ROOM TEMPERATURE COMPRESSION PROPERTIES OF TWO HEATS OF UNIRRADIATED V-4Cr-4Ti—M. B. Toloczko (Pacific Northwest National Laboratory)* and R. J. Kurtz (Pacific Northwest National Laboratory)*

OBJECTIVE

Cylindrical specimens fabricated from Heat 832665 (US Heat) of V-4Cr-4Ti and from Heat P8013 (NIFS-2 Heat) of V-4Cr-4Ti were tested in compression at room temperature on a screw-driven test frame. The average value of the yield strength was 344 MPa for the US Heat and 315 MPa for the NIFS-2 Heat. The average strain hardening exponent calculated from the first few percent of plastic strain was about 0.17 for both the US Heat and the NIFS-2 heat. As is common in a compression test, the specimens barreled somewhat during the tests.

PROGRESS AND STATUS

Introduction

Vanadium alloys are of interest to the Fusion program as potential first wall structural materials. The expected irradiation conditions for the first wall structural material include a range of temperatures where very high hardening caused by a high density of small, but shearable defect clusters results in a type of deformation called "localized deformation". At the onset of yield in a tensile test, a dislocation may move through a grain shearing the obstacles and clearing out a channel. Subsequent dislocations may easily pass through this channel. As the test progresses, more channels form. In the early stages of deformation, it is thought that the plastic deformation is confined to these channels. One important macroscopic result of this deformation behavior is rapid onset of necking in a tensile test and very low uniform elongation. As a means to help understand the range of stress states where localized deformation may adversely affect macroscopic ductility in vanadium alloys, compression test specimens fabricated from two heats of V-4Cr-4Ti are currently under irradiation in the High Flux Isotope Reactor (HFIR). The results of room temperature compression tests on the unirradiated control materials are presented here and compared with uniaxial tensile values from the literature.

Experimental Procedure

Heat 832665 (US Heat), and Heat P8013 (NIFS-2 Heat) were utilized. The US Heat was received in the form of thirty 3.0 mm diameter by 6.6 mm long cylinders electro-spark machined (EDM'ed) from a 40% cold-worked plate (called the R-plate). The NIFS-2 Heat was received in the form of a ~4 mm thick plate in a 98% cold-rolled condition. 3.0 mm diameter by 3.5 mm long specimens were EDM'ed from the plate. A limitation of the EDM process is that a small ridge is left running down the length of the specimens. This ridge was machined off. The US specimens were reduced in length to 3.5 mm, and the ridge on these samples was also removed. Specimen IDs were then laser engraved. After machining and engraving, the compression specimens were ultrasonically cleaned in methanol followed by ethanol, and then the specimens were loosely wrapped in tantalum and then titanium foil. (Foils were also cleaned in methanol and ethanol.) The foil packets were placed in a vacuum furnace and heat treated at 1000°C for 2 h at better than 1×10^{-6} torr.

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Compression tests were performed in a 10,000 lb screw-driven Instron test frame with a 1000 lb load cell. A special compression test fixture, as shown in Fig. 1, was constructed for the testing. The upper and lower loading surfaces of the fixture are made from a high modulus tungsten carbide composite with a polished surface. The upper loading surface is in the form of a piston which is guided by a cylinder made from a machineable carbide composite. A tight tolerance was maintained between the piston and cylinder to limit axial misalignment between the upper and lower loading surfaces. For these room temperature tests, the upper and lower loading surfaces were lubricated with a thin later of a light machine oil. (Tests performed without lubricant resulted in significantly greater specimen barreling.) Tests were run at an initial strain rate of $5x10^{-4}$ sec^{-1}. Specimen displacement was monitored with a capacitance-type displacement transducer with a resolution better than 0.0002 mm (better than 0.006% strain). The transducer directly monitors the displacement between the upper and lower loading surfaces. Data were recorded electronically. Yield strength (YS) measurement and curve fits to the plastic strain data were done by hand. Three tests each were done on the two heats.

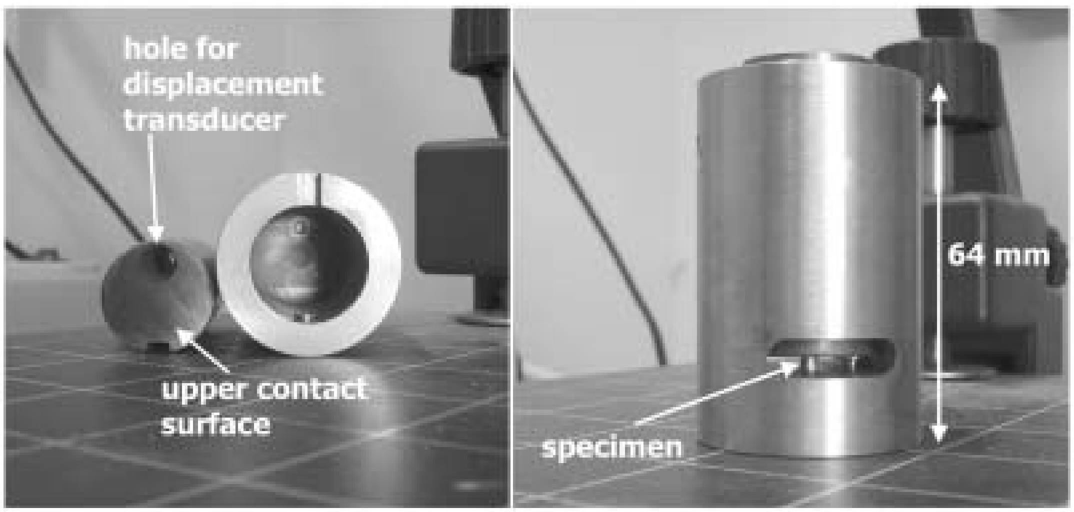

Fig. 1. Picture of the compression test fixture used for the tests.

Results and Discussion

The specimens deformed predictably with some amount of barreling occurring as shown in Fig. 2. Typical engineering stress versus engineering strain plots for the US Heat and the NIFS-2 Heat are shown in Fig. 3 The Young's modulus of vanadium is around 130 GPa. The slope of the linear loading region varied from 37 GPa to 48 GPa indicating some load train elasticity is present in the displacement measurement. Both heats show a smooth transition into plastic deformation, and upper/lower yield point behavior is apparent. The 0.2% strain offset line almost exactly intersected the upper yield point, so the two stress values are equivalent here. Yield strength values are shown in Table 1. For each heat, the YS values are consistent, with a spread in the three tests of no greater than 10 MPa (3% of the YS value). Strain hardening exponents were also measured. Examples of curve fits to the true stress versus true plastic strain plots are shown in Fig. 4. From these curve fits, strain hardening exponents were calculated assuming the material obeys power law strain hardening (PLSH) behavior ($\sigma = k\varepsilon^n$). Because of barreling, these are not exact true stress and true plastic strain values, but the curves nevertheless serve as a means to estimate the strain hardening coefficient. Curve fits were done either in the range of 1% to 2% true plastic strain, 4% to 6% true plastic strain, or 6% to 11% true plastic strain. The curve fits were confined to ranges of plastic strain (rather than the entire curve) because the true stress versus true strain curves do not obey the PLSH equation over the entire range. The strain hardening exponents calculated from these curve fits are shown in Table 1. As with the YS measurements, the strain hardening exponents over any particular range of strain had a low spread.

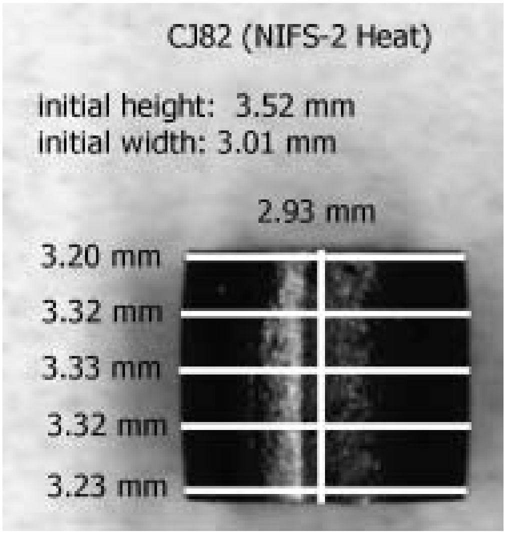

Fig. 2. Image of a specimen tested to 16% engineering strain. Some barreling is evident.

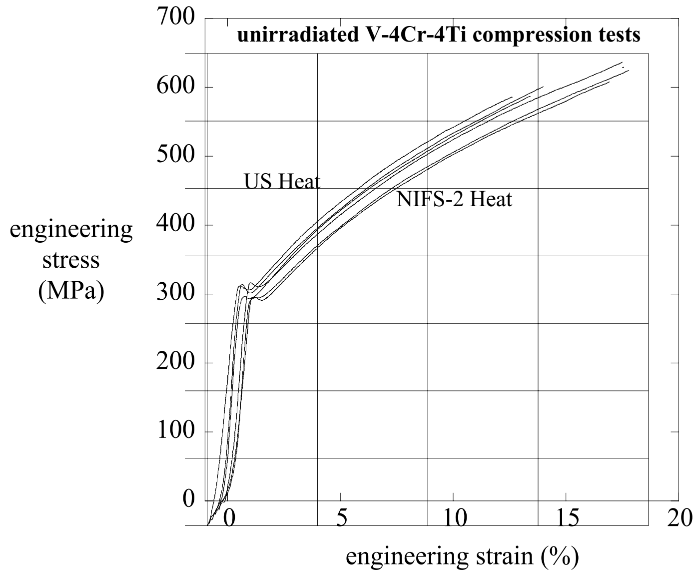

Fig. 3. Engineering stress versus strain plots for room Temperatuare compression tests of the US Heat and the NIFS-2 Heat of V-4Cr-4Ti in the unirradiated condition.

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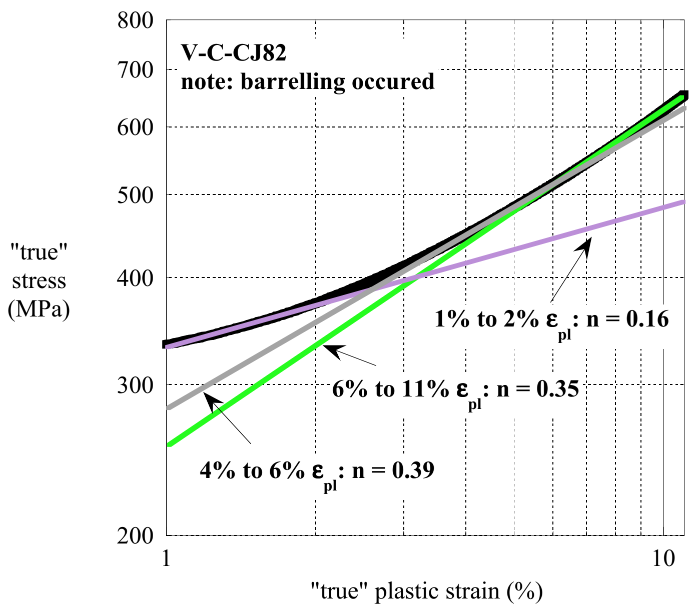

Fig. 4. Example of PLSH fits to the true stress versus true plastic strain compression test plots. Because of barreling, these are not exact true stress and true plastic strain values. The reader should note the logarithmic scales in this plot.

Table 1 -- Yield stress and strain hardening exponents found from the compression test curves

	Yield stress (MPa)				Strain hardening coefficient		
ID code	0.2% Offset strain	Upper yield point	Average	Ratio of US/Japan	1% ≤ ε_{pl} ≤ 2%	4% ≤ ε_{pl} ≤ 6%	6% ≤ ε_{pl} ≤ 11%
CA19*	340	340	344	1.09	0.17	0.34	0.40
CA25	348	348			0.17	0.34	0.40
CA28	344	344			0.16	0.33	0.40
CJ82†	320	320	315		0.16	0.34	0.39
CJ88	310	310			0.16	0.35	0.41
CJ99	315	315			0.17	0.37	0.42

* CA## = US Heat

† CJ## = NIFS-2 Heat

Uniaxial tensile data at 25°C from the literature shows a YS of about 315-355 MPa for the US Heat [1-3] and about 300 MPa for the NIFS-2 Heat [4]. The YS of the US Heat is stronger most likely because of the greater amount of oxygen in this material [5]. These tensile specimens received the same final heat treat that the compression specimens received. The YS values measured in compression are very close to the values measured in tension. The similarity between tension and compression is not unexpected because ductile polycrystalline materials with random grain orientation usually have an isotropic von Mises yield surface. If there were a significant difference between the tension and compression values, it would have likely been due to some difference in grain size or shape or orientation between the tensile and compression specimens.

For compression tests, it is useful to extract some measure of ductility that can be compared to ductility parameters from other tests. There is no uniform elongation in a compression test, but the strain hardening exponent can be measured (assuming the material obeys PLSH). In a tensile test, if the material obeys PLSH, then the strain hardening exponent will equal the true uniform elongation (TUE). This relationship can be used to compare the strain hardening exponent from compression tests to the TUE from tensile tests. Uniform elongation (UE) values in the literature for the US Heat are in the range of 16-18%[1-3]. Values for NIFS-2 Heat are not readily available, but values for NIFS-1 Heat are in the range of 18% [6]. These UE values from the literature are probably engineering values. TUE can be found from

$$\varepsilon_u = \ln(1 + e_u) \tag{1}$$

where e_u is the engineering value. A UE of 18% is equivalent to a TUE of about 16.5%. From Table 1, it can be seen that for the compression tests, the strain hardening exponent found from the range of 1% to 2% true plastic strain in the compression tests matches up well with the TUE obtained from the literature data on tensile properties. For strain hardening exponents measured by the authors on tensile data from a variety of materials [7] the best match between tensile strain hardening exponent and true uniform elongation (from the same tensile specimen) has occurred when the strain hardening exponent was measured at relatively high values of plastic strain. The situation is the exact opposite for the compression specimens. It is thought that barreling of the compression specimens affected the apparent true stress and true plastic strain behavior with the low range of plastic strain being the least affected, and thus, providing the strain hardening exponent that matches best with the true uniform elongation found from tensile data.

Barreling of the specimens was assessed by measuring radial displacement at regularly spaced intervals along the length of a tested sample and comparing these values to the radial displacement that would have occurred if the specimen had not barreled. The axial displacement and the volume of the sample can be used to find the "ideal" radius after deformation if the sample had not barreled:

$$r_{ideal} = \sqrt{\frac{V}{\pi h_f}} \tag{2}$$

where V is the volume of the specimen, and h_f is the final height of the tested specimen. The radial strain values at five positions along the length of one tested specimen are compared to the ideal radial displacement in Table 2. There is a several percent radial strain difference between the ends and the middle of the specimen. However, in the mid-region of the sample, the variation in radial strain is small, showing that the majority of the barreling occurred outside the middle section of the samples.

Table 2. Measured radius at positions along the length of one NIFS-2 sample after a compression test Measurement points are shown in Fig. 2.

Specimen CJ82		
Item	Radius (mm)	Strain (%)
calculated radius from measured axial strain and sample volume	**3.29**	**9.2**
measured radius at top of specimen	3.20	6.7
measured radius in top half of specimen	3.32	10.6
measured radius at mid-point of specimen	3.33	10.9
measured radius in bottom half of specimen	3.32	10.6
measured radius at bottom of specimen	3.23	7.7
average of the five measured values	**3.28**	**9.3**

The observed values of between 37 GPa and 48 GPa for the elastic loading slope was much lower than expected. It was thought that the position of the displacement measurement transducer in the compression test fixture would have eliminated any load train elasticity from the measurement. The cause of the low values will be investigated in the future.

The smooth curvature of the compression test traces around the upper/lower yield area is different from tensile tests on these materials. In the tensile tests, the initial yield point at room temperature is typically sharp. This is followed by a relatively small yield drop and propagation of a Lüders band at constant load. Consideration was first given to the possibility that a soft load train may have smoothed the appearance of the upper/lower yield point behavior in compression, but a review of the effects of machine stiffness on observed yield point behavior suggests that a soft load train would not cause this [8]. So, further consideration was given to the yield point phenomenon in compression and in tension. Presumably, during a tension test, yielding initiates at a stress concentration in the gauge section, and a sharp yield drop occurs as dislocations break free from their Cottrell atmosphere. Plastic deformation occurs in the vicinity of the stress concentration until the material hardens. During a compression test, a stress concentration may still form, but geometric hardening of the material due to plastic deformation in the region of the stress concentration may more rapidly strengthen this region and promote more homogeneous deformation throughout the sample.

Two heats of unirradiated V-4Cr-4Ti were tested in compression at room temperature. The yield strength in compression matched up well with the values for the same materials in tension, and the strain hardening exponent calculated from the first few percent of plastic strain matches up well with the uniform elongation values from tensile tests. Barreling, which typically occurs in a compression specimen, was observed in the vanadium samples.

Overall, the material behaved predictably, and these tests will serve as a reference for tests to be conducted in the future on irradiated vanadium compression specimens. The combined data from tensile and compression (and perhaps other test geometries) will be useful in determining the deformation behavior of vanadium under more complex loading conditions.

Future Work

Elevated temperature tests will be performed on unirradiated vanadium compression specimens. Compression tests will also be performed on the irradiated specimens when they become available.

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