EFFECTS OF IRRADIATION TO 4 DPA AT 390°C ON THE FRACTURE TOUGHNESS OF VANADIUM ALLOYS*

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OBJECTIVE

The objective of this task is to study the effects of neutron irradiation on the fracture toughness of vanadium–base alloys.

SUMMARY

Fracture toughness J–R curve tests were conducted at room temperature on disk-shaped compact-tension DC(T) specimens of three vanadium alloys having a nominal composition of V-4Cr-4Ti. The alloys in the nonirradiated condition showed high fracture toughness; J_{IC} could not be determined but is expected to be above 600 kJ/m^2. The alloys showed very poor fracture toughness after irradiation to 4 dpa at 390°C, e.g., J_{IC} values of ≈10 kJ/m^2 or lower.

EXPERIMENTAL PROGRAM

The heats of vanadium alloy selected for the study had compositions of V-3.8 wt.%Cr-3.9 wt.%Ti (Heat #832665, designated BL-71, 783 wppm Si, 310 wppm O, 85 wppm N, 80 wppm C); V-4.1 wt.%Cr-4.3 wt.%Ti (Heat #9144, designated BL-47, 870 wppm Si, 350 wppm O, 220 wppm N, 200 wppm C); and V-4.0 wt.%Cr-4.1 wt.%Ti-B (designated BL-70 or QN74, 350 wppm Si, 480 wppm O, 79 wppm N, 54 wppm C, ≈250 appm B-10). Prior to testing, the alloys were annealed in high-purity vacuum for 1 h (at 1025-1050°C for BL-47, and at 1000°C for BL-71 and BL-70). Alloy BL-71 was tested in the nonirradiated condition and alloys BL-47 and BL-70 were irradiated to ≈4 dpa at 390°C in lithium in the EBR-II reactor experiment X530 (located in subcapsule S2 for BL-47 and S14 for BL-70). The room–temperature tensile properties of the various vanadium alloys [1] before and after irradiation are given in Table 1. The tensile properties of BL-47 were also used to determine the flow stress for irradiated alloy BL-70.

Table 1. Room-temperature tensile properties of nonirradiated and irradiated vanadium alloys

Alloy Designation	Irradiation Experiment	Yield Strength (MPa)	Ultimate Stress (MPa)
BL-47	–	404	460
BL-71	–	355	429
BL-47[a]	X530[b]	880	935

[a]Prior to irradiation, the alloy was warm-rolled at 400°C and annealed at 950°C.
[b]DC(T) specimens irradiated to ≈4 dpa at 390°C in EBR II reactor.

Fracture toughness J–R curve tests were conducted according to ASTM Specification E 1737 (Standard Test Method for J–Integral Characterization of Fracture Toughness) at room temperature on disk-shaped compact-tension DC(T) specimens of the various vanadium-base alloys. The method involves pin loading of fatigue-precracked specimens and determination of the J-integral as a function of crack growth. A detailed description of the facility is presented in Ref. 2. The facility is designed for conducting fracture toughness J-R or fatigue crack growth tests on 1/4 T DC(T) or C(T) specimens in air or light water reactor (LWR) environments at temperatures up to 300°C. Specimen extension is monitored and controlled outside of the high-temperature zone. The displacement of load points (center of the loading pins) is determined by subtracting the machine compliance from the measured extension. Crack length was determined by the elastic unloading compliance method. The configuration of the 1/4T DC(T) specimens used in the present study is shown in Fig. 1. Crack length and J–integral were calculated by using the correlations recommended for DC(T) specimens in ASTM Specification E 1737.

Several validation tests were conducted in which the actual displacements of load points were measured optically and compared with the estimated loadline displacements. Measured loadline displacements showed very good agreement with the estimated values [3]; for loadline displacements of up to 2 mm, the error in the estimated values was <0.02 mm. Fracture toughness J–R curve tests were also conducted at room temperature and 288°C on 1/4-T C(T) specimens of two heats of thermally aged CF-8M cast stainless steel; the results were compared with data obtained on 1-T C(T) specimens to validate the test procedure [3].

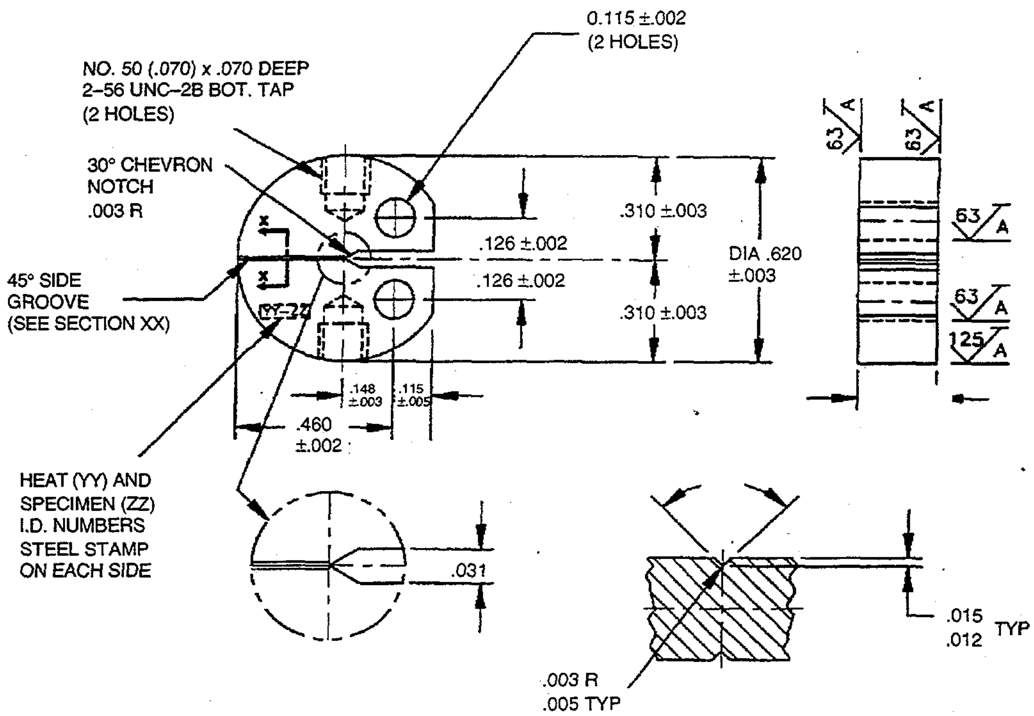

Figure 1. Configuration of disk–shaped compact–tension specimen for this study

Prior to testing, the specimens were fatigue–precracked at room temperature and at loads based on the maximum allowable load P_m given by the relation

$$P_m = (0.4\, \sigma_f\, B_N\, b^2)/(2W + a), \quad (1)$$

where W is specimen width, a is crack length, B_N is net specimen thickness (distance between roots of the side grooves), b is noncracked ligament (distance from the crack front to the back edge of the specimen, i.e., $W - a$), and σ_f is flow stress expressed as the mean of the yield and ultimate stress. The final fatigue precrack extension was carried out at loads $\leq P_m$, or a load such that the ratio of the maximum stress intensity applied during fatigue precracking to the elastic modulus (K_{max}/E) was $\leq 1.6 \times 10^{-4}$ $m^{1/2}$ (≤ 0.001 in.$^{1/2}$).

The fatigue-precracked specimens were loaded at a constant extension rate and the tests were interrupted periodically to determine the crack length. The maximum range of unload/reload for crack extension measurements was the smaller of $0.5P_m$ or 50% of the current load. The final crack size was marked by fatigue cycling. After the test, the specimens were fractured and the initial (i.e., fatigue-precrack) and final (test) crack lengths were measured optically on both halves of the fractured specimen. The crack lengths were determined by the 9/8 averaging technique, i.e., the two–near–surface measurements were averaged and the resultant value was averaged with the remaining seven measurements.

RESULTS AND DISCUSSION

The load-versus-loadline displacement curves and fracture toughness J–R curves for nonirradiated specimens of alloy BL-71 are shown in Figures 2 and 3, and for irradiated specimens of alloys BL-47 and BL-70 in Figures 4 and 5. A slope of two times the flow stress was used to define the blunting and offset lines. Also, because displacement was monitored and controlled away from the specimen, loadline displacement is not constant during periods of unstable crack growth (observed in irradiated alloys) but is increased because of the accompanying load drop.

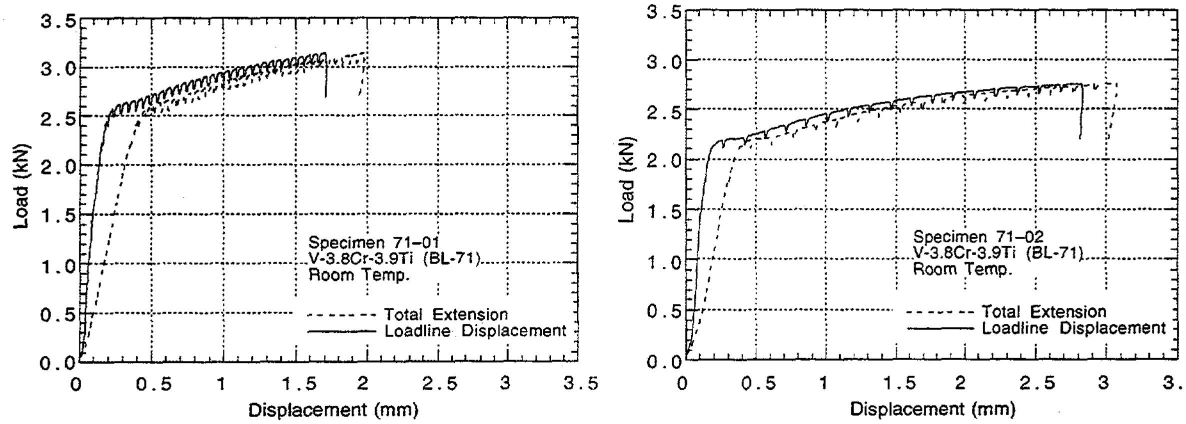

Figure 2. Load versus loadline displacement for specimens V71–01 and V71–02 of nonirradiated Heat 71 tested at room temperature

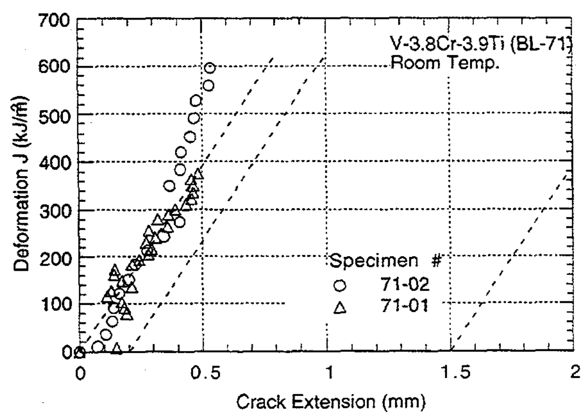

Figure 3. Fracture toughness J–R curves for specimens V71–01 and V71–02 of nonirradiated Heat 71 tested at room temperature

For the nonirradiated alloy BL-71, maximum load or displacement limit for the test facility was reached before the onset of stable crack extension, i.e., J_{IC} could not be determined but is expected to be above 600 kJ/m^2. The results for alloy BL-71 (Fig. 3) show excellent agreement with the data obtained earlier on production-scale Heat 832665 of V-4Cr-4Ti alloy [4].

Alloys BL-47 and BL-70 irradiated to ≈4 dpa at 390°C show very poor room-temperature fracture toughness. The J_{IC} values are 6 and 11 kJ/m^2 for BL-47 and BL-70, respectively. Both alloys showed several bursts of unstable crack extension. A detailed metallographic evaluation of the fracture surface has not been conducted; however, preliminary examination indicates that fracture occurred predominantly by cleavage.

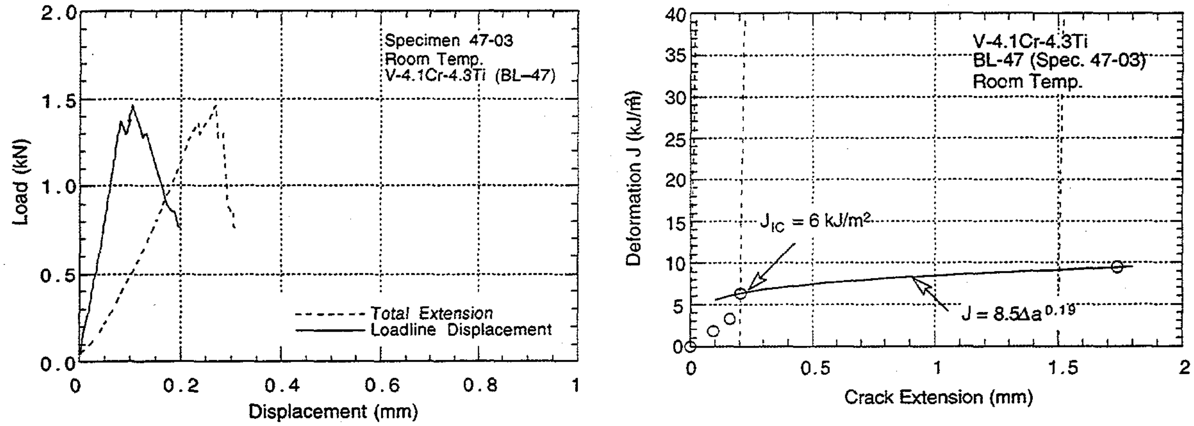

Figure 4. Load versus loadline displacement and fracture toughness J–R curve for irradiated Heat 47 tested at room temperature

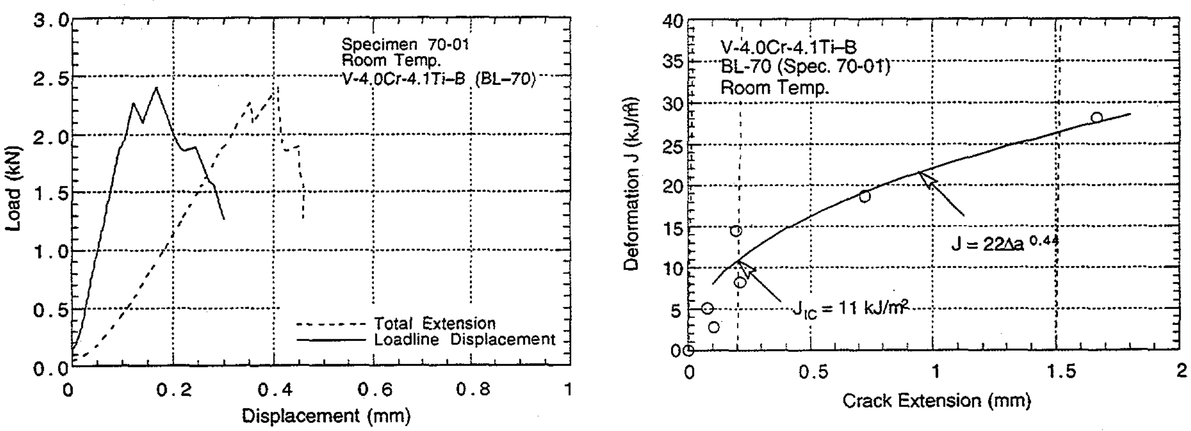

Figure 5. Load versus loadline displacement and fracture toughness J–R curve for irradiated Heat 70 tested at room temperature

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