolling direction of the plate from which the tensile specimens were machined. All specimens were annealed in vacuum at 1000°C for 1.0 h before the test.

Specimens for the W1 and W2 tests were machined from sheet material from the 832665 heat of V-4Cr-4Ti. The W1 specimens were exposed for an entire DIII-D operation cycle from February through December 1995 and the W2 specimens were exposed for 4 complete cycles, from January 1996 through July 1999. Specimens for the B1 test were made from sheet material from the 832864 heat and were exposed to one DIII-D operation cycle from November 1999 through November 2000. The B1 test included weldment samples to evaluate the welds for fabricating the baffle support brackets; however, the analyses are not complete and the performance of the weldment will not be discussed in this paper.

During the tests, the specimens were exposed to a full range of DIII-D operating conditions, including air and nitrogen vessel vents, bakeouts, helium glow discharge cleanings, boronizations of the first wall (graphite armor tiles), and plasma operations. The frequencies of these events are summarized in Table 1. In their positions behind the divertor baffle plate, the specimens were expected to be most affected by interaction with gaseous impurities during DIII-D elevated temperature operations, i.e., bakeouts and boronizations. Based on the thermocouple data, the temperatures of the specimens tracked with that of the inside vessel wall and reached values in the range of $\approx$150 - 350°C during bakeouts and $\approx$250 - 280°C during boronizations.

Analysis of residual gas analyzer data indicated that, at temperature, the specimens were exposed to partial pressures (atm) of H_2O, N_2, CO, and O_2, in the ranges of $\approx$30 - 1400 x 10^{-9}, 3 - 30 x 10^{-9}, 3 - 80 x 10^{-9}, and 1 - 8 x 10^{-9}, respectively. By design, none of the test specimens directly interacted with the plasma.

Table 1. Number of Events to which specimens were exposed in DIII-D during testing

	Vents		Bakeouts(1)				Plasma
	Air	N_2	150-200°C	250-320°C	325-350°C	Boronization(2)	Shots(3)
W1	5	5	2	3	20	2	1413
W2	7	7	5	11	69	15	6852
B1	1	0	0	0	11	6	2274

(1) Typical durations of bakeouts were 2-5 h for 150-200°C; 5-16 h for 250-320°C; 4-20 h for 325-350°C.
(2) 5-8 h duration at 280°C.
(3) Each plasma shot is followed by a helium glow discharge cleaning of the armor tiles of duration of 5-10 min.

Test Results

After removal from DIII-D, the specimens were tested to determine the effects of the exposure on their mechanical properties. The tensile tests were performed at room temperature in air and at 350°C, the peak temperature experienced during DIII-D bakeout, in high-purity argon. The strain rate for all tests was 1.1 x 10^{-3}/s. The Charpy impact tests were performed with a drop-weight tester in air at temperatures that ranged from -195 to +200°C. Sibling unexposed specimens were tested with identical methods to determine the baseline properties of the alloys.

The comparison of the Charpy impact properties of exposed and non-exposed materials is shown in Fig. 3. Both 832665 and 832864 materials appear to show a slight decrease in the upper-shelf energy and possibly an increase in the ductile/brittle transition temperature after exposure. However, all materials remained ductile at temperatures well below ambient. Extending the exposure time from 1 to 4 years (W1 vs. W2) appears mostly to affect the impact properties at very low temperature, i.e., below -100°C. The change of macroscopic appearance of the W2 specimens as a function of impact test temperature, i.e., progressive reduction of ductility, is shown in Fig. 4. Whereas the fracture surfaces of the room-temperature-tested specimens are entirely ductile, those of the -156°C specimens displayed local regions of brittle cleavage (Fig. 5). These brittle regions are near the exposed surfaces of the specimens. Microchemical analysis is necessary to determine whether the cleavage behavior near the surfaces is related to impurity uptake during the exposure test.

The results of the tensile tests are summarized in Table 2. Also shown in Table 2 are properties of control samples with no exposure history. The results show that, in spite of the long exposure, there was little change in either the strength or ductility of the materials. In all cases, the fractures are marked with pronounced necking and significant elongation (>20%). Scanning electron microscopy of the fracture surfaces shows that the fractures were ductile and consisted entirely of dimples and microvoids, as shown in Fig. 6.

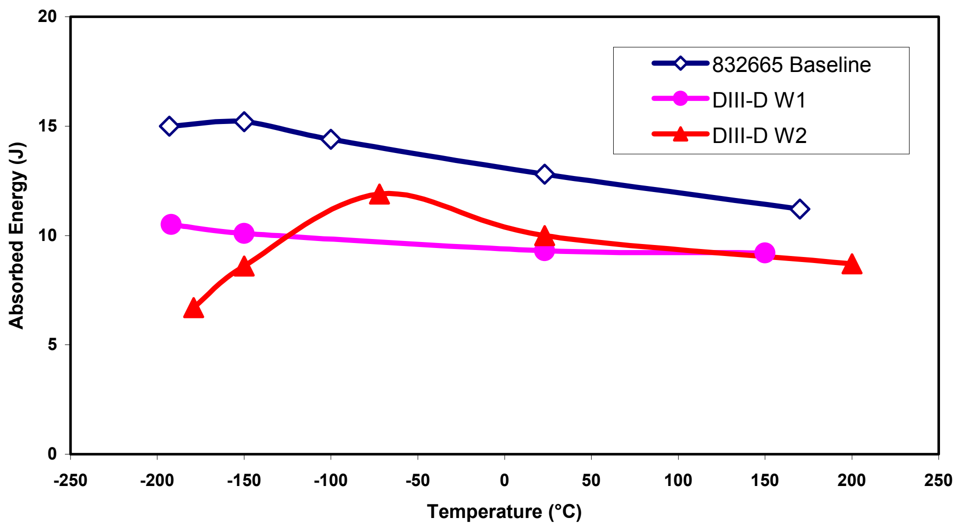
Table 2 Tensile properties[1] before and after exposure tests in DIII-D

Heat	Condition	Test Temp. (°C)	YS (MPa)	UTS (MPa)	UE (%)	TE (%)
832665	Baseline	25	357	428	19.1	29.2
	After W1	25	334	449	19.0	27.0
	After W2	25	327	434	16.0	29.5
	Baseline	400	205	359	17.6	25.4
	After W1	350	241	377	14.8	22.0
	After W2	350	235	365	16.3	24.4
832864	Baseline	25	315	410	19.3	28.5
	After B1	25	280	367	13.6	26.1
	Baseline	380	228	355	15.3	22.8
	After B1	350	192	323	16.8	27.1

(1) YS: 0.2% offset yield stress; UTS: engineering ultimate tensile stress; UE: uniform elongation; TE: total elongation.

Conclusions

Data from samples exposed for up to four DIII-D operating cycles (≈4 years) indicate that the performance of the V-4Cr-4Ti alloy would not be significantly affected by the environmental exposure in the DIII-D environment (room temperature to 350C). Brittle cleavage fractures are noted near the surface of some of the impact specimens, but only at very low (<-150°C) test temperatures. Above -150°C, all of the fractures were ductile. There appears to be no noticeable effect of the exposure on the tensile properties of the material.



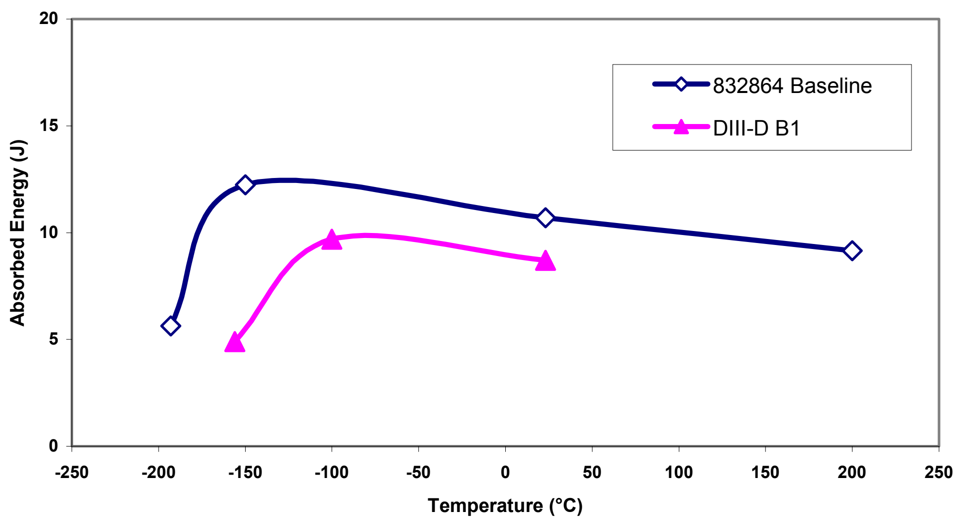
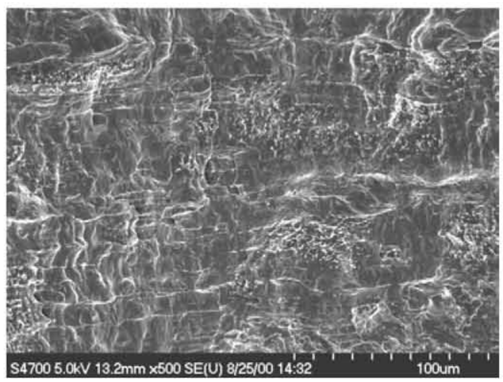


Fig. 3 Charpy impact properties of Heats 832665 and 832864 of V-4Cr-4Ti alloys as affected by exposure to DIII-D environment.

Fig. 4 Change of appearance of Charpy impact specimens with test temperature. The specimens are from the W2 test after ≈4-year exposure in DIII-D.



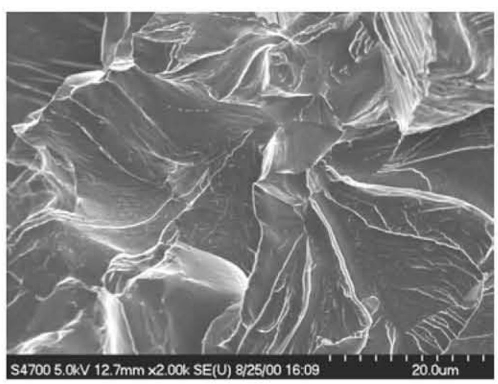


Fig. 5. Whereas the fracture of the W2 Charpy specimen tested at room temperature is completely ductile (top), that of the -150°C specimen contained brittle cleavage features near specimen external surfaces (bottom).

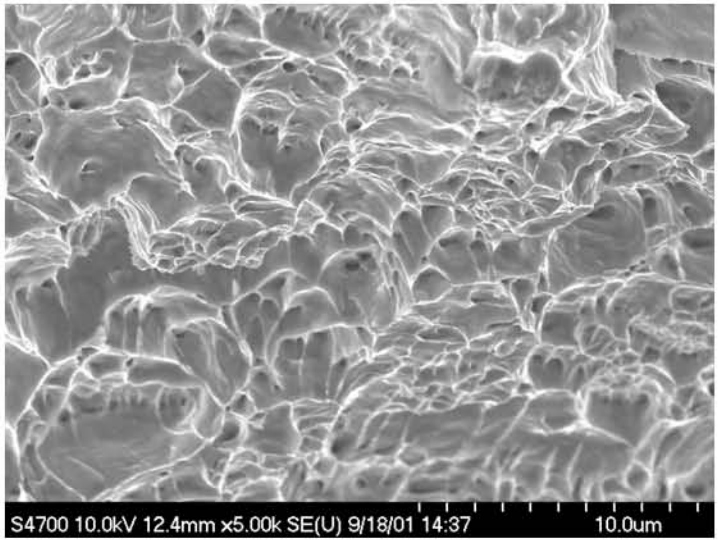


Fig. 6 Fracture surface of a room-temperature-tested tensile specimen from the B1 test after ≈1 year of exposure. The surface consists of dimples and microvoids, indicating that fracture is ductile.

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