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Critical issues and current status of vanadium alloys for fusion energy applications

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Abstract

Vanadium alloys are widely regarded as possessing desirable mechanical and physical properties for application as structural materials in fusion power systems. The bulk of the recent research on vanadium is focussed on ternaries containing 4–5% Cr and 4–10% Ti. The aim of this paper is to review significant results generated by the international research and development community on this alloy system and to highlight the critical issues that must be resolved before alloy development can proceed to the next stage. Recent progress on understanding the physical metallurgy, fabrication and joining behavior, and compatibility with hydrogen and oxygen containing environments of unirradiated vanadium alloys is discussed. The effect of low-temperature neutron irradiation on mechanical properties and their relationship to the observed microstructure are briefly summarized. Current efforts to characterize the high-temperature mechanical properties, develop constitutive equations describing flow and fracture, and understand and mitigate the effects of non-metallic impurities on properties are presented.

1. Introduction

Vanadium-base alloys have been identified as an attractive high-performance structural material for the first-wall and blanket components of fusion power systems due to their favorable mechanical and physical properties. Considerable progress has been made on the development of vanadium alloys for fusion applications as noted in several recent reviews [1–5]. The worldwide vanadium alloy development effort has focused on the V–Cr–Ti system with an emphasis on compositions in the range V–(4–5)Cr–(4–10)Ti. An alloy with a composition of V–4Cr–4Ti is considered the reference composition in many international research programs. This paper highlights recent progress on V–4Cr–4Ti with regard to (1) large-scale production issues, (2) understanding its physical metallurgy, (3) development of joining techniques, (4) evaluating the compatibility with various environments, (5) assessing the effects of low-temperature irradiation on mechanical properties, and (6) determining high-temperature mechanical performance. Most of the discussion is concerned with the V–4Cr–4Ti alloy system, but variations on this basic composition to improve its irradiation performance are also presented. Current issues that require further research and development are described.

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2. Production and physical metallurgy

Even though considerable progress has been made in demonstrating that satisfactory mechanical and physical properties can be obtained on large heats of V–4Cr–4Ti [6,7], there remains a continuing interest in improving existing industrial-scale production methods to achieve better chemical homogeneity and reduced impurity levels. Research efforts are underway in both Japan and Russia to prepare 200–300 kg quantities of V–Cr–Ti alloys [8,9]. The objective of the Japanese program is to reduce the total interstitial impurity (C,N,O) content below 300 wppm, the Al concentration below 200 wppm, and the concentration of Mo and Nb each below 10 wppm. Detailed analyses of each step of the production process for pure vanadium were conducted, and the most effective methods to reduce impurity pick-up identified. Several small heats of pure vanadium (~25 kg) have been prepared where the total interstitial concentration (O, N and C) was about 290 wppm. Alloying techniques are also being reviewed and evaluated to identify promising methods to reduce impurity pick-up. In preparation for production of a 200 kg heat of V–4Cr–4Ti, several medium size ingots (~30 kg) were made where the total interstitial concentration was about 340 wppm [8].

In Russia, one of the research and development objectives is the development of high-purity, chemically homogeneous V–Cr–Ti alloy ingots. The main compositions being investigated are V–5Cr–10Ti and V–4Cr–4Ti. Two 50 kg ingots of these alloys were vacuum-arc melted to study and develop optimal processing methods. One problem encountered in development of vanadium alloys with acceptable properties is the lack of quantitative criteria for the quality of the starting vanadium ingot. To address this need, technical specifications for a new grade of high-purity vanadium were developed [9]. Control of interstitial impurities was emphasized. The maximum allowed concentration of O, N and C was specified at 200, 100 and 150 wppm, respectively. The limits established for Al, Mo and Nb are 250, 100 and 10 wppm, respectively. Lessons learned from the production of medium-scale heats will be used to develop appropriate criteria for the production of 300 kg heats.

Important progress has been made recently in identifying the underlying cause of microstructural inhomogeneity in V–4Cr–4Ti. Bimodal grain size distributions have been observed in certain batches of mechanical property specimens prepared from the 500 kg heat (832665) of V–4Cr–4Ti [10]. The inhomogeneous microstructure is typified by bands of coarse grains (~ 40 μm) interspersed with regions of finer grains (15–20 μm). These microstructural inhomogeneities may give rise to variations in mechanical properties [11]. Careful optical microscopy has shown that the finer grains are associated with bands of Ti (OCN) particles aligned along the rolling direction of the plate [10]. These particles form during hot extrusion of the cast billet whenever the temperature drops below the Ti (OCN) solvus and are typically 0.1–0.3 μm in size. An annealing study performed on Charpy impact specimens demonstrated that the Ti (OCN) solvus is approximately 1125°C [12]. The formation of these precipitates serves the important function of removing interstitial elements from the matrix, which lowers the ductile-to-brittle transition temperature (DBTT) and increases the lower shelf energy of V–4Cr–4Ti [3,12].

A crystallographic investigation of representative Ti (OCN) particles has shown that these particles are based on the fcc TiC phase [13], which is incoherent with the matrix. This phase is able to accommodate other interstitials such as O and N because all three Ti–x phases share the same space group and are therefore isomorphous with each other [13]. Due to the incoherent nature of the particle/matrix interface, precipitation will be favored in regions of high-dislocation density. Preliminary studies of alternative secondary processing such as room temperature cross-rolling have shown that a much more uniform dispersion of Ti (OCN) is produced by such techniques [10]. The results of this work suggest that much more needs to be learned about the kinetics of recovery, recrystallization and precipitation in V–4Cr–4Ti before optimal processing schedules can be developed.

Recent work [14] has led to a more fundamental understanding of the tensile deformation behavior of V–4Cr–4Ti. The focus of the research was to explore the sensitivity of unirradiated and irradiated V–4Cr–4Ti to changes in strain rate over the temperature range 20–800°C. Experiments were carried out at five strain rates ranging from 10^{-5} to 10^{-1} s^{-1} and the results were characterized in terms of the strain rate dependence of the stress at 8% strain, σ_s. The σ_s parameter is an arbitrary value of stress selected to represent material in the strain-hardening regime. Under certain conditions of test temperature and applied strain rate a phenomenon known as dynamic strain aging (DSA) or jerky flow is found. This phenomenon manifests itself as serrations in the stress–strain curve and it is caused by diffusion of solute atoms to dislocations during the tensile test. Solute atoms with sufficient mobility are able to temporarily pin mobile dislocations giving rise to load fluctuations. Fig. 1 presents a plot of the data for unirradiated V–4Cr–4Ti. In Fig. 1, the σ_s parameter is plotted against the applied strain rate. At room temperature, σ_s, always increases with increasing strain rate. In contrast, at temperatures from 400°C to 700°C, σ_s, decreases with increasing strain rate. This is the temperature regime in which DSA is observed. The transition from normal strain hardening to DSA occurs at 300°C for strain rates below 10^{-3} s^{-1}. Diffusion of

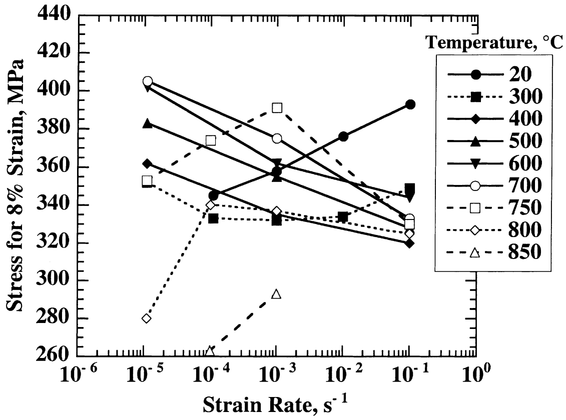

Fig. 1. Effect of strain rate on the flow stress (stress at 8% strain) of unirradiated V–4Cr–4Ti alloy tested at temperatures between 20°C and 850°C [14].

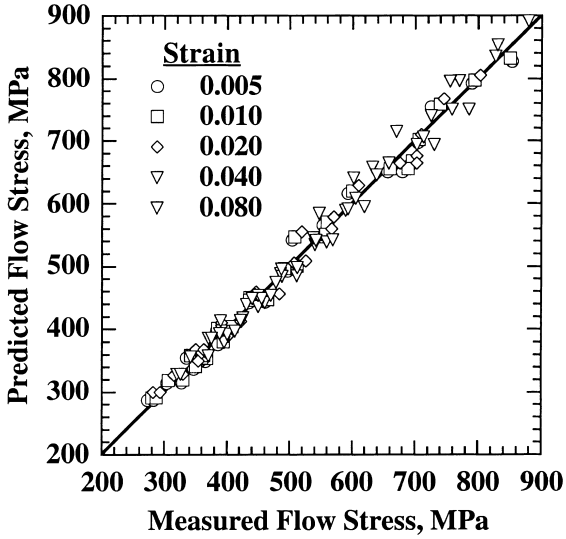

Fig. 2. Measured versus predicted flow stress for unirradiated V–4Cr–4Ti tested from −196°C to 100°C at strain rates between 4×10^{-4} and 2 s^{-1} [17].

oxygen and carbon are believed to be responsible for DSA at the lower end of the temperature spectrum, while diffusion of nitrogen and titanium probably contribute to DSA at temperatures greater than 500°C [14]. Another transition in behavior was found at test temperatures greater than 750°C. At these temperatures, σ_s displays a negative strain rate sensitivity for strain rates above 10^{-3} s^{-1} and a positive strain rate sensitivity at lower values. This change is believed to be indicative of a change in deformation mode from dislocation glide to a power-law creep dominated deformation regime [14].

Tensile tests at different strain rates were also performed on specimens irradiated at 100–500°C to doses of between 0.1 and 4 dpa [15]. The effect of irradiation was to reduce the magnitude of the strain rate sensitivity exponent relative to unirradiated specimens. This decrease was attributed to a weak positive contribution to the strain rate exponent by the presence of a high-number density of defect clusters [15]. In addition, the temperature at which a transition from positive to negative strain rate dependence occurred was shifted upward to about 400°C.

Safe operation of fusion power systems requires detailed information on the fracture behavior of candidate structural materials to avoid catastrophic failure by unstable propagation of cracks. Fracture toughness values, determined by standard test methods, yield an intrinsic material property only under very restricted conditions that are seldom met in practice. To address this need, physically based, micro-mechanical models of fracture are being developed for vanadium alloys to define the transition from ductile to brittle behavior so that quantitative evaluations of fusion power plant structural components can be performed. A technique known as confocal microscopy/fracture reconstruction (CM/FR) is being used to examine crack blunting, tearing and damage development ahead of the crack tip. The information obtained from CM/FR when coupled with finite element calculations of local crack-tip stress fields can be used to determine the critical conditions for cleavage fracture.

To conduct finite element analyses of crack-tip stress fields the constitutive properties of vanadium alloys over a range of temperatures and strain rates are needed. Recently, tensile testing of V–4Cr–4Ti at temperatures ranging from −196°C to 100°C and strain rates from 4×10^{-4} to 2/s was performed [16,17]. The yield and flow stress behavior was analyzed to formulate a general constitutive model as

$$\sigma(T,\varepsilon,\dot{\varepsilon}) = \sigma_{ya} + \sigma_y(T,\dot{\varepsilon}) + \sigma_{sh}(\varepsilon), \quad (1)$$

where σ_{ya} and $\sigma_y(T,\dot{\varepsilon})$ are the athermal and thermally activated components of the yield stress, and $\sigma_{sh}(\varepsilon)$ is the strain hardening contribution. The thermally activated component of the yield stress was treated in terms of a strain-rate compensated temperature. The dependence of the strain hardening term on strain transitions from a linear hardening model at small strain levels ($\varepsilon \leqslant 0.025$) to a power-law model at larger strain with an exponent of about 0.5, which is consistent with dislocation theories of work hardening. The predicted flow stresses are in excellent agreement with measured values as shown in Fig. 2.

3. Joining research

Development of joining techniques for vanadium alloys that give acceptable mechanical properties is a critical need that must be met before construction of large-scale fusion power systems is feasible. The susceptibility of vanadium alloys to interstitial contamination is greatest during joining operations since ultra-high-vacuum conditions are difficult to achieve on large structural components. Joining techniques are needed for a broad range of applications. Consequently many different approaches are under investigation, including gas tungsten arc welding (GTA) [18,26,27], laser welding [19–22], diffusion bonding [23,24], resistance welding [24], explosive bonding [24], inertia welding [24], and brazing [25]. The goal of these studies is to develop robust joining techniques that produce joints with adequate strength, ductility and fracture toughness.

Significant progress has been made in lowering the DBTT of GTA welds created in a glove box environment. By installing gettering systems to remove oxygen, hydrogen and water vapor from the glove box the DBTT was reduced from 228°C to −27°C [26,27]. High-temperature (950°C/2 h) post-weld heat treatments to remove interstitial oxygen from solution by formation of Ti (OCN) precipitates reduced the DBTT of low-to-medium purity GTA welds, but was of no benefit on high-purity GTA welds [26,27].

Development of laser welding techniques has also advanced in the past couple of years. Laser weld penetration studies utilizing a high-purity argon cover gas have successfully achieved 4 mm penetration depths with essentially no change in the oxygen, carbon and nitrogen levels [22]. Charpy impact tests have not been performed, but hardness profiles taken from the weld centerline to the base metal show only a 16% increase in hardness.

Joining research conducted in support of the DIII-D radiative divertor program has enjoyed considerable success in recent years [3,24]. The research program has emphasized solid-state methods, which can be performed in air without the need for a vacuum or inert gas environment to prevent interstitial impurity contamination of the vanadium alloy base metal. Resistance welding techniques have been developed to join vanadium alloy panel sheets. Explosive bonding and inertia welding have also been explored for joining vanadium alloy to Inconel 625. These methods have successfully produced ductile, high-strength, and vacuum leak-tight joints [24].

4. Environmental effects

The known affinity of vanadium alloys for gases such as oxygen and hydrogen has spawned many investigations into the effect of these gases on the tensile properties of V–Cr–Ti alloys between 300°C and 700°C for exposure times up to about 2000 h [28–41]. The bulk of the mechanical property data has been generated at 500°C. Research has also been performed to characterize the effect of time and temperature on the oxidation behavior in air and low-pressure oxygen environments. The results of these studies show that the oxidation kinetics exhibited parabolic behavior in both air and low-pressure oxygen over a temperature range of 300°C to 650°C [28,29,40]. Weight gains measured in air were found to be larger than in low-pressure oxygen [29,33]. The chemical composition of the oxide scale formed in air and pure oxygen is predominantly V_2O_5 and in low-pressure oxygen it is VO_2 [33,34,40]. The primary effect on tensile properties from an exposure to air or low-pressure oxygen in this temperature regime is to reduce ductility, as measured by the uniform and total elongation. Significant hardening of the alloy did not occur since the yield and ultimate tensile strengths were not greatly affected by exposure to these conditions [29,30]. Intergranular failure was the primary fracture mode seen in these tests [29,30], but transgranular cleavage has also been observed [40]. This behavior suggests that oxygen diffusion along grain boundaries is the rate controlling process for temperatures less than ~650°C. Microstructural studies performed to date show an oxygen denuded zone 150–250 nm in extent near the grain boundaries with precipitates at the grain boundaries and a uniform distribution of fine-scale oxide particles in the matrix [34]. Coarsening of the precipitates both in the matrix and on the grain boundary is observed following a 950°C/4 h anneal to restore ductility. The denuded zone adjacent to the grain boundary did not disappear however. Since grain boundary precipitates are found before and after annealing at 950°C it is hypothesized that their presence does not affect ductility [34].

A series of exploratory experiments have been recently performed to evaluate the effect of oxygen on the crack growth behavior of V–4Cr–4Ti at 600°C [42]. Tests were run in gettered argon, argon containing 2000 ppm oxygen, and laboratory air using fatigue precracked compact tension specimens. Crack growth was measured primarily by post-test fracture surface examination, but also by in-test compliance measurements. Crack growth rates measured in air and gettered argon were about 23×10^{-3} mm h^{-1} at a stress intensity factor of about 40MPa $\sqrt{m}$. The crack growth rate in argon with 2000 ppm oxygen was about 7×10^{-2} mm h^{-1} at the same stress intensity level. The crack growth rates were very sensitive to the stress intensity factor. Over a limited range of stress intensity values (35–55MPa $\sqrt{m}$) the crack growth rate in argon plus 2000 ppm oxygen was found to be power-law dependent on stress intensity with an exponent of about 8.9. The fracture mode in air and gettered argon was transgranular cleavage with 20–30% intergranular fracture. In the oxygenated argon environment, crack growth occurred predominantly by transgranular cleavage.

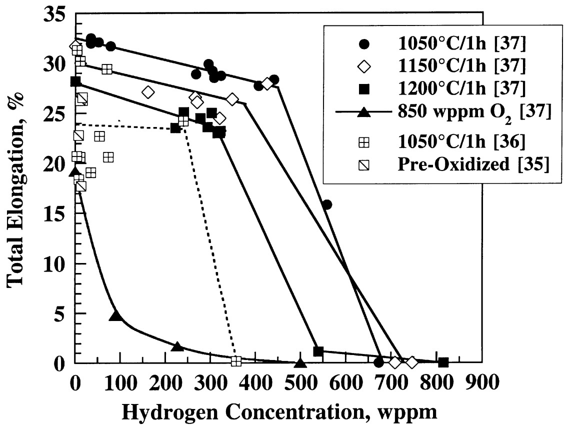

Fig. 3. Effect of hydrogen and hydrogen plus oxygen on the room temperature total elongation of unirradiated V–4Cr–4Ti [36–38].

The effect of hydrogen and hydrogen combined with oxygen on the room temperature tensile properties has been the focus of recent research efforts [35–38]. In a manner similar to the effect of oxygen on tensile response, the presence of hydrogen did not substantially change the yield or ultimate tensile strengths appreciably [37,38]. Only about a 20% increase in tensile strength is found for hydrogen levels of about 350 wppm [37]. As with oxygen, the main effect of hydrogen is to reduce tensile ductility. The available data plotted in Fig. 3 show that the total elongation is not substantially decreased by additions of up to 400 wppm hydrogen. Above that level, where hydride formation sets in [38,39], the ductility decreases drastically. The data in Fig. 3 also display a slight grain size effect. The critical hydrogen concentration required to embrittle the alloy seems to shift to lower levels with increasing grain size. Another significant recent finding [38] is that hydrogen becomes a much more potent embrittling element when it acts synergistically with oxygen. As depicted in Fig. 3, the total elongation of V–4Cr–4Ti is reduced to less than 2% at a hydrogen level of 220 wppm when 850 wppm oxygen is present. Fractures due to hydrogen embrittlement tend to be transgranular cleavage with an increasing intergranular component as the oxygen level rises [38]. This effect of hydrogen on fracture mode may serve to explain why some tests performed in oxygenated environments exhibit cleavage predominantly rather than intergranular facets [41,42].

5. Effect of low-temperature neutron irradiation

Previous irradiation studies of V–Cr–Ti alloys were largely performed in fast reactors, where the focus was on determining behavior in the 430–600°C temperature regime. With the possible use of vanadium alloys as structural materials for ITER the recent research emphasis has been on defining the minimum operating temperature limit. Consequently several experiments were performed in several reactors (BOR-60, EBR-II, HFBR, ATR) to explore irradiated properties in the range ~100–500°C at doses less than 12 dpa. Post-irradiation examination of the specimens irradiated in these experiments is nearly complete, and it is now possible to summarize the important findings.

Irradiation of V–4Cr–4Ti at < 400°C produces dramatic changes in its mechanical properties [15,43–49,52]. The yield and ultimate tensile strength increase by approximately a factor of three over unirradiated values, and the uniform elongation drops to below 1% [43–47]. Reduction of area measurements on unirradiated specimens typically gives values greater than 80%. For specimens irradiated between 160°C and 320°C, the reduction of area appears to depend on dose. At doses $\leqslant$ 0.5 dpa, the reduction of area is essentially unchanged from the unirradiated value [46]. At doses ranging from 4 to 6 dpa, the reduction of area decreases to between 50% and 70% at 200°C [49,50], and between 5% and 28% at approximately 320°C [47,50]. Accompanying the changes in tensile properties are corresponding changes in the fracture behavior [15,51–54]. Charpy impact results show pronounced increases in the DBTT with the peak increase at an irradiation temperature of around 250°C at a constant dose of 0.5 dpa, [3]. Pre-cracked Charpy specimens display a similar trend, but with even higher DBTTs owing to increased notch tip acuity [3]. In contrast, statically tested Charpy specimens, pre-cracked and side-grooved to increase mechanical constraint, give lower transition temperatures as shown in Fig. 4 [53]. These results serve to highlight the fact that the DBTT is not a fundamental material property, but depends on the specimen geometry and test conditions. A more useful quantitative parameter is the effective fracture toughness as a function of temperature or Master Curve approach [16]. Changes in specimen geometry, strain rate, irradiation conditions, or yield stress can then be represented as a temperature shift of the Master Curve away from a reference state.

The general microstructural features that give rise to the increase in matrix hardness of V–4Cr–4Ti at low-irradiation temperatures have been delineated in several studies [55–59]. Changes in properties can be correlated with the production of a high-number density (~10^{23}–10^{24} m^{-3}) of small ($\leqslant$5 nm) defect clusters, or radiation-induced precipitates. At low-irradiation temperatures and doses the principal defects produced are dislocation loops. As the dose increases, and for irradiation temperatures greater than about 300°C, radiation-induced precipitation begins to occur. The presence of these small defects impedes the motion of dislocations, elevating the yield stress considerably. The small size of the

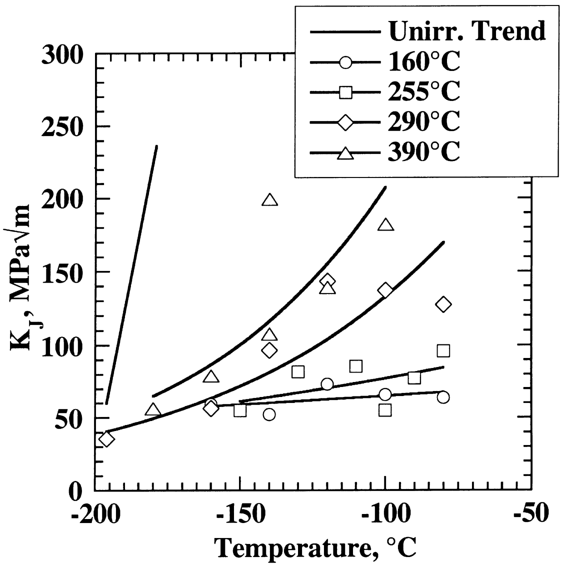

Fig. 4. Temperature dependence of the quasi-static fracture toughness for V–4Cr–4Ti irradiated to 0.1 dpa between 160°C and 390°C [53].

defect clusters allows them to be easily sheared by mobile dislocations. Pronounced flow localization associated with dislocation channeling is observed on specimens irradiated in this temperature regime [3,55,58]. Recovery of tensile ductility and fracture toughness is due to coarsening of the defect clusters with increasing irradiation temperature. Analytical electron microscope analysis of V–4Cr–4Ti irradiated at low-temperatures has yielded mixed results on the chemical composition of radiation-induced precipitates [59]. There is general agreement that the precipitates contain Ti and the interstitial impurities O, C and N, but some investigators suggest that these precipitates also contain Cr and/or V [57,59]. The apparent link between radiation-induced precipitation and the interstitial impurity content has led Japanese researchers to alter the composition of V–4Cr–4Ti by adding from 0.1% to 1% of Al, Si and Y. The intended function of these elements is to scavenge interstitial impurities and thereby improve the low-temperature irradiation performance. Preliminary evidence suggests that this modification may increase the uniform elongation of V–4Cr–4Ti irradiated at ~400°C [48].

6. High-temperature mechanical properties

With the completion of several studies of the low-temperature irradiation behavior of vanadium alloys attention is now turning toward defining the high-temperature operational limit. In power system design studies, the upper temperature limit for vanadium alloys is assumed to be 700°C [60]. A recent evaluation of the performance limits of fusion structural materials suggested that vanadium alloys might be capable of operation at 750°C [4]. The maximum operating temperature will be controlled by (1) corrosion and compatibility with the fusion environment, (2) the effect of gaseous transmutants such as helium, and (3) mechanical properties such as tensile strength and creep resistance (both thermal and irradiation).

Until lately, there were no tensile property data on V–4Cr–4Ti at temperatures above 700°C. Three studies have recently been completed which extended the data base to 800°C [14,61,62]. The results show that the yield strength of V–4Cr–4Ti is nearly independent of test temperature between 300°C and 800°C. The ultimate tensile strength peaks at a temperature near 600°C, and then begins to decrease at 800°C. Above room temperature, the uniform and total elongation gradually decrease to values of around 10% and 20%, respectively, at 800°C. Reduction of area is typically greater than 70% at all test temperatures, indicating substantial tensile ductility.

Several investigations of irradiation creep have been performed recently [63–66], but only limited information is available on the thermal creep properties of vanadium and vanadium alloys [67–72]. Wheeler et al. [67] determined the secondary creep rate of pure vanadium from 477°C to 1600°C. Their results showed that creep was controlled by climb of dislocations. At high-temperatures diffusion of di-vacancies was rate controlling, but as the temperature decreased climb was controlled by mono-vacancy diffusion. A power-law dependence of the creep rate on stress was found with a stress exponent, n, of 10 for temperatures below 1000°C. Between 650°C and 800°C Schirra [68] observed an n of 11.3 above 40 MPa, but n dropped to 6.2 below 30 MPa. The temperature and stress dependence of the stress exponent for V–Ti alloys is similar to that for pure vanadium [69–72]. Alloying vanadium with up to 3% Ti increases creep strength, but increasing the Ti concentration further causes a substantial decrease in creep resistance. Addition of up to 15% Cr to V–(3–5)Ti appears to increase the creep resistance between 600°C and 800°C, although this observation is not unequivocal [71,72]. The stress exponent for V–(4–15)Cr–(4–5) Ti alloys tested at 600°C was also found to be about 10 [72], but it should be noted that all of the creep data generated were at stress levels above the yield strength, where a high-stress exponent would be expected.

A study of the biaxial creep behavior of V–4Cr–4Ti between 600°C and 800°C was recently initiated to compliment ongoing efforts to characterize the irradiation creep performance of this alloy [73,74]. Creep tubes nominally 4.57 mm OD by 0.25 mm wall thickness were pressurized with high-purity helium gas to mid-wall

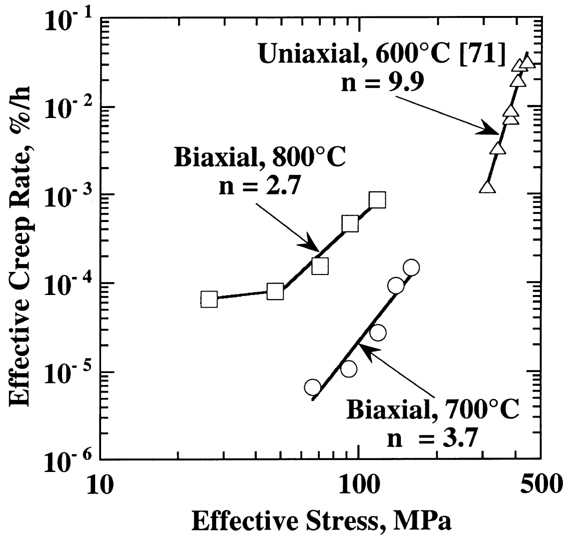

Fig. 5. Stress dependence of the minimum creep rate of unirradiated V–4Cr–4Ti between 600–800°C [73].

effective stresses below the yield strength. Specimens were heated to 700°C and 800°C in an ultra-high vacuum furnace and periodically removed to measure the change in OD with a high-precision laser profilometer. The dependence of the effective secondary creep rate on effective stress is given in Fig. 5. Results from a previous investigation conducted at 600°C using uniaxial test specimens are also shown in Fig. 5. Note the stress exponent for the biaxial tests is about 3.7 at 700°C and 2.7 at 800°C, which follows the trend seen on other vanadium alloys tested at similar stresses and temperatures. The average activation energy for creep of V–4Cr–4Ti was 299 kJ mol^{-1}, which is close to the activation energy for self-diffusion in pure vanadium in this temperature regime [67]. Based on these results, a preliminary conclusion is that the predominant mechanism of creep deformation in V–4Cr–4Ti at 700–800°C and for effective stresses from 50 to 120 MPa is climb-assisted dislocation motion. The operation of other mechanisms such as Coble creep or grain boundary sliding, acting in conjunction with dislocation creep, cannot be excluded at the present time. The relatively fine grain size (~20 μm) of the tube specimens, and the stress-temperature regime being investigated suggest that these deformation modes may be operative. The decrease in stress exponent for the lowest stress specimens tested at 800°C support this conclusion.

7. Critical issues for future research

Although considerable progress has been made on the development of vanadium alloys for fusion applications, there remain a number of critical issues that must be resolved before the next steps in material development can be taken. Clearly, from the foregoing discussion, one of the critical issues that should be addressed during the next 2–3 years is the need for a better mechanistic understanding of the effects of O, C and N interstitials and precipitates on the mechanical properties. Opportunities for pick-up of interstitial impurities occur during primary production, fabrication, joining operations, and exposure to the environment during service. As has been seen the effect of interstitial impurities on mechanical properties can be profound. Although large-scale, production-size heats of V–4Cr–4Ti have been successfully produced with relatively low-levels of interstitials there is a growing realization that perhaps lower levels may be needed in order to develop a structural material resistant to low-temperature embrittlement. In the same vein, demonstration of the control of high-activation impurities (e.g., Ag, Mo, Nb) in production size heats should also be a near-term goal. Progress has been made on understanding the basic physical metallurgy of vanadium alloys, but more remains to be done before optimal alloy compositions, processing steps, and service limits can be specified. Several joining techniques are being pursued with increasingly favorable results, but methods that can be applied in the field on large-scale structures without the need for high-temperature post-weld heat treatments remain to be demonstrated. Evaluating the effect of the environment on oxidation resistance, tensile properties, and subcritical crack growth and fracture behavior are vitally important for establishing the serviceability of vanadium alloys. What appears to be a synergistic effect of oxygen and hydrogen needs to be fully explored. Even though the status of insulating coating development work was not discussed in this paper, it is apparent that much more progress will be needed in order to make Li/V blanket systems attractive for fusion. There are many difficult problems that need to be resolved to obtain self-healing, electrically insulating coatings. It is also apparent that some resources should be devoted to the exploration of the compatibility of vanadium alloys with other coolants (e.g., Flibe, He), along with development of coating barriers, if necessary. As has been demonstrated many times before, the effects of neutron irradiation on material properties can be dramatic. The recent emphasis has been on characterizing the effect of low-temperature irradiation on vanadium alloy properties and significant progress has been made, but further work on the influence of non-metallic interstitials, grain size, precipitates and possibly He on the low-temperature (350–450°C) fracture properties is needed. Although several studies [1] were performed more than 25 years ago, investigating the effect of helium on elevated temperature mechanical properties introduced by cyclotron injection or 'tritium trick' doping, there remains a need to adequately characterize the effect of He generation coupled with neutron-induced displacement damage. Essentially only one experiment has been performed assessing He effects at ratios of He-to-cascade damage production that begin to approximate the level expected in the fusion irradiation environment [75]. The effect of simultaneous generation of He and neutron damage on creep ductility and tensile properties in the temperature range 600–800°C is a critical issue that must be addressed. Coupled with the exploration of high-temperature He effects is the necessity for continued measurement and improvement of the thermal creep resistance of vanadium alloys in the temperature range 700–800°C, and continued development of constitutive deformation models. Consideration should be given to development of alternate alloy compositions that offer multiphase microstructures. This may provide a viable strategy for enhancing the thermal creep resistance above 700°C, and for controlling the copious quantities of He produced during service.

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