Conf-9009264--4

SWELLING AND TENSILE PROPERTIES OF NEUTRON-IRRADIATED VANADIUM ALLOYS*

CONF-9009264--4

DE91 006588

B. A. Loomis and D. L. Smith
Argonne National Laboratory
Argonne, Illinois 60439, USA

Rec'd by OSTI

JAN 22 1991

July 1990

The submitted manuscript has been authored by a contractor of the U. S. Government under contract No. W-31-109-ENG-38. Accordingly, the U. S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U. S. Government purposes.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER

Submitted for presentation at the Conference on The Effect of Irradiation on Materials of Fusion Reactors, September 18-20, Leningrad, USSR.

*Work supported by the Office of Fusion Energy, U.S. Department of Energy, under Contract W-31-109-Eng-38.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

SWELLING AND TENSILE PROPERTIES OF NEUTRON-IRRADIATED VANADIUM ALLOYS*

B. A. Loomis and D. L. Smith
Argonne National Laboratory
Argonne, Illinois 60439, USA

1. Introduction

Vanadium-base alloys are candidates for use as structural material in magnetic fusion reactors. In comparison to other candidate structural materials (e.g., Type 316 stainless and HT-9 ferritic steels), vanadium-base alloys such as V-15Cr-5Ti and V-20Ti have intrinsically lower long-term neutron activation, neutron irradiation after-heat, biological hazard potential, and neutron-induced helium and hydrogen transmutation rates [1-3]. Moreover, vanadium-base alloys can withstand a higher surface-heat flux than steels because of their lower thermal stress factor [4,5]. In addition to having these favorable neutronic and physical properties, a candidate alloy for use as structural material in a fusion reactor must have dimensional stability, i.e., swelling resistance, and resistance to embrittlement during the reactor lifetime at a level of structural strength commensurate with the reactor operating temperature and structural loads.

In this paper, we present experimental results on the swelling and tensile properties of several vanadium-base alloys after irradiation at 420, 520, and 600°C to neutron fluences ranging from 0.3 to 1.9 x 10^{27} neutrons/m^2 (17 to 114 atom displacements per atom [dpa]).

2. Materials and procedure

Vanadium alloys with the compositions listed in Table 1 were obtained in the form of 50% cold-worked sheets. Tensile specimens with a gauge length of 7.62 mm, gauge width of 1.52 mm, and thickness of ≈0.9 mm, and, for the swelling determinations, disc-shape specimens with ≈3.0 mm diameter and ≈0.3 mm thickness were obtained from the cold-worked sheet. The surfaces of the specimens were mechanically ground and polished to a surface finish of 0.3 μm.

The cold-worked specimens were annealed at 1125°C for 1 h in an ion-pumped vacuum system with a typical pressure of 1.3 x 10^{-6} Pa. The average recrystallized grain diameter in these annealed materials was 0.020 mm. The specimens were irradiated in the Materials Open Test Assembly (MOTA) of the Fast Flux Test Facility (FFTF) reactor at Richland, Washington, USA. They were contained in sealed, Li^7-filled, TZM molybdenum capsules during irradiation to prevent contamination from oxygen, nitrogen, and carbon impurities in the FFTF sodium coolant. The specimens were irradiated at 420, 520, and 600°C to neutron fluences (E > 0.1 MeV) ranging from 0.3 X 10^{27} neutrons/m^2 (17 dpa) to 1.9 X 10^{27} neutrons/m^2 (114 dpa) during Cycles 7, 8, 9, and 10 of the FFTF-MOTA facility. The irradiated specimens were removed from the Li-filled TZM molybdenum capsules by immersion of the opened capsules in liquid NH_3 and subsequent immersion of specimens in a mixture of 50% ethanol and 50% methanol.

The swelling (S) of an irradiated specimen was obtained from a de-

*Work supported by the Office of Fusion Energy, U.S. Department of Energy, under Contract W-31-109-Eng-38.

termination of the density of an unirradiated specimen (D_{ann}) and the density of an irradiated specimen (D_{irr}) by immersion in CCl_4, i.e., $S = (D_{ann} - D_{irr})/D_{irr}$. Specimen density was determined with a precision of ±0.1% from three to six separate determinations on a specimen.

Table 1
Vanadium and Vanadium Alloy Composition[1]

ANL I.D.	Nominal Alloy Composition[2] (wt.%)	Concentration (ppm)				
		O	N	C	Si	Al
BL-1	V-4Mo	230	73	90	110	<100
BL-2	V-9W	300	150	120	59	<100
BL-3	V-12Ni	490	280	500	405	<100
BL-4	V-10Cr	530	76	240	<50	1190
BL-5	V-14Cr	330	69	200	<50	2740
BL-10	V-15Ti-7.5Cr	1110	250	400	400	30
BL-11	V-5Ti	1820	530	470	220	115
BL-12	V-10Ti	1670	390	450	245	<100
BL-13	V-14Ti	1580	370	440	205	<100
BL-15	V-18Ti	830	160	380	480	33
BL-16	V-20Ti	390	530	210	480	-
BL-20	V	570	110	120	325	<100
BL-24	V-15Cr-5Ti	1190	360	500	390	40
BL-25	V-14Cr-0.3Ti	390	64	120	<50	3270
BL-26	V-14Cr-1Ti	560	86	140	<50	3090
BL-27	V-3Ti-1Si	210	310	310	2500	160
BL-28	Vanstar-7[3]	275	540	740	-	-
BL-34	V-9Ti	990	180	420	290	<100
BL-35	V-10Cr	340	45	120	<50	1450
BL-36	V	810	86	250	<50	<100
BL-42	V-3Ti-1Si	580	190	140	5400	290
BL-43	V-10Cr-5Ti	230	31	100	340	140

[1] Chemical analyses of these materials were performed by the Analytical Department of the Teledyne Wah Chang Albany Company.
[2] Complete analyses for these materials are presented in Ref.[6].
[3] V-9Cr-3Fe-1Zr.

The tensile tests were conducted at a strain rate of 0.0011 s^{-1} and a crosshead speed of 0.008 $mm \cdot s^{-1}$. All tensile tests were conducted in an environment of flowing argon of 99.9999% purity. Specimen temperature during the tensile test was determined from a chromel-alumel thermocouple that was arc-welded to the edge of the specimen.

3. Experimental results

3.1 Swelling

The dependence of density change (i.e., swelling) of vanadium-base alloys on Ti concentration after irradiation at 420°C to 114 dpa and at 600°C to 77-84 dpa is shown in Figs. 1 and 2, respectively. The V-3Ti-1Si alloy showed the highest swelling of the alloys on irradiation at 420°C to 114 dpa. Even so, swelling of all of the alloys at 420°C was

<0.02% per dpa (Fig. 1). The addition of 0.3% Ti to the V-14Cr alloy resulted in reduction of swelling of this alloy from 39% to 14% on irradiation at 600°C to 84 dpa (Fig. 2). An increase of Ti concentration to 5% caused a further reduction of swelling of the V-14Cr alloy to <10%. The swelling data presented in Figs. 1 and 2 suggest that swelling of V-Ti and V-Cr-Ti alloys is relatively independent of Ti concentration in the range of 3-20%.

Addition of either 9% W, 4% Mo, or 12% Ni to V resulted in a slight decrease in the swelling of V on irradiation at 420°C to 114 dpa and at 600°C to 84 dpa. The Vanstar-7 alloy exhibited 7-10% swelling on irradiation at 600°C to 77 dpa.

The dependence of swelling of V-15Ti-7.5Cr, V-15Cr-5Ti, V-10Cr-5Ti, V-3Ti-1Si, and V-20Ti alloys on irradiation damage (dpa) at 600°C is shown in Fig. 3. Swelling data obtained from transmission electron microscopy (TEM) observations of the irradiated alloys are also shown in Fig. 3 [7]. On the basis of these data, the swelling of V-15Ti-7.5Cr, V-15Cr-5Ti, V-10Cr-5Ti, V-3Ti-1Si, and V-20Ti alloys on irradiation at 600°C to 84 dpa is (in % per dpa) 0.10, 0.03, 0.03, 0.01, and 0.01, respectively.

3.2 Tensile properties

The dependence of yield strength on irradiation and/or test temperature for the specimens irradiated to 41-46 dpa is shown in Fig. 4. Whereas yield strength of unirradiated alloys was independent of test temperature between 420 and 600°C [8], that of irradiated alloys was strongly dependent on irradiation/test temperature (Fig. 4). The yield strength of irradiated V-15Cr-5Ti alloy was significantly higher than that for the other irradiated alloys at all irradiation and/or test temperatures. The yield strength of alloy specimens irradiated at 420°C and tested at 25°C was 200-300 MPa higher than that for specimens irradiated at 420°C and tested at 420°C.

The dependence of the increase in yield stress, i.e., irradiation hardening, of the neutron-irradiated alloy specimens (relative to an unirradiated specimen) on radiation damage (dpa) is shown in Fig. 5. Also shown in Fig. 5 is the increase in yield stress for ion-irradiated V-15Cr-5Ti alloy [9]. Increase in yield stress of the ion-irradiated alloy was determined from analyses of TEM microstructures for dislocation density, void number density, and number density and diameter of precipitates and from consideration of these microstructural features as obstacles to dislocation motion [9]. The data in Fig. 5 for the V-15Cr-6Ti alloy were obtained by Braski [10]. Increase in yield stress on neutron irradiation of alloy specimens at 420, 520, and 600°C was on the order of V-15Cr-5Ti > V-3Ti-1Si > V-10Cr-5Ti > V-15Ti-7.5Cr > V-20Ti. The V-15Ti-7.5Cr and V-20Ti alloy specimens underwent significantly less irradiation hardening, based on the results of tensile tests, than did the other alloys. The data in Fig. 5 show that irradiation hardening of these vanadium alloys attained a maximum for radiation damage in the range of 25 to 50 dpa.

The dependence of the ultimate tensile strength on irradiation and/or test temperature for specimens irradiated to 41-46 dpa is shown in Fig. 6. Tensile strength of the irradiated alloys decreased approximately 400 MPa on increasing the irradiation/test temperature from 420°C to 600°C.

The dependence of total elongation, i.e., ductility, on irradiation and/or test temperature for specimens irradiated to 41-46 dpa is shown in Fig. 7. The uniform elongation of irradiated alloys was ≈75% of the total elongation. Ductility of the irradiated (41-46 dpa) alloys was on the order of V-20Ti > V-15Ti-7.5Cr > V-3Ti-1Si > V-10Cr-5Ti > V-15Cr-5Ti. With the exception of the V-15Cr-5Ti specimen irradiated at 420°C and tested at 25°C, all of the specimens irradiated to 41-46 dpa underwent a significant, although localized, reduction in cross-sectional area during the tensile test. The V-15Cr-5Ti specimen fractured in a totally transgranular manner before attainment of maximum load during the tensile test at 25°C.

The dependence of ductility, i.e., total elongation, on irradiation damage (dpa) for V-20Ti, V-15Ti-7.5Cr, V-3Ti-1Si, and V-15Cr-5Ti specimens irradiated at 600°C is shown in Fig. 8. The alloys exhibited a substantial reduction in ductility for damage levels up to ≈25 dpa. Ductility of the V-15Cr-5Ti and V-3Ti-1Si alloys was not significantly changed on additional irradiation to 87 dpa. While ductility of the V-20Ti alloy increased significantly on further irradiation to 87 dpa, ductility of the V-15Ti-7.5Cr alloy decreased significantly. The V-15Ti-7.5Cr specimen irradiated at 600°C to 87 dpa underwent total transgranular fracture before the attainment of maximum load during the tensile test. Even though the V-15Ti-7.5Cr alloy exhibited high ductility (15.7%) after irradiation at 600°C to 44 dpa, this alloy specimen fractured under the maximum load.

4. Discussion of results

The tensile test data presented in this paper, together with the data presented previously by Loomis et al. [9] and Braski [10], provide substantial evidence for the existence of a maximum irradiation hardening, i.e., increase of yield stress, of vanadium alloys on neutron irradiation. In the case of neutron-irradiated vanadium alloys at 420, 520, and 600°C, maximum irradiation hardening occurs in the range of 25 to 50 dpa. A previous evaluation of irradiation-induced microstructural features in ion-irradiated V-15Cr-5Ti alloy likewise showed the existence of a yield stress maximum at approximately 50 dpa [9]. In the ion-irradiated alloy, the decrease in yield stress (after the yield stress maximum) was due to a reduction in dislocation density, an increase in irradiation-produced precipitate diameter, and a decrease in precipitate number density. Loomis and Smith reported the results of analyses of microstructural features observed by TEM in vanadium alloys after neutron irradiation at 600°C [7]. These results showed that hardening of neutron-irradiated vanadium alloys attains a saturation value, rather than a maximum hardening, in the range of 25 to 50 dpa.

It might be concluded that the existence of a radiation-hardening maximum for an alloy would result in that alloy being less susceptible to embrittlement at irradiation damage levels above the hardening maximum. On the basis of the tensile ductility parameter, this conclusion would not be justified, without exception, because the V-15Ti-7.5Cr alloy exhibited embrittlement after irradiation at 600°C to 87 dpa (Fig. 8).

Total elongation, i.e., ductility, of the vanadium alloys irradiated at 600°C to 87 dpa (Fig. 8) was inversely related to the swelling of these alloys on irradiation at 600°C to 84 dpa (Fig. 3). On the basis of TEM observations by Loomis and Smith of the alloys irradiated at 600°C [7], the high ductility of the V-20Ti alloy was due to the relatively low density of forest dislocations, precipitates, and voids. On the contrary, the V-15Ti-7.5Cr alloy contained very-large-diameter voids (≈180 nm) that resulted in little resistance to crack propagation during tensile testing and, therefore, in low ductility [7].

5. Conclusions

The swelling of V-Cr-Ti alloys on neutron irradiation at 600°C is strongly dependent on Ti concentration. The V-Cr-Ti alloys with >3% Ti exhibit greater resistance to irradiation-induced swelling.

Swelling of V-Ti and V-Cr-Ti alloys is nearly independent of Ti concentration in the range of 3-20%.

The swelling of V-15Ti-7.5Cr, V-15Cr-5Ti, V-10Cr-5Ti, V-3Ti-1Si, and V-20Ti alloys on neutron irradiation at 600°C to 84 dpa is (in % per dpa) 0.10, 0.03, 0.03, 0.01, and 0.01, respectively. Swelling of these alloys on irradiation at 420°C to 114 dpa is <0.02% per dpa.

Vanadium-base alloys, on neutron irradiation at 420, 520, and 600°C, undergo maximum irradiation hardening at radiation damage levels in the range of 25 to 50 dpa.

The V-15Cr-5Ti, V-10Cr-5Ti, V-15Ti-7.5Cr, V-3Ti-1Si, and V-20Ti alloys exhibit significant ductility (>3%) after irradiation at 420, 520, and 600°C to radiation damage levels ranging up to 87 dpa.

References

[1] T. Noda, F. Abe, H. Araki, and M. Okada, J. Nucl. Mater. 155-157 (1988) 581.

[2] R. Santos, J. Nucl. Mater. 155-157 (1988) 589.

[3] S. J. Piet, H. G. Kraus, R. M. Neilson, Jr., and J. L. Jones, J. Nucl. Mater. 141-143 (1986) 24.

[4] F. L. Yaggee, E. R. Gilbert, and J. W. Styles, J. Less-Com. Metals 19 (1969) 39.

[5] S. Majumdar, Fusion Technology, 15 (1989) 1560.

[6] B. A. Loomis, D. L. Smith, and F. A. Garner, "Swelling of Neutron-Irradiated Vanadium Alloys," in: Proceedings of the Fourth International Conference on Fusion Reactor Materials, December 4-8, 1989, Kyoto, Japan.

[7] B. A. Loomis and D. L. Smith, "Relationship of Microstructure and Tensile Properties for Neutron-Irradiated Vanadium Alloys," in: Proceedings of the 15th International Symposium on the Effects of Radiation on Materials, June 19-21, 1990, Nashville, TN.

[8] B. A. Loomis, R. H. Lee, D. L. Smith, and J. R. Peterson, J. Nucl. Mater. 155-157 (1988) 631.

[9] B. A. Loomis, B. J. Kestel, and D. L. Smith, J. Nucl. Mater. 155-157 (1988) 1305

[10] D. N. Braski, in: Fusion Reactor Materials Semiannual Progress Report for Period Ending September 30, 1987, DOE/ER-0313/3, Oak Ridge National Laboratory, Oak Ridge, TN (March, 1988) p. 235.

List of Figures:

Fig. 1. Dependence of density change (swelling) on Ti concentration of vanadium alloys irradiated at 420°C to 114 dpa.

Fig. 2. Dependence of density change (swelling) on Ti concentration of vanadium alloys irradiated at 600°C to 77-84 dpa.

Fig. 3. Dependence of swelling of vanadium alloys at 600°C on irradiation damage.

Fig. 4. Dependence of yield strength of neutron-irradiated vanadium alloys on irradiation/test temperature.

Fig. 5. Dependence of increase in yield stress of neutron-irradiated vanadium alloys on irradiation damage (dpa).

Fig. 6. Dependence of ultimate tensile strength of neutron-irradiated vanadium alloys on irradiation/test temperature.

Fig. 7. Dependence of ductility of neutron-irradiated vanadium alloys on irradiation/test temperature.

Fig. 8. Dependence of ductility of neutron-irradiated vanadium alloys on irradiation damage (dpa).

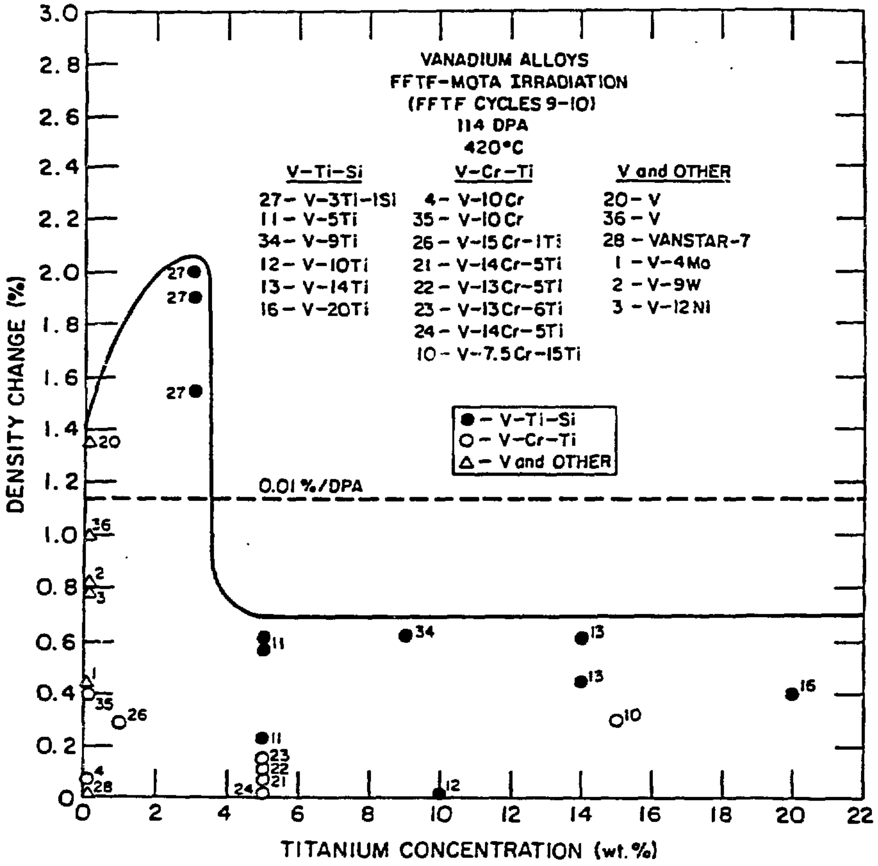

Fig. 1. Dependence of density change (swelling) on Ti concentration of vanadium alloys irradiated at 420°C to 114 dpa.

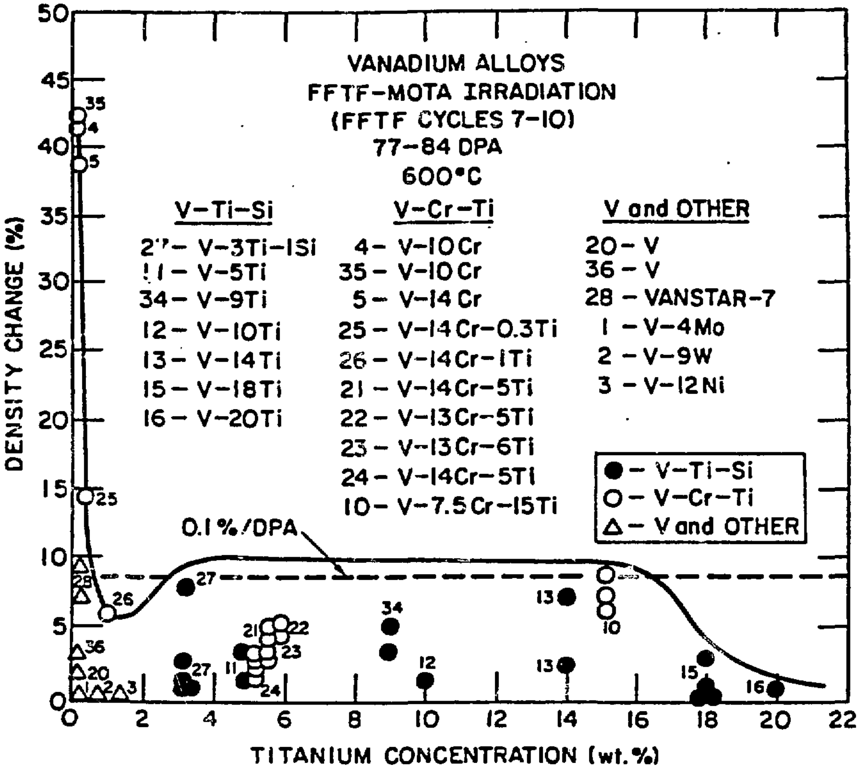

Fig. 2. Dependence of density change (swelling) on Ti concentration of vanadium alloys irradiated at 600°C to 77-84 dpa.

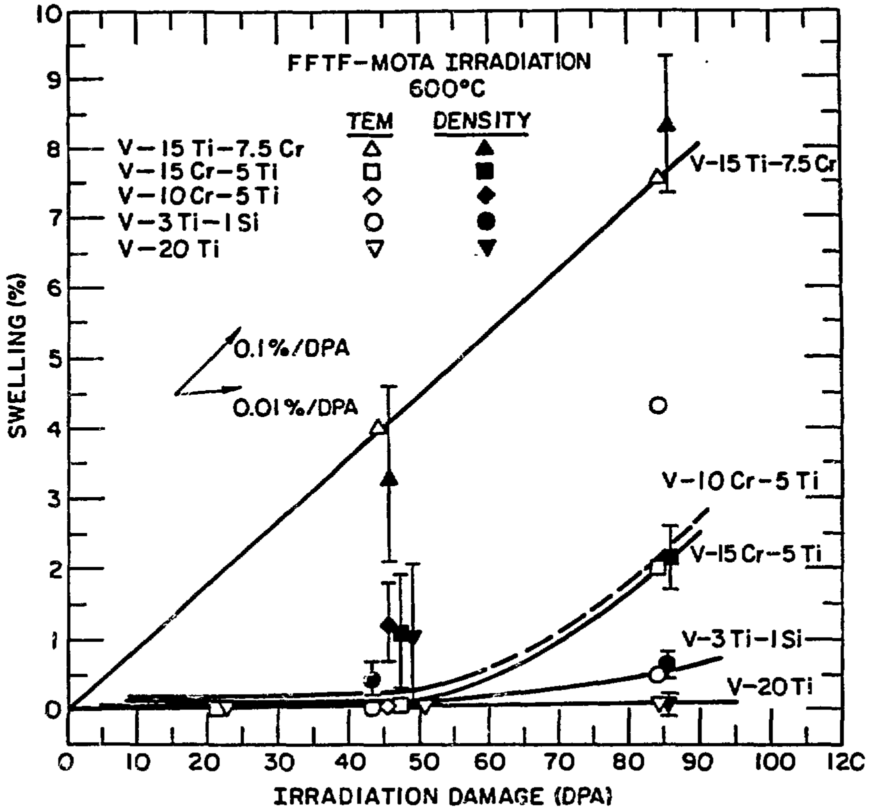

Fig. 3. Dependence of swelling of vanadium alloys at 600°C on irradiation damage.

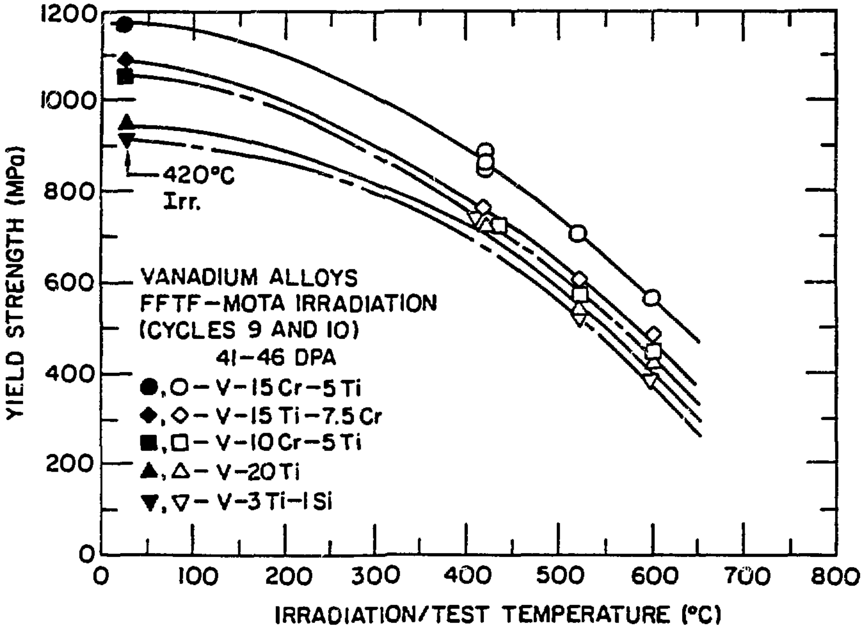

Fig. 4. Dependence of yield strength of neutron-irradiated vanadium alloys on irradiation/test temperature.

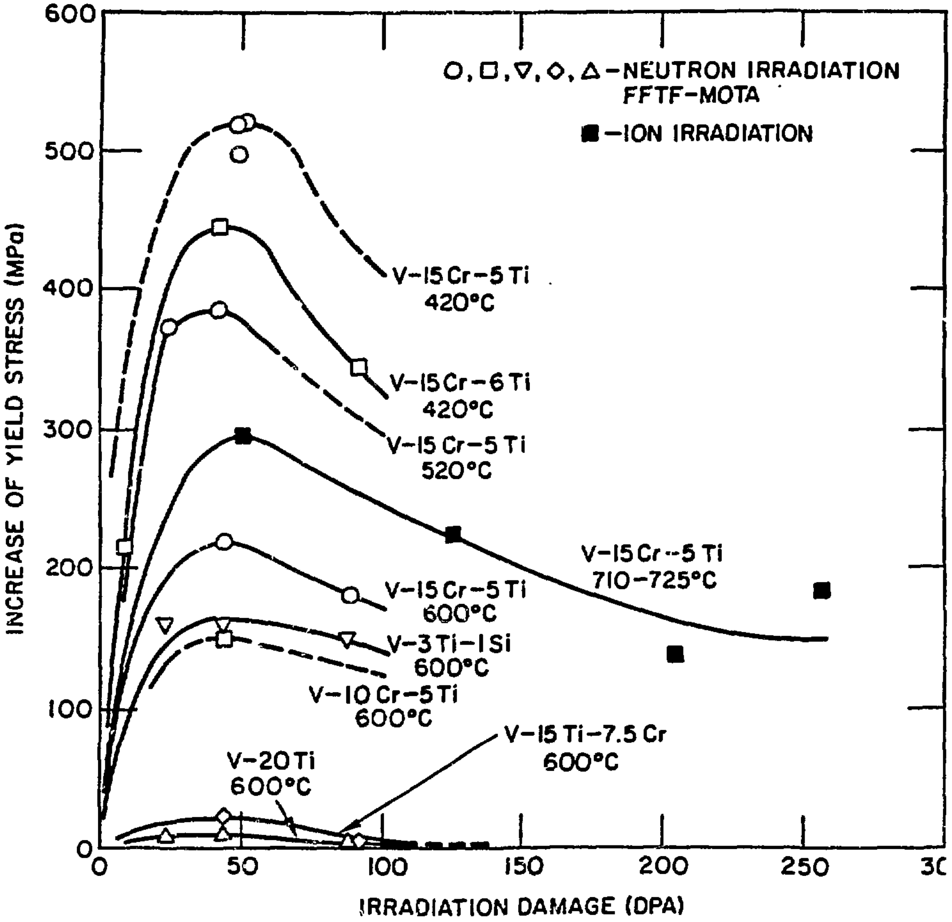

Fig. 5. Dependence of increase in yield stress of neutron-irradiated vanadium alloys on irradiation damage (dpa).

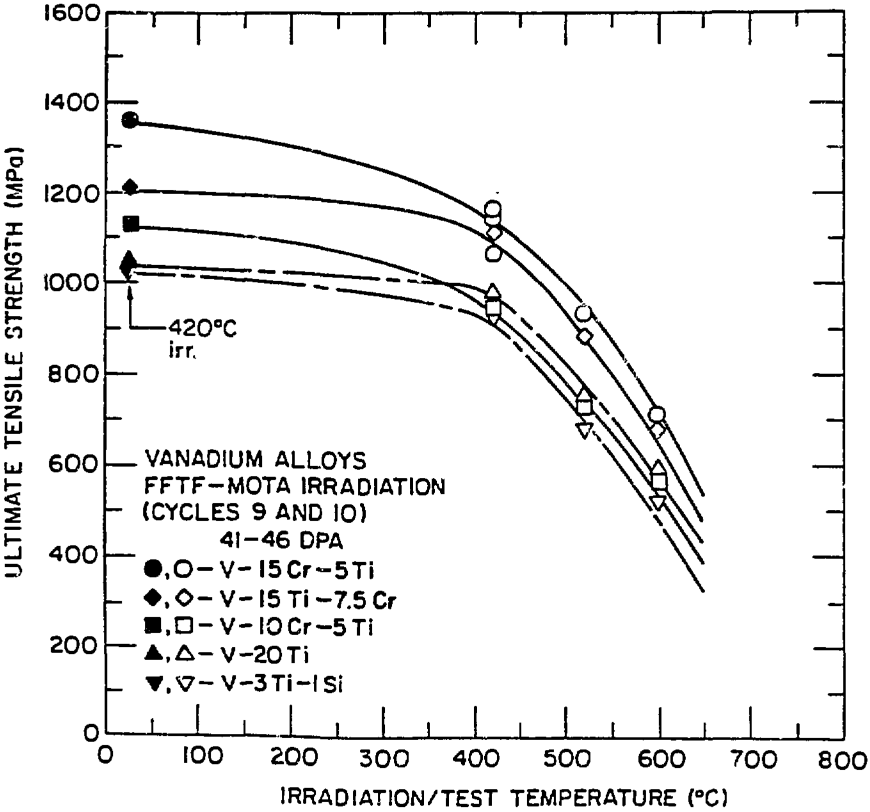

Fig. 6. Dependence of ultimate tensile strength of neutron-irradiated vanadium alloys on irradiation/test temperature.

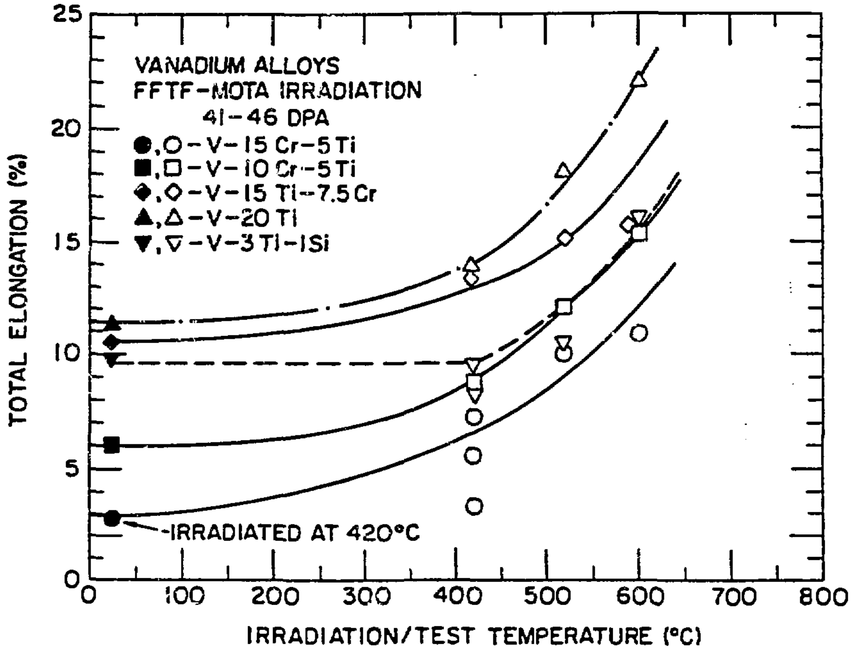

Fig. 7. Dependence of ductility of neutron-irradiated vanadium alloys on irradiation/test temperature.

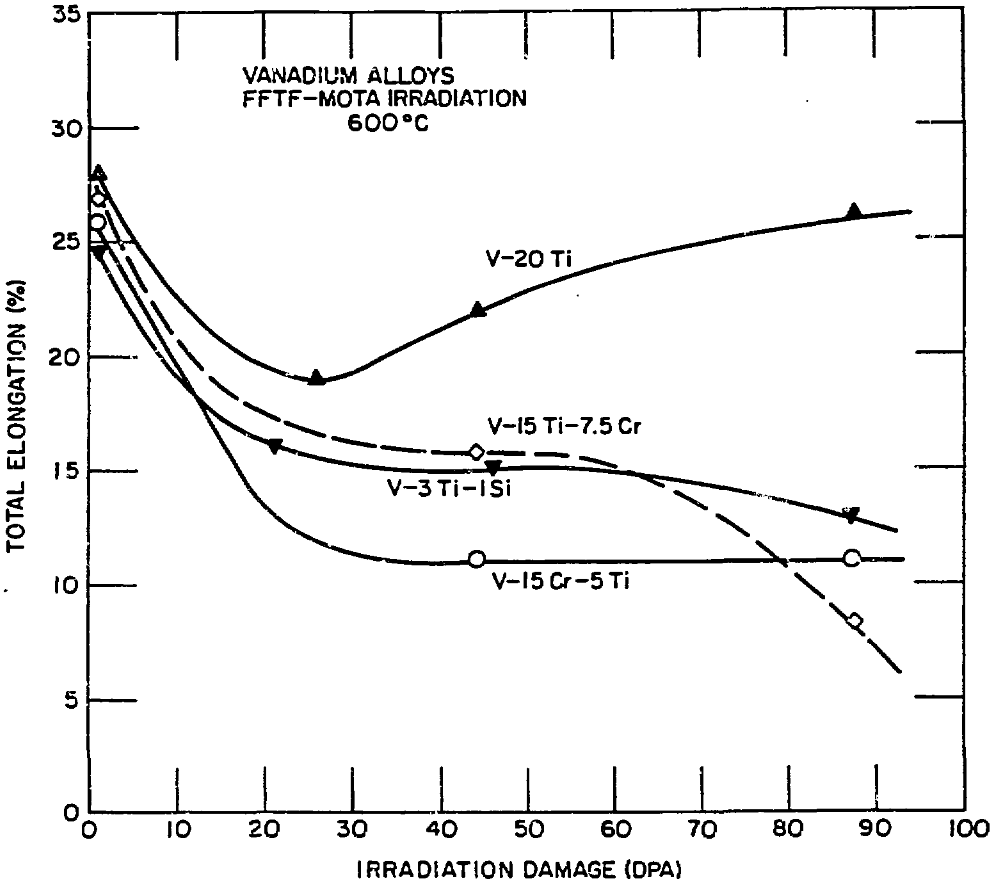

Fig. 8. Dependence of ductility of neutron-irradiated vanadium alloys on irradiation damage (dpa).