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Effect of low temperature irradiation on the mechanical properties of ternary V–Cr–Ti alloys as determined by tensile tests and shear punch tests

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Abstract

Tensile tests and shear punch tests were performed on a variety of vanadium alloys that were irradiated in the Advanced Test Reactor (ATR) at temperatures between 200°C and 300°C to doses between 3 and 5 dpa. Tests were performed at room temperature and the irradiation temperature. The results of both the tensile tests and the shear punch tests show that following low temperature irradiation, the yield strength (YS) increased by a factor of 3–4 while the ultimate strength increased by a factor of approximately 3. Uniform elongation (UE) and tensile reduction in area show that the ductility diminishes following irradiation. The correlation between uniaxial ultimate strength and effective shear maximum strength was in excellent agreement with previous studies on other materials. Using the room temperature test data, the correlation between uniaxial YS and effective shear YS was in excellent agreement with previous studies on other materials.

1. Introduction

Vanadium-base alloys are considered to be attractive candidates for low activation structural materials in future fusion power devices. Most attention is currently focused on V–Cr–Ti alloys because of their relatively attractive mechanical properties after irradiation at relatively high temperature and because these alloys are resistant to void swelling [1]. Recent studies at lower temperatures, however, have shown significant degradation in mechanical properties during irradiation, with large increases in strength and large decreases in ductility observed following irradiation at temperatures below 400°C [2]. The purpose of the current work is to provide further data on the change in mechanical properties of V–Cr–Ti alloys following low temperature irradiation. Mechanical properties were determined from tensile tests and shear punch tests; the latter is a transmission electron microscopy (TEM) disk-based test developed to provide strength and ductility information [3–9]. This experiment is the first in which the tensile–shear punch correlation work has been extended to an irradiated bcc material, and it is for the first time that the viability of the correlation has been evaluated extensively at elevated test temperatures.

2. Experimental procedure

The alloys of interest were V–3Cr–3Ti, V–4Cr–4Ti, V–5Cr–5Ti and V–6Cr–3Ti. These alloys will be referred to as V33, V44, V55, and V63, respectively. All were annealed at 1000°C prior to irradiation for either 1 h (V44 and V55) or 2 h (V33 and V63). These alloys were irradiated as both tensile and TEM specimens in the Advanced Test Reactor (ATR) in the A1 experiment at nominal temperatures of 200°C and 300°C to doses between 3 and 5 dpa [10]. As ATR is a mixed spectrum reactor, the specimens were irradiated in lithium-bonded subcapsules that were shielded to reduce the number of thermal neutrons. Actual irradiation temperatures and doses for the TEM specimens were 205°C (3 dpa) and 293°C (4.7 dpa). The V33 tensile specimens were irradiated at 205°C (3 dpa) and 295°C (3 dpa), while the V44

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and V55 tensile specimens were irradiated at 229°C (3.5 dpa) and 293°C (4.7 dpa).

The tensile specimens, cut from sheet stock by electro-discharge machining (EDM), were S1 miniature specimens with nominal gauge dimensions of 5 mm × 1.2 mm × 0.25 mm (0.2 in. × 0.05 in. × 0.010 in.). Specimen thickness ranged from 0.25 to 0.36 mm (0.010–0.014 in.) between the alloys, but for any one alloy, the specimen thickness was uniform across the specimen to within 0.01 mm (0.0005 in.). Tensile tests were performed at a cross-head speed of 0.127 mm/min (0.005 in./min), resulting in an initial strain rate of 4×10^{-4}/s. For each irradiation condition, tests were performed at the actual irradiation temperature and at room temperature. Room temperature tests were performed in air. Specimens tested at elevated temperature required about 90 min for heat-up and stabilization prior to testing in static argon. One test was performed for each alloy/irradiation condition.

The 0.2% offset yield strength (YS), ultimate tensile strength (UTS), and uniform and total elongations (UE and TE, respectively) were obtained by the usual methods. Reduction of area (RA) measurements were obtained by calibrated digital analysis of SEM photomicrographs taken from one of each of the tensile specimen fracture surfaces.

Shear punch tests were performed by methods described elsewhere [3–9] using standard 3 mm diameter TEM disks of the same thickness as the tensile specimens. The specimen thickness was uniform across the TEM disk to within 0.005 mm (0.0002 in.). The TEM disks were also cut from sheet stock by the EDM method. Tests were performed at a cross-head speed of 0.127 mm/min (0.005 in./min). Specimen displacement during a test was assumed to be equal to cross-head displacement. For each irradiation condition, tests were performed at the actual irradiation temperature and at room temperature. Room temperature tests were performed in air. Specimens tested at elevated temperature required about 90 min for heat-up and stabilization prior to testing in slowly flowing argon. One test was performed for each alloy/irradiation condition.

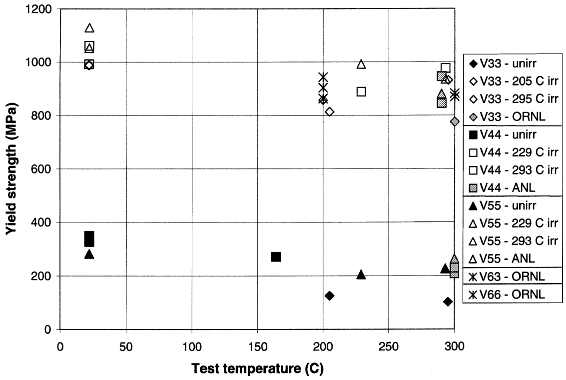

Fig. 1. Yield strength of vanadium alloys irradiated in ATR. Note that the ORNL and ANL data were obtained on specimens irradiated and tested at essentially identical conditions to those considered in this work.

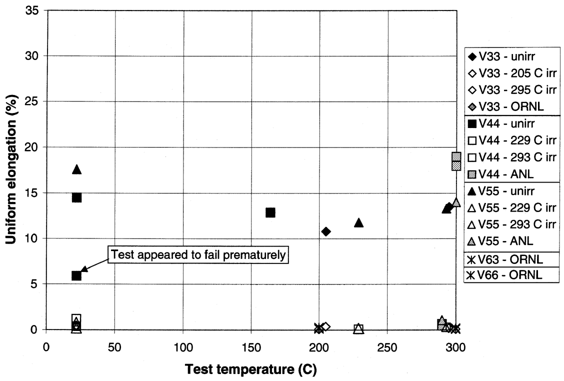

Fig. 2. Uniform elongation of vanadium alloys irradiated in ATR. Note that the ORNL and ANL data were obtained on specimens irradiated and tested at essentially identical conditions to those considered in this work.

3. Results

3.1. Tensile data

The tensile results are shown in Figs. 1 and 2 (YS and UE) along with other vanadium alloy tensile data that were generated in this same experiment by researchers at ANL and ORNL [11,12]. Ultimate strength and TE behaved similarly but are not shown due to space limitations. Significant strengthening was observed in the V33, V44, and V55 alloys following irradiation at both temperatures (recall that tensile specimens of the V63 alloy were not irradiated). YS typically increased by at least a factor of 3–4, and UE decreased typically to less than 1%. No significant differences in mechanical properties were observed between alloys. As shown in the figures, these results are very consistent with the vanadium tensile data generated by the ANL and ORNL researchers [11,12]. Irradiation also caused significant changes in RA as well, with the RA dropping from the unirradiated value of about 90–95% to an RA of 60–70% for most tests after irradiation at ~200°C and to an RA of 5–30% for most tests after irradiation at ~300°C.

3.2. Shear punch data

Effective shear strength data exhibited the same trends in strength as observed in the tensile data, i.e., significant strengthening occurred at all temperatures for all alloys. The strength derived from the shear punch data also showed the same test temperature-dependence observed in the tensile data. The effective shear stress data indicate that the V63 alloy behaved similarly to the other three alloys.

4. Discussion

4.1. Tensile and shear punch data

The tensile traces from the unirradiated material exhibited both a yield plateau (or evidence of a yield plateau for those tests where the phenomenon was less distinct) and serrated yielding at all test temperatures. The corresponding shear punch traces exhibited neither of these phenomena. However, in tests of other materials such as low carbon steels and aluminum alloys, the fine detail observed in tensile tests, such as a Luders plateau or serrated yielding, has been observed in corresponding shear punch tests. Both tensile and shear punch traces from unirradiated specimens exhibited a large amount of plastic deformation. The UTS was typically 40–60% higher than the YS in both types of tests for the unirradiated condition.

The tensile traces obtained from the irradiated specimens exhibited none of the features observed in the traces from the unirradiated specimens. The load increased rapidly to the maximum value with very little work hardening; the UTS was generally within a few percent of the YS. The test traces from irradiated specimens typically exhibited relatively sharp 'peaks' at maximum load and since no serrations or yield plateaus were observed, it appears that the irradiation-induced defects were much more effective than interstitial atmospheres at pinning dislocations. These features in the tensile traces suggest that dislocation channeling is the prevalent deformation mechanism in the irradiated alloys, although this has not yet been verified with electron microscopy.

While UE was consistently very low, and exhibited no variation with irradiation temperature, RA exhibited a significant difference with irradiation temperature, being consistently much lower after irradiation at about ~300°C. This suggests that although neither YS nor UE varied significantly with irradiation temperature, one might expect that the fracture toughness of these alloys after irradiation at ~300°C would be much lower than after irradiation at ~200°C.

4.2. Tensile–shear punch correlation

While the irradiation temperature and dose received by the TEM specimens was often significantly different than that for the corresponding tensile specimens, it was judged worthwhile to construct a correlation between uniaxial and effective shear yield and maximum strengths. The uniaxial yield and the effective shear YS data are compared in Fig. 3. Two linear regression lines are shown for the YS correlation in Fig. 3. One is the fit to all the data, while the other is the fit to just the room temperature data. Both correlations have nearly the same slope, and the slope is in good agreement with previous correlations on other unirradiated and irradiated materials [4,6–9]. However, as is evident in Fig. 3, the tensile and shear punch data obtained from elevated temperature tests do not fall on the same line as the data obtained from room temperature tests. An examination of both the tensile and the shear punch test traces revealed that the shear punch traces obtained from elevated temperature tests exhibited a very smooth transition from linear elastic to plastic behavior making it difficult to exactly define the yield point. In keeping with the standard method of choosing the yield point as the deviation from linearity, the yield point was taken as the earliest discernable deviation from linearity, which resulted in low values for the effective shear yield stress.

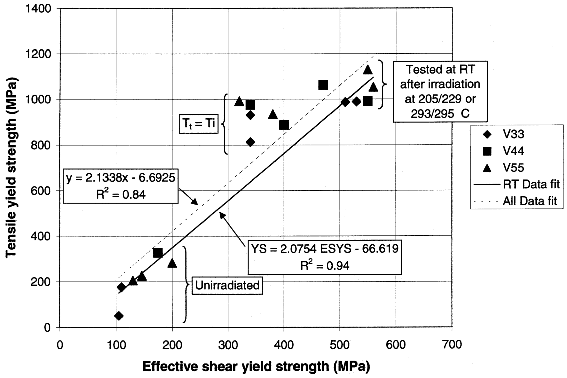

Fig. 3. Correlation between tensile yield and effective shear yield strength for vanadium alloys irradiated in ATR.

The reason for the smooth transition from linear elastic to plastic behavior is not understood at this time. It has been suggested that an offset effective shear yield stress be used in a manner analogous to the 0.2% offset YS. This was investigated, and due to the geometry of the deformation zone of the shear punch test, a 0.2% offset shear strain is equivalent to only a fraction of the width of the trace line. Thus, such an offset would have no effect on the measurement of the effective shear YS value.

The correlation for maximum strength, as shown in Fig. 4, is in excellent agreement with previous maximum strength correlations obtained from unirradiated and irradiated materials, and as with previous correlation studies, the maximum strength correlation clearly exhibits less scatter than the YS correlation [4,6–9]. Unlike the YS correlation, there is no stratification of the values

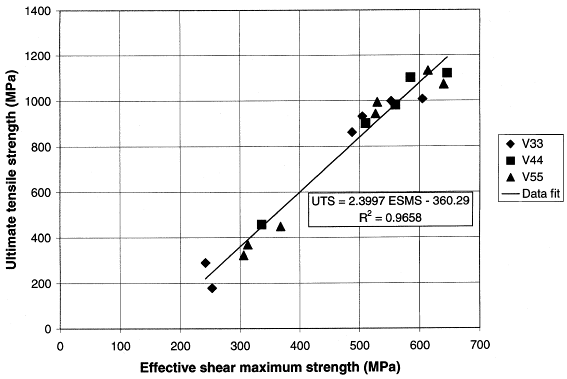

Fig. 4. Correlation between maximum tensile and effective shear maximum strength for vanadium alloys irradiated in ATR.

obtained at room temperature and at elevated temperature.

5. Summary and conclusions

Tensile and shear punch tests on vanadium alloys irradiated in ATR at ~200–300°C to 3–5 dpa indicate that significant strengthening and loss of ductility occur after a small amount of low temperature irradiation and also indicate that both the yield and ultimate strength at the irradiation temperature are slightly lower than at room temperature. RA is significantly lower following irradiation at ~300°C than at ~200°C. No significant difference in mechanical properties was observed between V33, V44, V55 and V63. The tensile–shear punch relationship for the ultimate strength was in excellent agreement with previous correlations on other materials. A YS correlation based only on room temperature tensile and shear punch tests is in excellent agreement with previous correlations on other materials, although the data points obtained at elevated temperatures do not lie on the linear trend line established by the room temperature tests.

Acknowledgements

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