STRAIN RATE DEPENDENCE OF THE TENSILE PROPERTIES OF V-(4-5%)Cr-(4-5%)Ti IRRADIATED IN EBR-II AND HFBR — S. J. Zinkle, L. L. Snead, J. P. Robertson and A. F. Rowcliffe (Oak Ridge National Laboratory)

OBJECTIVE

The objective of this report is to summarize recent data on the effect of strain rate on the temperature-dependent tensile properties of neutron-irradiated V-(4-5)Cr-(4-5)Ti.

SUMMARY

Elevated temperature tensile tests performed on V-(4-5)Cr-(4-5)Ti indicate that the yield stress increases with increasing strain rate for irradiation and test temperatures near 200°C, and decreases with increasing strain rate for irradiation and test temperatures near 400°C. This observation is in qualitative agreement with the temperature-dependent strain rate effects observed on unirradiated specimens, and implies that some interstitial solute remains free to migrate in irradiated specimens. Additional strain rate data at different temperatures are needed.

PROGRESS AND STATUS

Introduction

One of the common features in the load-elongation curve of body-centered cubic tensile specimens is the appearance of serrations in the work-hardening portion of the curve at elevated test temperatures. Numerous studies have concluded that this "dynamic strain aging" effect is associated with the migration of interstitial solute atoms to dislocations during the deformation (e.g., refs. 12-18 in ref. [1]). In vanadium and vanadium alloys, dynamic strain aging is observed at temperatures above ~300°C for typical tensile test strain rates of ~10^{-4} to 10^{-3} s^{-1} [1,2]. At low test temperatures and high strain rates, where dynamic strain aging is not observed due to the limited migration of interstitial solute atoms, the yield and ultimate strength increase with increasing strain rate, i.e., the hardening strain rate exponent is positive. The appearance of dynamic strain aging at high temperatures is accompanied by a shift in hardening strain rate exponent to negative values.

Figure 1 shows the results of some recent strength measurements on unirradiated type SS-3 sheet tensile specimens of the U.S. fusion program heat of V-4Cr-4Ti (heat #832665) tested at different strain rates and temperatures [3]. At room temperature, the tensile strength (measured at 8% strain) increased monotonically with increasing strain rate between 10^{-4} and 1 s^{-1}. The value of the hardening strain rate exponent at 25°C was m = 0.024, where m is defined by [4]

$$m = \frac{1}{\sigma}\frac{\partial \sigma}{\partial \ln \dot{\varepsilon}} \qquad (1)$$

where σ is the stress and $\dot{\varepsilon}$ is the strain rate. Conversely, at temperatures ≥400°C, the tensile strength *decreased* monotonically with increasing strain rate between 10^{-5} and 10^{-1} s^{-1}. The value for the strain rate exponent ranged from m = - 0.013 at 400°C to m = - 0.025 at 600°C. Tensile tests performed at 300°C clearly showed the transition from negative to positive strain rate exponents as the strain rate was increased above 10^{-3} s^{-1}. Similar temperature-dependent behavior was also observed for the lower yield point strain rate exponent. Strain rate experiments were performed on several neutron-irradiated V-(4-5)Cr-(4-5)Ti tensile specimens in order to determine the magnitude of the strain rate exponent at temperatures above and below 300°C.

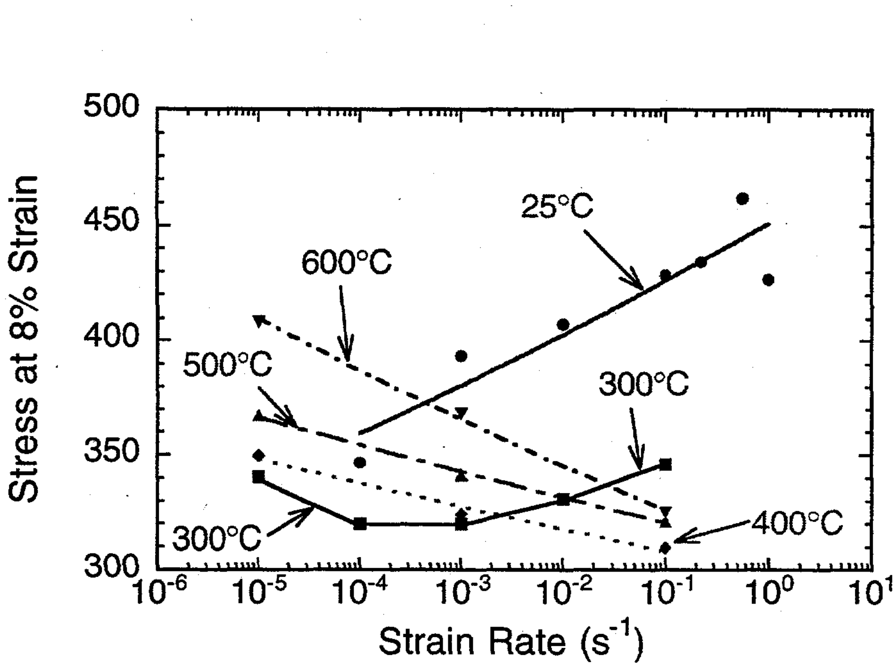

Fig. 1. Effect of strain rate on the tensile strength (measured at 8% strain) of V-4Cr-4Ti tested at temperatures between 25 and 600°C [3]. The curves for data obtained at 25°C and 400-600°C are least square fits using equation 1.

Experimental Procedure

Type SS-3 sheet tensile specimens (nominal gage dimensions 0.76 × 1.52 × 7.6 mm) from two recent neutron irradiation experiments [5,6] were selected for the strain rate study. The first set of specimens were fabricated from the 500 kg US fusion program heat of V-4Cr-4Ti (heat 832665) and were irradiated at 200°C to a dose of 0.5 dpa in the High Flux Beam Reactor [5]. The second set of specimens were fabricated from mill-annealed (1050°C) or cold-rolled and annealed (1050°C) plates of the BL-63 heat of V-5Cr-5Ti, and were irradiated at 400°C to a dose of 4 dpa in the EBR-II X530 irradiation experiment [6]. Following irradiation, the specimens were tensile tested in vacuum ($<2.5 \times 10^{-6}$ torr) at the irradiation temperature at constant crosshead speeds ranging from 0.025 to 12.7 mm/minute, which corresponds to initial strain rates of 5.6×10^{-5} to 0.028 s^{-1}. Further experimental details are given elsewhere [5,6].

Results and Discussion

The tensile properties of the irradiated V-(4-5)Cr-(4-5)Ti specimens tested at different strain rates are listed in Table 1. The relatively low irradiation temperatures used for this study caused considerable radiation hardening with an accompanying reduction in strain hardening capacity at all strain rates investigated. The uniform elongation in the specimens irradiated at 200 and 400°C were ~0.1 and 1% , respectively, which may be compared to the unirradiated uniform elongations in these alloys of15-20% at 200-400°C. The tensile curves in the specimens irradiated at 200°C were characterized by a yield peak at elongations <0.2%, followed by a monotonically decreasing engineering stress with increasing elongation. A significant change in the slope of the engineering stress-strain curve in these specimens occurred at elongations of ~0.2-0.4% and this
Table 1. Summary of strain rate data on irradiated V-(4-5)Cr-(4-5)Ti specimens. The yield strength was determined at 0.2% plastic offset for the specimens irradiated at 400°C, whereas the lower yield point was used for the specimens irradiated at 200°C. The specimens labeled "63C" were cold-rolled and annealed at 1050°C prior to irradiation.

Specimen ID, dpa, T_{irr}	Test conditions	Yield strength	Ultimate strength	Uniform elongation	Total elongation
WH11, 0.5dpa, 203°C	200°C, 5.6×10^{-5} s^{-1}	587 MPa*	612 MPa[a]	0.1%	9.0%
WH08, 0.5dpa, 203°C	200°C, 1.1×10^{-3} s^{-1}	580 MPa*	650 MPa[a]	0.05%	9.4%
WH02, 0.5dpa, 207°C	200°C, 1.1×10^{-3} s^{-1}	603 MPa*	652 MPa[a]	0.05%	8.7%
WH10, 0.5dpa, 203°C	200°C, 0.028 s^{-1}	605 MPa*	656 MPa[a]	<0.1%	9.3%
WH03, 0.5dpa, 207°C	20°C, 1.1×10^{-4} s^{-1}	655 MPa*	672 MPa[a]	0.67%	10.3%
WH01, 0.5dpa, 207°C	20°C, 1.1×10^{-3} s^{-1}	657 MPa*	732 MPa[a]	<0.1%	9.9%
63C10/12,4dpa, 400°C	400°C, 5.6×10^{-5} s^{-1}	734 MPa	793 MPa	1.4%	7.9%
63C10/11, 4dpa, 400°C	400°C, 1.1×10^{-3} s^{-1}	723 MPa	765 MPa	0.95%	7.0%
63/4, 4dpa, 400°C	400°C, 1.1×10^{-3} s^{-1}	733 MPa	774 MPa	1.2%	7.3%
63/5, 4dpa, 400°C	400°C, 0.028 s^{-1}	734 MPa	775 MPa	1.1%	6.0%

*lower yield point

[a]upper yield point

was defined to be the location of the lower yield point, as discussed elsewhere [5]. Yield drops were not observed in the specimens irradiated to 4 dpa at 400°C.

From inspection of Table 1, the lower yield point and the ultimate strength of the specimens irradiated to 0.5 dpa at 200°C exhibited a slightly positive strain rate exponent. The magnitude of the irradiated strain rate exponent at 200°C was considerable smaller than that observed at room temperature in unirradiated specimens (Fig. 1). Conversely, the 0.2% yield strength and ultimate strength of the specimens irradiated to 4 dpa at 400°C were nearly independent of strain rate or exhibited a slightly negative strain rate exponent. This behavior at 400°C is qualitatively similar to that observed in unirradiated specimens, although the magnitude of the negative strain rate exponent appears to be considerably reduced in the irradiated specimens. The value of the irradiated strain rate exponent varied from $m=0.011$ at 200°C to $m= -0.004$ at 400°C. The irradiated ultimate tensile strength data are plotted in Figure 2 along with some recent data obtained on the 500 kg heat of V-4Cr-4Ti following neutron irradiation to ~5 dpa at 330°C [7]. The data by van Osch [7] suggest that the irradiated strain rate exponent does not become negative for temperatures at least as high as 330°C, in contrast to the unirradiated behavior where the strain rate exponent became negative at temperatures above 300°C.

The appearance of a negative strain rate exponent is an indication of a significant interstitial solute concentration in the matrix which is free to migrate to dislocations during tensile testing. This implies that some of the C, O, N solute in the irradiated V-Cr-Ti alloys remains dissolved in the matrix and is not contained in titanium oxycarbonitride precipitates or solute-point defect clusters. It is interesting to note that the apparent change in the strain rate exponent from positive values to negative values at temperatures above ~330°C in the irradiated specimens occurred even though serrated stress-strain behavior was not observed in the stress-strain curve (due to the low strain hardening capacity in the irradiated specimens). The magnitude of the irradiated strain rate exponent at 200°C is smaller than the room temperature unirradiated value, which may be due to the effect of point defect clusters on the strain rate dependence [8]. Defect clusters exhibit a positive strain rate exponent, and would be included in the experimentally measured strain rate exponent of irradiated materials. The positive defect cluster strain rate term may also be partially responsible for the small negative strain rate exponent observed in the vanadium alloys

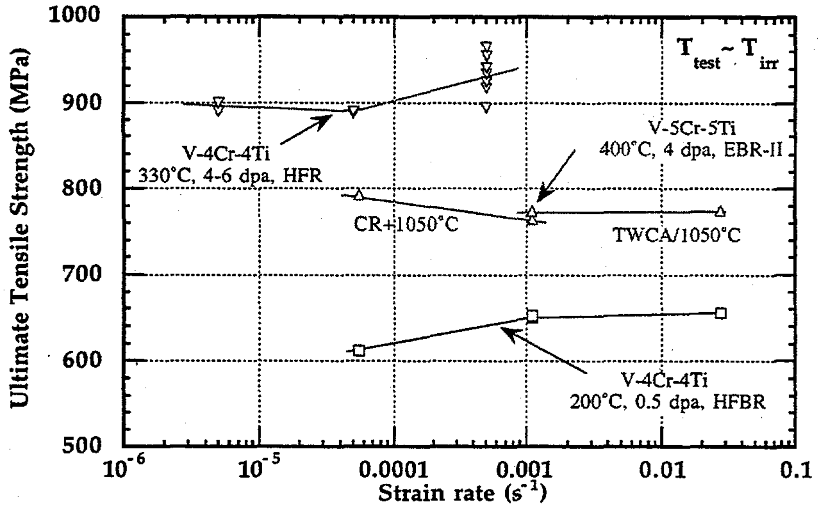

Fig. 2. Effect of temperature (T_{test}~T_{irr}) and strain rate on the tensile strength of neutron-irradiated V-(4-5)Cr-(4-5)Ti tensile specimens. Data obtained by van Osch [7] on round (4 mm diam.) tensile specimens are also included in this plot.

irradiated and tested at 400°C. Interstitial solute bound to defect clusters or small precipitates would also decrease the magnitude of the strain rate exponent at 400°C.

Additional strain rate data on irradiated specimens are clearly needed in order to establish the behavior of the strain rate exponent behavior as a function of irradiation temperature and dose. Such strain rate investigations (performed at different test temperatures) would provide useful information on the barrier strengths of defect clusters in irradiated vanadium alloys [8].

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