THERMOPHYSICAL AND MECHANICAL PROPERTIES OF V-(4-5)%Cr-(4-5)%Ti ALLOYS — S.J. Zinkle (Oak Ridge National Laboratory)

OBJECTIVE

The objective of this report is to summarize available data on the thermophysical and mechanical properties of V-(4-5)Cr-(4-5)Ti alloys in order to provide a reference design basis for the Advanced Power EXtraction (APEX) project.

SUMMARY

Solid solution V-Cr-Ti alloys exhibit a good combination of high thermal conductivity, adequate tensile strength, and low thermal expansion. The key thermophysical and mechanical properties for V-(4-5)%Cr-(4-5)%Ti alloys are summarized in this report. Some of these data are available in the ITER Materials Properties Handbook (IMPH), whereas other data have been collected from recent studies. The IMPH is updated regularly, and should be used as the reference point for design calculations whenever possible.

PROGRESS AND STATUS

1. Ultimate tensile strength (unirradiated)

The ultimate tensile strength for the BL47 (30 kg) [1] and Teledyne Wah Chang #832665 (500 kg) [1-3] heats of V-4Cr-4Ti has been measured by several researchers. Figure 1 summarizes ultimate tensile strength (UTS) data obtained in tensile tests at strain rates near $1 \times 10^{-3}\ s^{-1}$ on annealed (1000-1100°C for 1 to 2 h) specimens in the longitudinal orientation. The data in refs. [1,2] were obtained on "type SS3" miniature sheet tensile specimens with gage dimensions of 0.76 x 1.52 × 7.6 mm, whereas the data in ref. [3] were obtained on round tensile specimens with gage dimensions of 4 mm diam × 20 mm. Good agreement was obtained for both types of specimen geometries over the investigated temperature range. The least squares fitted equation for the ultimate tensile strength over the temperature range of 20-700°C is

$$\sigma_{UTS}(\mathrm{MPa}) = 445.7 - 0.80616{*}T + 0.002211{*}T^2 - 1.7943\mathrm{e}{-06}{*}T^3 + 1.8176\mathrm{e}{-10}{*}T^4$$

where the temperature (T) is in °C. The correlation coefficient for the plotted data using this equation is R=0.76505. The relatively low value for the correlation coefficient is due to the limited number of tensile tests which have been performed on V-4Cr-4Ti.

2. Ultimate tensile strength (irradiated)

Neutron irradiation causes a large increase in the tensile strength of V-Cr-Ti alloys, particularly at temperatures below ~400°C. Figure 2 summarizes the tensile strength data for V-4Cr-4Ti irradiated to doses above 4 displacements per atom (dpa) [1,3-8]. It can be seen that the ultimate strength in the irradiated specimens is higher than that of unirradiated specimens (Fig. 1) over the investigated temperature range of 80-600°C. Generation of fusion-relevant amounts of helium (~4 appm He/dpa) appears to have a relatively minor effect on the ultimate tensile strength of vanadium alloys at temperatures between 420 and 600°C and doses up to 80 dpa [1,9-11].

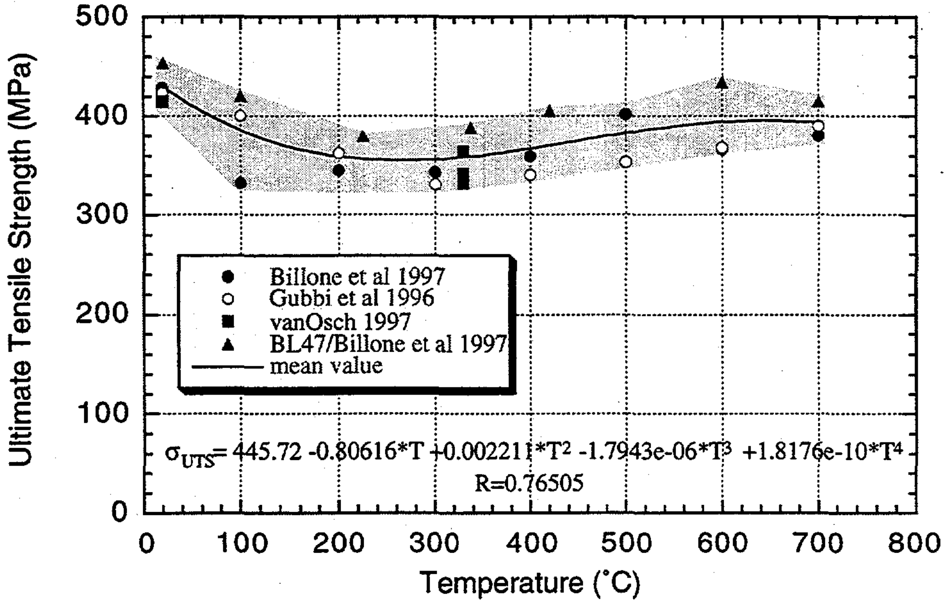

Fig. 1. Ultimate tensile strength of unirradiated V-4Cr-4Ti [1-3].

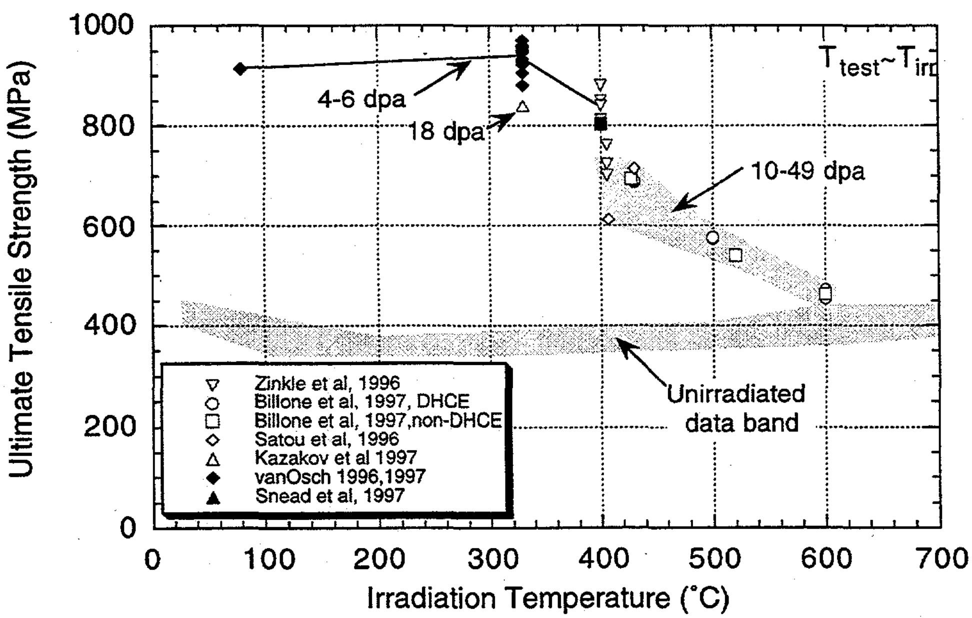

Fig. 2. Ultimate tensile strength of irradiated V-(4-5)%Cr-(4-5)%Ti alloys [1,3-8].

3. Yield strength (unirradiated)

Figure 3 summarizes the yield strength and uniform elongation data obtained in tensile tests at strain rates near $1 \times 10^{-3}\ s^{-1}$ on annealed (1000-1100°C for 1 to 2 h) specimens in the longitudinal orientation for two different heats of V-4Cr-4Ti. The data in refs. [1,2] were obtained on "type SS3" miniature sheet tensile specimens with gage dimensions of $0.76 \times 1.52 \times 7.6$ mm, whereas the data in ref. [3] was obtained on round tensile specimens with gage dimensions of 4 mm diam × 20 mm. Good agreement was obtained for both types of specimen geometries over the investigated temperature range. The least squares fitted equation for the yield strength over the temperature range of 20-700°C is

$$\sigma_Y(\mathrm{MPa}) = 377.2 - 0.70384{*}T + 0.00089973{*}T^2 - 1.2279\mathrm{e}{-}07{*}T^3 - 1.9824\mathrm{e}{-}10{*}T^4$$

where the temperature (T) is in °C. The correlation coefficient for the plotted data using this equation is R=0.9461.

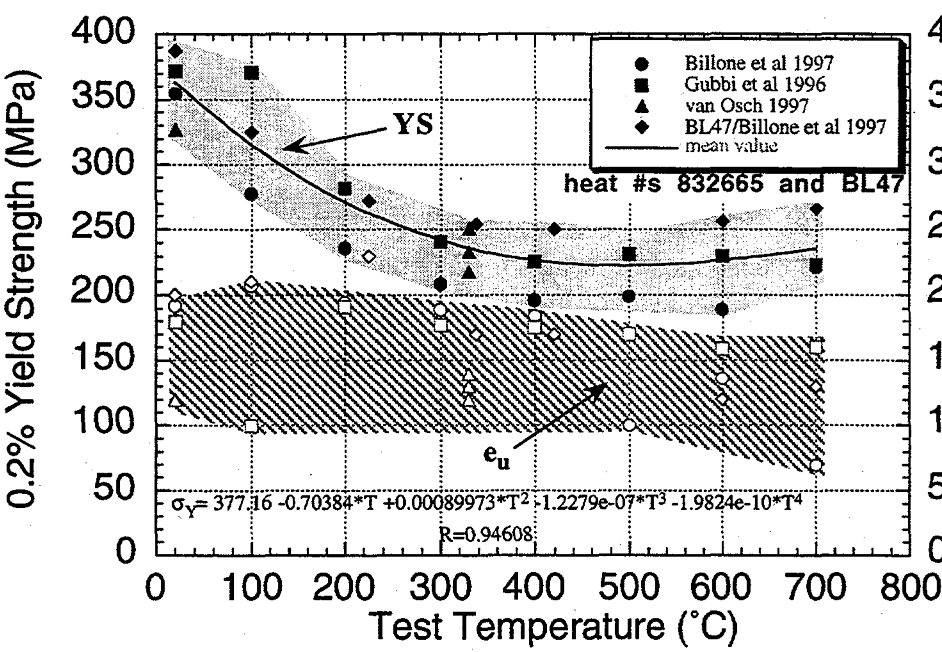

Fig. 3. Yield strength and uniform elongation of unirradiated V-4Cr-4Ti [1-3].

4. Yield strength (irradiated)

Neutron irradiation causes a pronounced increase in the yield strength of V-Cr-Ti alloys, particularly at temperatures below ~400°C. Figure 4 summarizes the yield strength and uniform elongation data for V-(4-5)%Cr-(4-5)%Ti alloys irradiated to doses above 4 dpa [1,3-8]. The yield strength in the irradiated specimens is significantly higher than that of unirradiated specimens (Fig. 3) over the investigated temperature range of 80-600°C. Fusion-relevant helium generation (~4 appm He/dpa) has a relatively minor effect on the yield strength of vanadium alloys at temperatures between 420 and 600°C and doses up to 80 dpa [1,9-11].

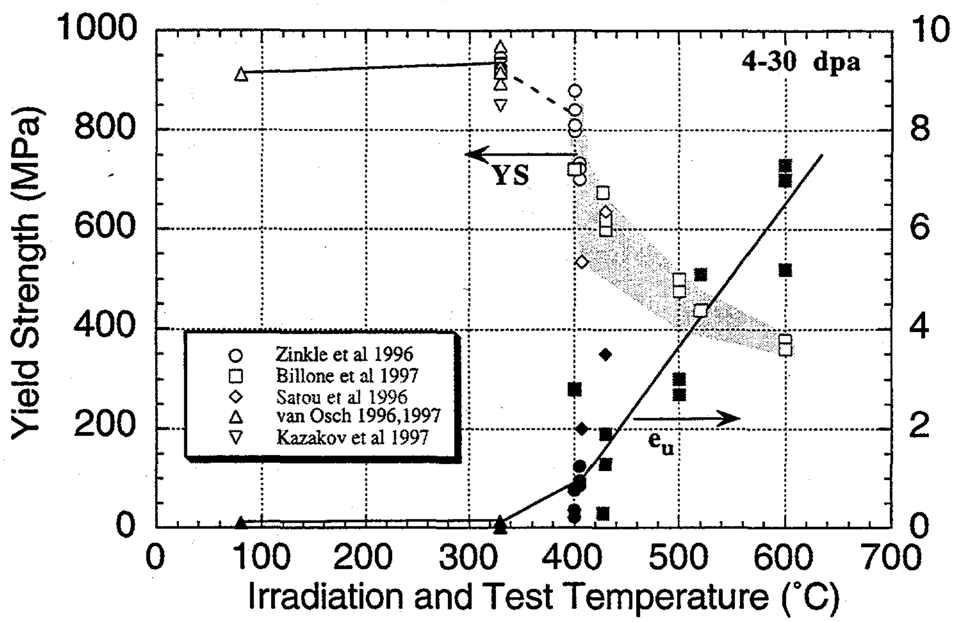

Fig. 4. Yield strength and uniform elongation of irradiated V-(4-5)%Cr-(4-5)%Ti alloys [1,3-8].

5. Elongation (unirradiated and irradiated)

The uniform and total elongation of unirradiated V-4Cr-4Ti determined from tensile testing at strain rates near $1 \times 10^{-3}\ s^{-1}$ exhibit high values at all temperatures from 20 to 700°C [1-3]. As shown in Fig. 3, the unirradiated uniform elongation decreases slowly from ~15% to ~10% over this temperature range. The corresponding total elongation decreases from ~30% to ~20% as the temperature increases from 20 to 700°C (Fig. 5). As shown in Figs. 4 and 5, irradiation causes a decrease in the uniform and total elongations, particularly for irradiation temperatures below 400°C [1,3-8]. The total elongation remains above ~5% for all irradiation conditions investigated to date (Fig. 5). The uniform elongation decreases to <0.2% for irradiation temperatures ≤330°C and is >2% for irradiation temperatures above 400-450°C.

6. Reduction in area

The reduction in area (RA) as measured on unirradiated and irradiated V-4Cr-4Ti tensile specimens deformed at strain rates of $\sim 1 \times 10^{-3}\ s^{-1}$ is shown in Fig. 6. The unirradiated reduction in area is very high (~90%) at low test temperatures, and decreases to a moderate value of ~50% at 700°C. Irradiation causes a significant decrease in the RA (particularly at low irradiation and test temperatures), but the reduction in area remains acceptably high in the tensile specimens examined to date.

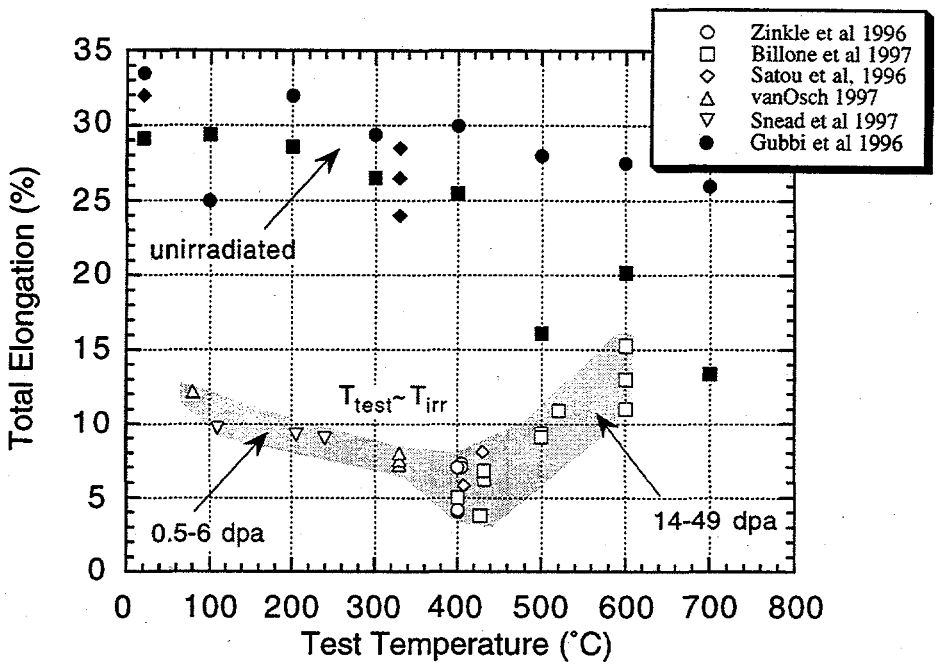

Fig. 5. Total elongation of unirradiated [1-3] and irradiated [1,3-5,7,8] V-(4-5)%Cr-(4-5)%Ti .

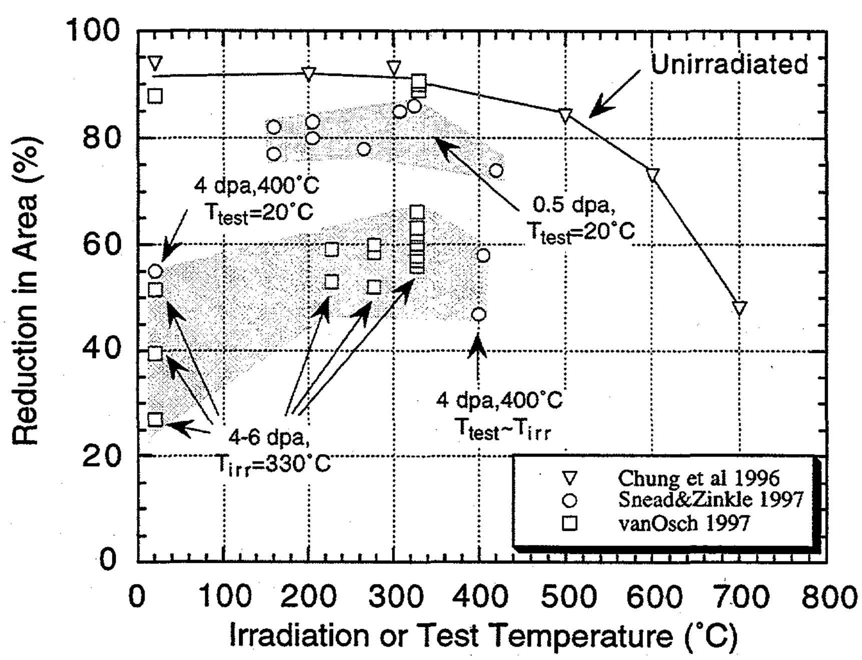

Fig. 6. Reduction in area of unirradiated [3,12] and irradiated V-4Cr-4Ti [3,8].

7. Stress-strain curves

Figure 7 shows representative stress-strain curves obtained on miniature "type SS-3" sheet tensile specimens (0.76 × 1.52 × 7.6 mm gage dimensions) for V-4Cr-4Ti tensile tested at a strain rate of 1.1×10^{-3} s^{-1} [2]. Serrations in the stress strain curve due to dislocation interactions with dissolved O, C, N interstitial solute (dynamic strain aging) become evident at test temperatures above 300°C. The strain rate exponent for the yield and ultimate tensile strength was positive at low test temperatures, and became negative at high temperatures where dynamic strain aging effects were present.

Figure 8 shows stress-strain curves obtained on miniature type SS-3 sheet tensile specimens of V-4Cr-4Ti following irradiation to a dose of 0.5 dpa at 110-420°C [8]. Pronounced flow localization is observed for irradiation temperatures up to 400°C [4,8], whereas adequate work hardenability occurs at temperatures above 425°C.

8. Elastic constants

The elastic constants for V-5Cr-5Ti (heat BL63) have been measured at room temperature, and were found to be in good agreement with published data for pure vanadium [13]. The room temperature elastic constants were: Young's modulus E_Y=125.6±0.4 GPa, shear modulus G=45.9±0.2 GPa, and Poisson's ratio 0.367±0.001. The following equations were recommended for extrapolation to temperatures above 20°C:

$$E_Y=((1.28 - 9.61 \times 10^{-5} {*}T)\pm 0.040) \times 10^{11}\ \mathrm{Pa}$$

$$G=((0.488 - 8.43 \times 10^{-5} {*}T)\pm 0.011) \times 10^{11}\ \mathrm{Pa}$$

where the temperature is given in Kelvin. Poisson's ratio at elevated temperatures can be obtained using the well-known relation $\nu=(E_Y/2G) - 1$.

9. Stress-rupture

Vanadium alloys exhibit good stress-rupture behavior at temperatures up to 600°C (0.4 T_M) [14-16]. Oxygen pickup from the surrounding atmosphere becomes a serious experimental problem for creep tests performed in vacuum at temperatures ≥600°C, due to the high affinity of vanadium for oxygen [16,17]. Thermal creep data for V-4Cr-4Ti are only available at a test temperature of 600°C and for testing times up to 4000 h [16]. Data for other vanadium alloys in the thermal creep regime ≥650°C has been summarized in review papers [14,15]. Significant thermal creep is expected in V-4Cr-4Ti at or above ~700°C (0.45 T_M).

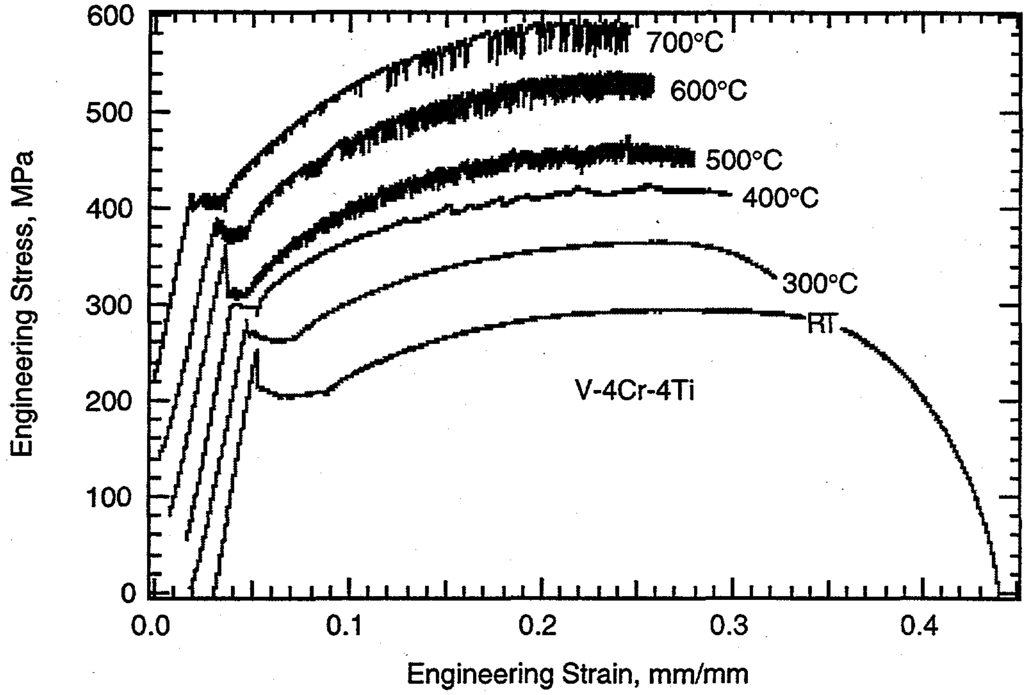

Fig. 7. Load vs. elongation tensile curves for V-4Cr-4Ti tested at temperatures between 20 and 700°C at a strain rate of 1.1×10^{-3} s^{-1} [2].

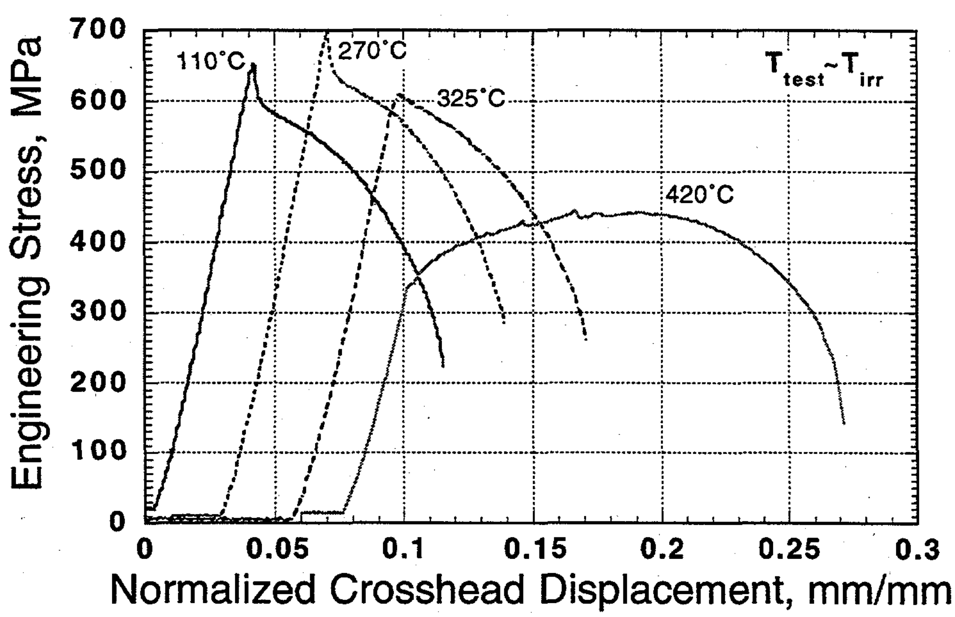

Fig. 8. Tensile load vs. elongation curves for V-4Cr-4Ti irradiated at low temperatures to a dose of 0.5 dpa [8].

10. Thermal expansion, specific heat and thermal conductivity

The thermophysical properties for V-5Cr-5Ti (heat BL63) have been measured from room temperature to 600°C, and are in agreement with published data for pure vanadium [18]. The instantaneous coefficient of thermal expansion varied from 9.1 ppm/°C at room temperature to 11.0 ppm/°C at 600°C. The fitted polynomial expressions for the linear thermal expansion ($\Delta L/L_0$) relative to the 20°C value and the instantaneous thermal expansion coefficient (α_{th}) are:

$$\Delta L/L_0 = -179.976 + 9.036385{*}T + 0.00154075{*}\ T^2 \text{ ppm}$$

$$\alpha_{th} = 9.03767 + 0.00301422{*}T + 4.95937 \times 10^{-7} * T^2 \text{ ppm/°C}$$

where the temperature (T) is given in °C.

The least squares fitted equation describing the specific heat at constant pressure over the temperature range of 100 to 600°C is

$$C_P = 0.57551 - 21.094/T \text{ J/g-K}$$

where the temperature (T) is given in Kelvin.

The thermal conductivity at 20-600°C was determined from thermal diffusivity measurements using either laser flash or xenon flash techniques with an overall accuracy of ±6%. The thermal conductivity was found to be in good agreement with literature values for pure vanadium. The least squares fitted equation for the thermal conductivity is

$$k_{th} = 27.827 + 0.008603\ T \text{ W/m-K}$$

where the temperature (T) is given in Kelvin.

11. Ductile to brittle transition temperature (unirradiated and irradiated)

The measured value of the ductile to brittle transition temperature (DBTT) in body-centered cubic materials depends on numerous experimental parameters, including the specimen geometry, strain rate, and the sharpness of the notch where the crack is initiated (notch acuity) [19,20]. The measured DBTT in miniature unirradiated V-4Cr-4Ti machined Charpy vee-notch (MCVN) specimens (25 × 3.3 × 3.3 mm) with a 30° notch depth of 0.67 mm and a notch root radius of 0.08 mm is near -200°C for L-T orientations [12,21]. Low temperature irradiation causes a sharp increase in the DBTT, even for relatively low doses of 0.5 dpa [8,21]. Figure 9 shows Charpy impact absorbed energy curves for V-4Cr-4Ti before and after neutron irradiation to doses of 0.5 and 4 dpa at temperatures near 400°C [4,8,21].

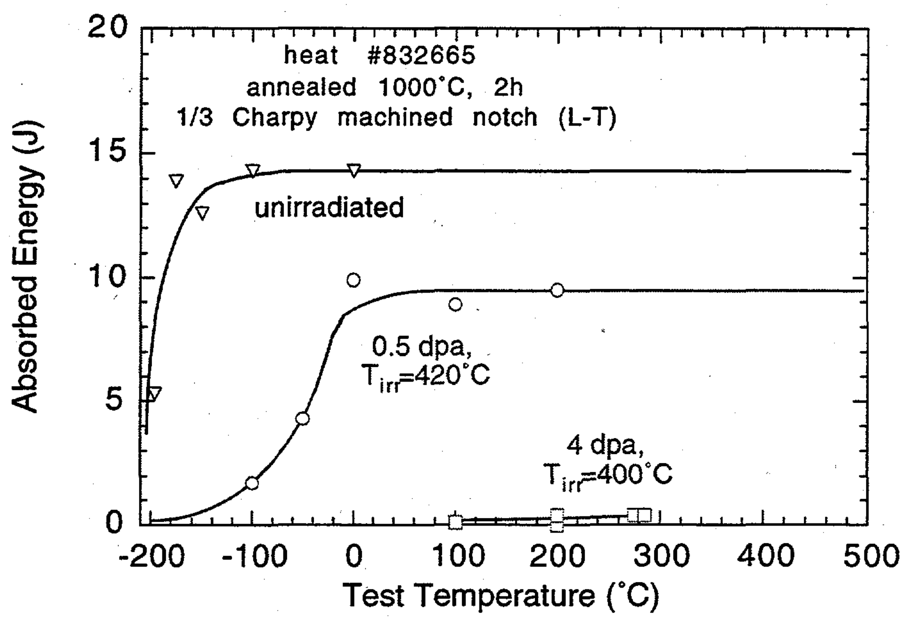

Fig. 9. Charpy impact absorbed energy curves of V-4Cr-4Ti MCVN specimens before and after low-dose neutron irradiation at ~400°C [4,8,21].

12. Recommended reference operating temperature limits

Additional work on unirradiated and irradiated specimens is needed before the maximum and minimum operating temperature limits for vanadium alloys can be established. The following reference operating temperature limits of 400 and 700°C are proposed until these data become available. The reference minimum operating temperature limit will be controlled by radiation hardening, which causes loss of ductility and an increase in the ductile to brittle transition temperature. According to analyses of the DBTT in unirradiated and irradiated V-4Cr-4Ti specimens, brittle fracture behavior in MCVN specimens occurs when the yield stress exceeds ~700 MPa [20,22,23]. From Fig. 4, this implies that the irradiation temperature must be greater than ~400°C to avoid brittle fracture behavior in structures containing undetected cracks.

The maximum operating temperature limit will likely be controlled by either thermal creep (creep rupture), helium embrittlement or chemical compatibility/corrosion effects. Significant thermal creep is expected in V-4Cr-4Ti at or above ~700°C (0.45 T_M), but experimental creep data on this alloy [16] are only available at 600°C (0.4 T_M). Slow strain rate tests to check for helium embrittlement effects have not been performed on irradiated V-(4-5)%Cr-(4-5)%Ti alloys. Tensile tests performed on some other neutron-irradiated vanadium alloys containing fusion-relevant amounts of helium have generally not observed pronounced helium embrittlement at ≥700°C, but creep-rupture tests on helium-containing irradiated specimens are needed to further investigate this issue [11,24-26]. Whereas vanadium alloys have good compatibility with liquid lithium at temperatures up to 600°C, interstitial solute pickup and predicted corrosion rates become significant at 650-700°C [17,27]. These corrosion and interstitial solute pickup effects might be mitigated if fully adherent self-healing insulator coatings can be successfully developed.

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