SWELLING DEPENDENCE OF NEUTRON-IRRADIATED VANADIUM ALLOYS ON TEMPERATURE, NEUTRON FLUENCE, AND THERMOMECHANICAL TREATMENT

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ABSTRACT

Swelling of vanadium alloys was determined after irradiation at 420 and 600°C to neutron fluences ranging from \(0.3 \times 10^{27}\) neutrons/m² (17 dpa) to \(1.9 \times 10^{27}\) neutrons/m² (114 dpa). Binary and ternary vanadium alloys with Cr, Ti, Mo, W, Ni, Fe, Zr, and Si additions were irradiated in either the fully annealed, partially annealed, or 10% cold-worked condition. The addition of Cr to vanadium greatly exacerbated swelling of vanadium upon irradiation at 600°C, whereas the presence of Ti, Mo, W, and Ni (3-20%) did not significantly affect swelling of vanadium. The swelling of V-Cr alloys upon irradiation at 600°C was substantially reduced (<0.1%/dpa) by the addition of Ti (1-15%). The swelling of the vanadium alloys was <0.2%/dpa upon irradiation at 420°C. Partial annealing or 10% cold-working had an insignificant effect on swelling of the alloys.

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. Moreover, vanadium-base alloys can withstand a higher surface-heat flux than steels because of their lower thermal stress factor. 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. In this paper, we present experimental results on the swelling of several vanadium-base alloys after irradiation at 420 and 600°C to neutron fluences ranging from \(0.3 \times 10^{27}\) neutrons/m² (17 to 114 atom displacements per atom [dpa]).

MATERIALS AND PROCEDURES

Vanadium alloys with the compositions listed in Table 1 were obtained in the form of 50% cold-worked sheets. Disc-shape specimens with \(\approx 3.0\) mm diameter and \(\approx 0.3\) mm thickness were obtained from the cold-worked sheet for the swelling determinations.
### Table 1
Vanadium and Vanadium Alloy Composition

<table>
<thead>
<tr>
<th>ANL I.D.</th>
<th>Nominal Alloy Composition (wt.%&lt;sup&gt;b&lt;/sup&gt;)</th>
<th>Concentration (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>O</td>
</tr>
<tr>
<td>BL-1</td>
<td>V-4Mo</td>
<td>230</td>
</tr>
<tr>
<td>BL-2</td>
<td>V-9W</td>
<td>300</td>
</tr>
<tr>
<td>BL-3</td>
<td>V-12Ni</td>
<td>490</td>
</tr>
<tr>
<td>BL-4</td>
<td>V-10Cr</td>
<td>530</td>
</tr>
<tr>
<td>BL-5</td>
<td>V-14Cr</td>
<td>330</td>
</tr>
<tr>
<td>BL-10</td>
<td>V-15Ti-7.5Cr</td>
<td>1110</td>
</tr>
<tr>
<td>BL-11</td>
<td>V-5Ti</td>
<td>1820</td>
</tr>
<tr>
<td>BL-12</td>
<td>V-10Ti</td>
<td>1670</td>
</tr>
<tr>
<td>BL-13</td>
<td>V-14Ti</td>
<td>1580</td>
</tr>
<tr>
<td>BL-15</td>
<td>V-18Ti</td>
<td>830</td>
</tr>
<tr>
<td>BL-16</td>
<td>V-20Ti</td>
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<tr>
<td>BL-20</td>
<td>V</td>
<td>570</td>
</tr>
<tr>
<td>BL-24</td>
<td>V-15Cr-5Ti</td>
<td>1190</td>
</tr>
<tr>
<td>BL-25</td>
<td>V-14Cr-0.3Ti</td>
<td>390</td>
</tr>
<tr>
<td>BL-26</td>
<td>V-14Cr-1Ti</td>
<td>560</td>
</tr>
<tr>
<td>BL-27</td>
<td>V-3Ti-1Si</td>
<td>210</td>
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<tr>
<td>BL-28</td>
<td>Vanstar-7&lt;sup&gt;c&lt;/sup&gt;</td>
<td>275</td>
</tr>
<tr>
<td>BL-34</td>
<td>V-9Ti</td>
<td>990</td>
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<tr>
<td>BL-35</td>
<td>V-10Cr</td>
<td>340</td>
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<td>BL-36</td>
<td>V</td>
<td>810</td>
</tr>
<tr>
<td>BL-42</td>
<td>V-3Ti-1Si</td>
<td>580</td>
</tr>
<tr>
<td>BL-43</td>
<td>V-10Cr-5Ti</td>
<td>230</td>
</tr>
</tbody>
</table>

<sup>a</sup>Chemical analyses of these materials were performed by the Analytical Department of the Teledyne Wah Chang Albany Company, Albany, OR.
<sup>b</sup>Complete analyses for these materials are presented in Reference 6.
<sup>c</sup>V-9Cr-3Fe-1Zr.

The cold-worked specimens were annealed at either 1125, 950, or 850°C for 1 h in an ion-pumped vacuum system with a typical pressure of 1.3 x 10^-6 Pa. Specimens annealed at 1125°C had an average recrystallized grain diameter of 0.020 mm. In this paper, specimens that were annealed at 950 and 850°C are termed 'partially annealed'. In addition to these annealed and 'partially annealed' specimens, annealed specimens with 10% cold-work were also prepared. The specimens were irradiated in the Materials Open Test Assembly (MOTA) of the Fast Flux Test Facility (FFTF) reactor at Richland, Washington. They were contained in sealed, Li⁷-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 and 600°C to neutron fluences (E > 0.1 MeV) ranging from 0.3 x 10²⁷ neutrons/m² (17 dpa) to 1.9 x 10²⁷ neutrons/m² (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 NH₃ 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 determination of the density of an unirradiated specimen (D_{ann}) and the density (D_{irr}) 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.

EXPERIMENTAL RESULTS

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 and V-Ti alloys on irradiation damage (dpa) at 420°C is shown in Fig. 3. These results show that V and V-3Ti-1Si exhibit a maximum swelling (-3%) at 60-80 dpa, whereas swelling of V-(5-20)Ti alloys is relatively independent of irradiation damage.

The dependence of swelling of V-Cr-Ti alloys on irradiation damage (dpa) at 420°C is shown in Fig. 4. These results show that on irradiation at 420°C V-Cr binary alloys have maximum swelling at ~30 dpa whereas V-15Cr-(1-5) Ti alloys have maximum swelling at 60-80 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. 5. Swelling data obtained from transmission electron microscopy (TEM) observations of the irradiated alloys are also shown in Fig. 5. On the basis of these data, the swelling of V-15Ti-7.5Cr, V-15Cr-5Ti, V-10Cr-5Ti, V-3Si-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.

Swelling of the "partial annealed" and 10% cold-worked V-Ti and V-Ti-Cr alloys was not significantly different from the swelling of "annealed" alloys.

CONCLUSIONS

Swelling of V-Cr-Ti alloys on neutron irradiation at 600°C is strongly dependent on Ti concentration.

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% Ti.

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 the vanadium alloys on irradiation at 420°C to 114 dpa is <0.02% per dpa.

Partial annealing and 10% cold-work have an insignificant effect on swelling of the vanadium alloys.

References


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

Fig. 2. Dependence of density change (swelling) on titanium concentration for vanadium alloys irradiated at 600°C to 77-84 dpa.
Fig. 3. Dependence of density change (swelling) on irradiation damage (dpa) for V and V-Ti alloys irradiated at 420°C.

Fig. 4. Dependence of density change (swelling) on irradiation damage (dpa) for V-Cr-Ti alloys irradiated at 420°C.

Fig. 5. Dependence of swelling of vanadium alloys at 600°C on irradiation damage.