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Vanadium-base alloys for fusion first-wall/blanket applications

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Abstract

Vanadium alloys have been identified as a leading candidate material for fusion first-wall/blanket applications. Certain vanadium alloys exhibit favorable safety and environmental characteristics, good fabricability, high temperature and heat load capability, good compatibility with liquid metal coolants and resistance to irradiation damage. The current focus is on vanadium alloys with (3–9 wt%) Cr and (3–10 wt%) Ti with a V–4Cr–4Ti alloy as the reference composition. Substantial progress has been made in the development of vanadium alloys for the fusion first wall/blanket applications including production and welding, characterization of baseline properties, corrosion/compatibility, and effects of irradiation on the properties. This paper presents an overview of the development of vanadium alloys for fusion applications and a summary of key issues requiring further research. © 2001 Published by Elsevier Science Ltd.

Keywords: Vanadium alloys; Irradiation effects; Compatibility; Mechanical properties; Production/fabrication; Fusion materials

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1. Introduction

Vanadium alloys have been identified as a leading candidate material for fusion first-wall/blanket structure applications. Certain vanadium alloys exhibit favorable safety and environmental characteristics, good fabricability, and potential for high performance and long operating lifetime in a fusion environment. The current focus is on the vanadium–chromium–titanium alloy system with (3–9 wt%) Cr and (3–10 wt%) Ti with a V–4Cr–4Ti alloy as the reference composition.

Vanadium alloys have been selected and evaluated in major design studies including the Blanket Comparison and Selection Study (BCSS) [1], the Tokamak Power Systems Study (TPSS) [2], the TITAN Reversed Field Pinch Design [3], the ARIES-II Tokamak design [4], and the ARIES-RS Tokamak design [5]. Vanadium alloys were incorporated as the structural material in the top rated blanket concepts based on performance, reliability, safety and economics in the BCSS, which considered many combinations of breeder, coolant, and structure. The TPSS was based on a self-cooled lithium blanket with a vanadium alloy structure. This study also included an evaluation of a vanadium alloy structure with a helium-cooled ceramic breeder blanket concept. A vanadium alloy structure was selected for the TITAN design primarily because of the high surface heat load capability. The ARIES design, which placed a high priority on safety and environmental considerations, incorporated a self-cooled lithium blanket with a vanadium alloy structure. In addition, the Report on Environmental, Safety, and Economic Aspects of Magnetic Fusion Energy (ESECOM) identified important safety and environmental advantages of vanadium alloys [6]. Recent blanket studies, which incorporate vanadium alloys as the structure, emphasize high performance to improve the economic competitiveness of fusion as an energy source [5,7].

Considerable database has been developed which indicates that vanadium alloys, when used with a self-cooled lithium blanket, offer superior performance compared to other options for the first-wall/blanket structure of a magnetic fusion power plant. Systems analyses indicate that vanadium alloys can accommodate high first-wall heat loads corresponding to ~10 MW/m^2 neutron wall loading and can operate at temperatures up to ~750°C [7]. Vanadium alloys provide favorable safety and environmental features such as low long-term activation, low decay heat and contact dose, and a potential for recycle. These alloys can be

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rolled into thin sheets, fabricated into tubing, and welded by several methods. Available data indicate that vanadium alloys with a few percent titanium are resistant to irradiation-induced swelling and embrittlement at projected operating temperatures, and they are compatible with liquid-metal blankets. A major concern regarding the operation of structural alloys in a fusion neutron environment relates to effects on performance and lifetime caused by the nuclear transmutation of helium. As shown in Table 1, the helium and hydrogen transmutation rates in vanadium alloys are substantially less than those for other candidate materials exposed to high-energy neutrons characteristic of a deuterium–tritium plasma. The design and systems studies indicate that vanadium alloys offer a potential for long operating lifetime with subsequent economic and environmental advantages. Recycle of the vanadium is also considered feasible.

The key remaining issues and R&D requirements for vanadium alloys relate to production and joining, chemical compatibility, and effects of high-energy neutron irradiation, including helium effects, on the properties. Scale up of industrial capability for production and further weld development are required. Key issues related to chemical compatibility involve the kinetics of nonmetallic element interactions and the effects of the chemical environment on the mechanical properties. Additional data are needed on the effects of neutron irradiation with fusion-relevant helium and hydrogen concentrations on the swelling and mechanical properties of vanadium alloys. For the case of a self-cooled lithium system, which is the preferred option with a vanadium alloy structure, development of an electrically insulating coating on the vanadium alloy channel walls is a critical issue that must be resolved to mitigate the magnetohydrodynamic (MHD) pressure drop for the circulating lithium coolant in a high magnetic field. The status of insulator coating development is presented in related papers [8,9].

This paper presents an overview of the status of vanadium alloy development for fusion first-wall/blanket applications.

2. Candidate alloy selection

The vanadium alloy development program is currently focused on the vanadium–chromium–titanium alloy system. These three elements are mutually soluble in each other at elevated temperatures and they all exhibit favorable low-activation characteristics. Compositional variations produced by nuclear transmutations for this system are minimal since each element predominantly transmutes to the other two elements. Therefore, the composition of the alloy will not be significantly affected even after long periods of irradiation. As mentioned above, the helium and hydrogen transmutation rates in the high-energy neutron environment are lower than those for other candidate materials. It has been shown for many years that vanadium alloys with a few percent titanium additions are highly resistant to irradiation-induced void swelling [10,11], thus offering a potential for long operating lifetime in a fusion environment. Titanium additions also improve the fabricability of vanadium alloys. As shown later, a few percent chromium additions significantly improves the tensile and creep strength of vanadium–titanium alloys.

Recent investigations have included compositions (wt%) of V–(0–15)%Cr–(1–20)%Ti–(0–1)%Si [11–17]. Current emphasis is on a reference composition of V–4Cr–4Ti. A range of compositions is still being investigated to better understand the sensitivity of various properties to small compositional variations. The Japanese research also includes investigations of alloys in which the chromium is replaced by iron [18] and the Russian effort includes a V–10Ti–5Cr alloy in their program [19]. The current focus is on a simple solution anneal thermomechanical treatment (TMT) with an annealing temperature of about 1000°C for 1 h. However, variations in processing conditions, amount of warm or cold work, and variations in annealing temperature are still being investigated in order to better understand their effects and to optimize the properties for the advanced fusion applications.

The effects of variations in nonmetallic element concentrations, particularly O, N, C, and H, have also been

Table 1
Comparison of nuclear-related properties of candidate fusion structural materials

	Austenitic Steel 316SS	Ferritic Steel HT-9	V-alloy V–5Cr–5Ti	SiC
Melting temperature (°C)	1400	1420	1880	2600[a]
Radiation damage rate[b] (dpa)	11	11	11	12
Helium transmutation rate[b] (appm)	174	130	57	1500
Hydrogen transmutation rate[b] (appm)	602	505	240	560
Nuclear heating rate (W/cm^3)[c]	11	11	7	11

[a] Decomposition temperature.

[b] For 14 MeV neutron flux of 1 MW/m^2 for 1 year.

[c] For 14 MeV neutron flux of 1 MW/m^2.

Table 2
Selected physical properties of three candidate structural alloys

	316 SS	HT-9	VCrTi
Melting temperature (°C)	1400	1420	1890
Density (g/cm^3)	8.0	7.8	6.1
Poisson's ratio	0.27	0.27	0.36
Modules of elasticity, GPa @ 400°C	168	180	120
Linear thermal expansion (10^{-6}/K)			
400°C	17.6	11.8	10.2
500°C	18.0	12.3	10.3
600°C	18.3	12.6	10.5
Thermal conductivity (W/m K)			
400°C	19.5	26.8	33.6
500°C	21.0	27.3	34.5
600°C	22.5	27.7	35.3
Electrical resistivity (μm)			
400°C	1.01	0.91[a]	0.67
500°C	1.06	0.99[a]	0.74
600°C	1.12	1.05[a]	0.81
Specific heat (J/kg K)			
400°C	560	600	535
500°C	575	680	560
600°C	580	800	575

[a] Data for 410 SS.

investigated. Nominal concentrations of these elements are (200–400) wppm oxygen, (50–200) wppm nitrogen, (50–200) wppm carbon, and <5-wppm hydrogen. Investigations are underway to further evaluate the effects of varying the nonmetallic element concentrations on the mechanical properties.

3. High performance characteristics

Vanadium-base alloys exhibit physical properties that are favorable for the fusion first-wall applications. Table 2 lists selected physical properties for the vanadium alloys compared to the austenitic (Type 316) and ferritic/martensitic (HT-9) steels. In addition to the high melting temperature (~500°C higher than the steels), vanadium alloys have a lower coefficient of thermal expansion, a higher thermal conductivity, and a lower elastic modulus; all of which contribute to a higher heat load capability compared to the steels.

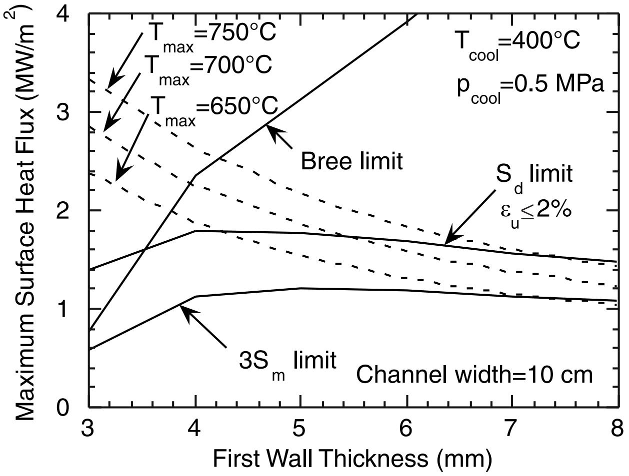

Fig. 1. Calculated time independent first wall heat flux limits as a function of wall thickness for a lithium-cooled blanket concept with a V–4Cr–4Ti alloy structure.

Depending on the design concept and system configuration, vanadium alloys can accommodate heat loads a factor of 4–7 higher than those of the steels [20]. Fig. 1 is a plot of the calculated time independent first-wall heat flux limits as a function of wall thickness for a lithium-cooled blanket concept based on several design criteria for a specific system configuration, viz., channel size, coolant pressure and coolant temperature [21,22]. For these design conditions and for a ductile material with a uniform elongation of >2%, the allowable stresses are defined by the Bree curve. For a low ductility material with an uniform elongation <2%, the allowable design stresses are defined by the S_d limit. In the past, designers have frequently assumed design stress limits defined by the $3S_m$ limit. The dotted lines indicate temperature limits dictated by other constraints such as corrosion or helium embrittlement considerations. If the vanadium remains ductile, $e_u > 2\%$, and the maximum

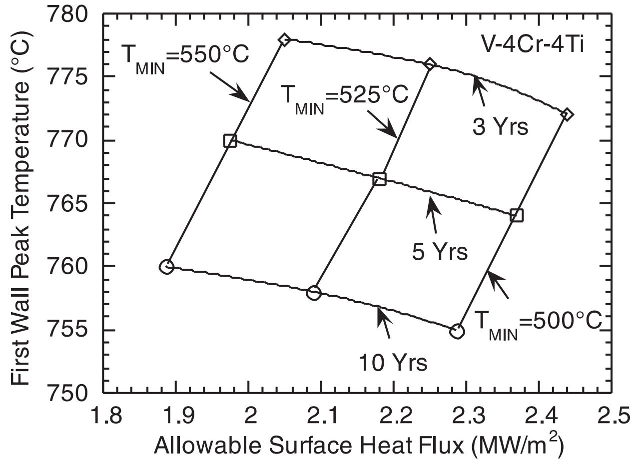

Fig. 2. Calculated surface heat flux limits vs. peak first-wall temperature based on creep-ratcheting constraints for a vanadium alloy structure.

temperature based on other considerations is 700–750°C, the maximum surface heat flux limit for this case is ~2.5 MW/m^2 for a wall thickness of 4 mm. This surface heat flux corresponds to a neutron wall loading of about 10 MW/m^2, which is considerably higher than corresponding values for the steels.

At high temperatures, thermal creep will become a dominant constraint. Fig. 2 presents a parametric analysis of the allowable surface heat flux vs peak first wall temperature corresponding to various allowable creep ratcheting times and coolant side-wall temperatures for a self-cooled lithium blanket with a V–4Cr–4Ti first wall [21]. Based on the temperature limits imposed by these design constraints for a self-cooled lithium–vanadium blanket concept, an energy conversion efficiency of 43% is obtainable at a high neutron wall load of ~10 MW/m^2 [7]. Higher energy conversion efficiencies can be obtained at lower neutron wall loads.

4. Safety and environmental features

The V–Cr–Ti alloys exhibit favorable safety and environmental features; particularly with respect to low long-term activation, low decay heat, and low contact dose. Fig. 3 shows the calculated radioactivity as a function of time after shutdown for several metallic elements after exposure to a first-wall fluence of 12.5 MW-y/mm^2 [23]. Vanadium exhibits the lowest long-term radioactivity of the elements shown, chromium is next best and titanium is significantly better than most. Silicon and aluminum exhibit lower radioactivity than does vanadium and chromium at times less than 10–20 years. Fig. 4 shows results of similar calculations for contact dose from the first wall of a system constructed

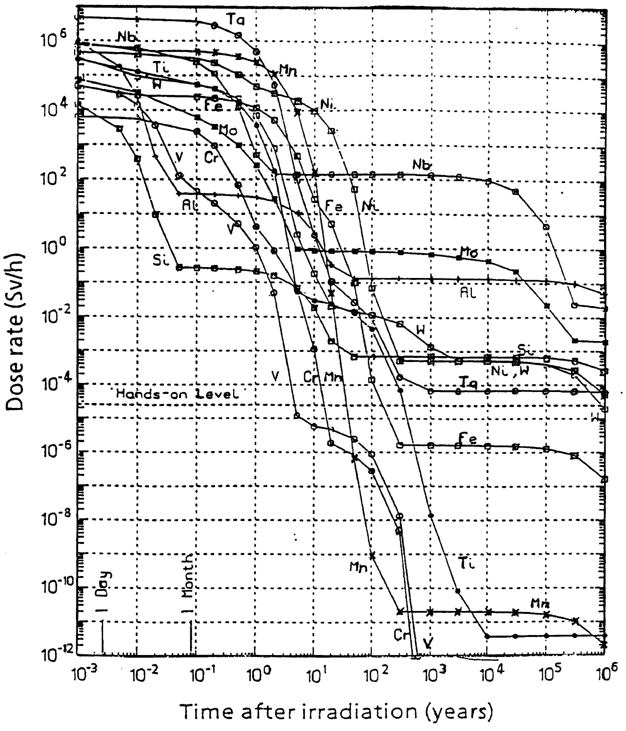

Fig. 3. Induced radioactivity after shutdown for selected elements exposed to first wall fluence of 12.5 MWy/m^2.

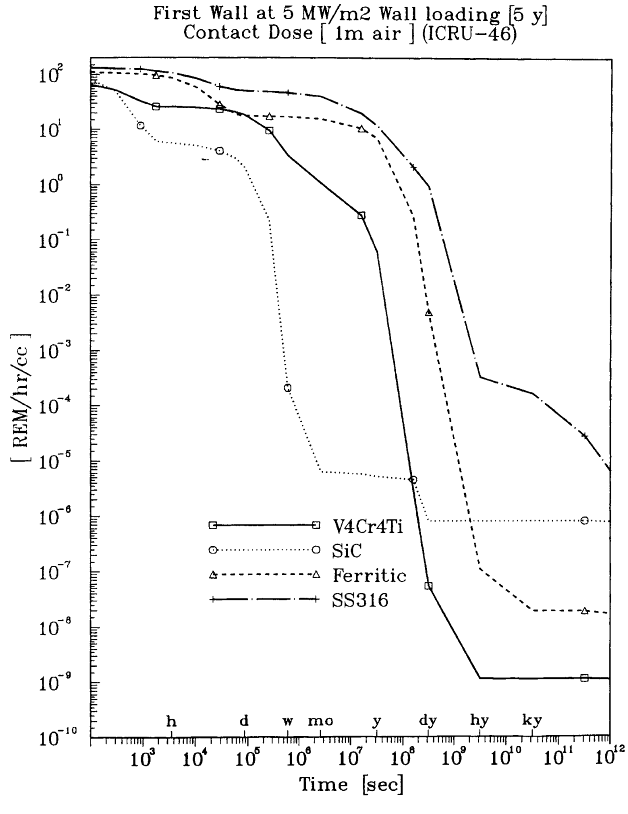

Fig. 4. Calculated contact dose after exposure for 5 years to a typical neutron wall load of 5 MW/m^2 for a first wall system constructed from candidate materials.

of a vanadium alloy, a low activation ferritic/martensitic steel, Type 316 austenitic steel, and SiC [24]. Vanadium alloys exhibit lower dose rates than the steels at all times and dose rates lower than SiC at times greater than 6 years. The effects of impurities must be considered in all cases; however, it is generally accepted that relatively pure materials can be obtained. Similar calculations for the specific decay heat-generation rate and biological hazard potential also show advantages of vanadium alloys compared to the steels at all times and compared to SiC at times greater than 5–50 years.

In addition, the high melting temperature of vanadium alloys and the relatively low volatility provide advantages in the event of an accidental release during thermal transients. One concern for the vanadium alloys is the relatively high-oxidation potential. This has been addressed in the design studies by providing an inert atmosphere in the reactor building. This inert environment is generally recommended or required to prevent oxidation of other materials, particularly the candidate plasma facing materials in the event of a plasma chamber failure. In addition, the first-wall surface of most fusion reactor designs are protected by some type of a coating.

The potential for recycle of a vanadium alloy structure has also been considered. The conclusions of these studies indicate that recycle is indeed feasible [25]; however, further assessment of the implications of recycle is recommended.

5. Production and fabrication

Substantial progress has been made in recent years on the production and fabrication of vanadium alloys. Resources are not a problem since the abundance of vanadium is greater than that of nickel, copper and several other common metals. Procedures for alloy production were developed and demonstrated in the US (Argonne National Laboratory and Westinghouse Electric Corporation) in the 1960s as part of the fast-breeder reactor program. Teledyne Wah Chang (now Oremet Wah Chang) has produced 7000 kg ingots of pure vanadium at a rate up to ~200,000 kg/y. In recent years Wah Chang has produced a 500 kg heat of a V–4Cr–4Ti alloy for Argonne National Laboratory [15] and a 1200 kg heat of the same alloy for General Atomics Corp [26], both as part of the US fusion program. Several 15–30 kg heats have been produced in the US with varying composition of V–Cr–Ti [27]. The Russian researchers have produced 50–100 kg heats of similar alloys [28] and the Japanese researchers are in the process of producing a 200 kg heat of the V–4Cr–4Ti alloy [29].

Secondary fabrication methods have been developed and demonstrated for producing plate (6–25 mm thick) and sheet (down to 0.2 mm). A major concern with secondary fabrication is the potential for contamination, particularly oxygen pickup; however, the procedures developed indicate that contamination can be avoided. Typical nonmetallic element concentrations obtained for most alloy heats are 200–400 wppm oxygen, 50–200 wppm nitrogen and 50–200 wppm carbon. Trace elements of primary concern with regard to long-term activation considerations, viz., niobium and molybdenum, are very low in some vanadium alloy heats, e.g., 0.4 wppm Nb and 2 wppm Mo in a V–9Cr–5Ti alloy produced at Argonne National Laboratory [30]. However, in several cases the vanadium alloys were produced in facilities that were previously used for production of niobuim alloys. Significant contamination by Nb and Mo apparent in these cases is not expected to affect the properties of the vanadium alloys and can be avoided by use of clean processing facilities.

The primary thermo-mechanical treatment being used for the V–4Cr–4Ti alloy is a solution anneal at ~1000°C for one hour. However, as will be discussed in more detail later, the properties appear to be rather insensitive to annealing temperatures of 950–1100°C and for annealing times of 0.5–2 h. It has also been shown (see Fig. 5) that thermal aging at temperatures up to 800°C for times of 5000 h has no effect on grain size [31].

There is very limited experience with production of vanadium alloy tubing; however, the vanadium alloys of interest are quite ductile and thin-walled tubing (0.25 mm) has been successfully fabricated.

Experience with welding of vanadium alloys is also quite limited; however, results of preliminary investigations indicate that most conventional methods including

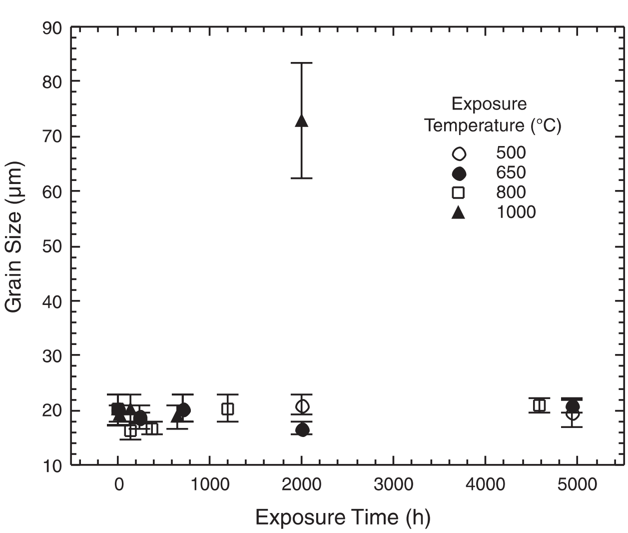

Fig. 5. Grain size of V–4Cr–4Ti as a function of aging time and temperature.

gas–tungsten–arc (GTA), electron-beam, laser, and resistance welding can all be used successfully. However, atmospheric control is essential to avoid excessive contamination during welding, particularly by oxygen. Significant effort is currently focused on development of procedures for welding vanadium alloys by laser [32] and GTA [33] methods. Recent results indicate that contamination can be avoided. Contamination-free GTA welds have been obtained in a high purity glove-box atmosphere. Contamination-free laser welds have been obtained by use of a simple shielded argon gas purge, which allows for welding outside a glove-box. This approach greatly increases the flexibility of laser welding for joining large components typical of a fusion system.

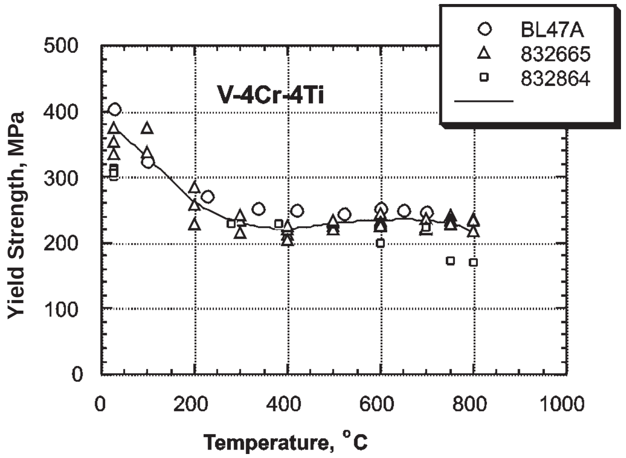

Fig. 7. Yield strength of several heats of V–4Cr–4Ti alloy as a function of temperature at a strain rate of ~0.001/s.

6. Baseline mechanical properties

A substantial database on baseline mechanical properties of vanadium alloys has been generated for a range of alloy compositions and test parameters. These include tensile, Charpy impact, thermal creep, and limited fatigue properties.

Tensile properties have been determined for several compositions of V–Cr–Ti- alloys to 700°C and for the V–4Cr–4Ti alloy to 800°C. Fig. 6 is a summary curve for the ultimate tensile strength of several V–Cr–Ti alloys up to 700°C illustrating the effect of chromium variation on the properties of alloys containing 4–5% titanium [34]. The tensile strengths of these alloys are relatively insensitive to temperature for the range 200–700°C. These data plus results for several other V–(0–15)Cr–(0–20)Ti alloys indicate that Cr and Ti have similar strengthening effects. Fig. 7 is a plot of the temperature dependent yield strength of several heats of the V–4Cr–4Ti alloy showing that the yield strength is insensitive to temperature up to 750–800°C [34–39]. These alloys also exhibit high ductility as represented by total and uniform elongations of 20–30%, and 10–20%, respectively, for temperatures from 25°C to 800°C. Also, the tensile ductility of the V–4Cr–4Ti alloy is relatively insensitive to strain rate as indicated in Fig. 8 [38].

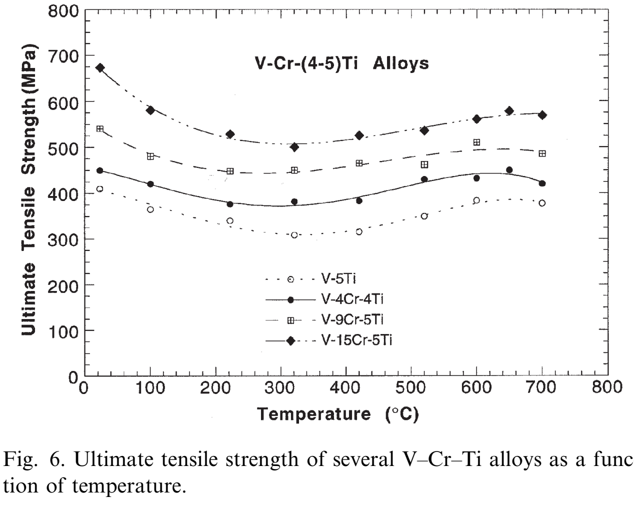

Fig. 6. Ultimate tensile strength of several V–Cr–Ti alloys as a function of temperature.

The toughness of this alloy class is characterized by a low ductile-to-brittle transition temperature (DBTT) as measured by Charpy impact tests on one-third of the ASTM-standard size specimens. Fig. 9 shows the Charpy impact energy as a function of temperature for four heats of V–(4–5)Cr–(4–5) Ti alloys [40]. All four heats exhibit DBTT's below −200°C. Alloys with higher additions of either Cr or Ti exhibit higher DBTT's as shown in Fig. 10.

In many applications the high temperature operating limits of structural materials will be constrained by the thermal creep response. In general, vanadium alloys exhibit good creep strength to temperatures of 700–750°C; however, it has been shown that the thermal

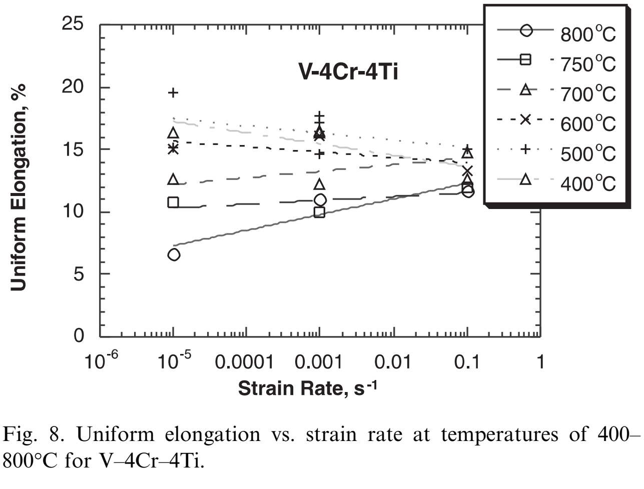

Fig. 8. Uniform elongation vs. strain rate at temperatures of 400–800°C for V–4Cr–4Ti.

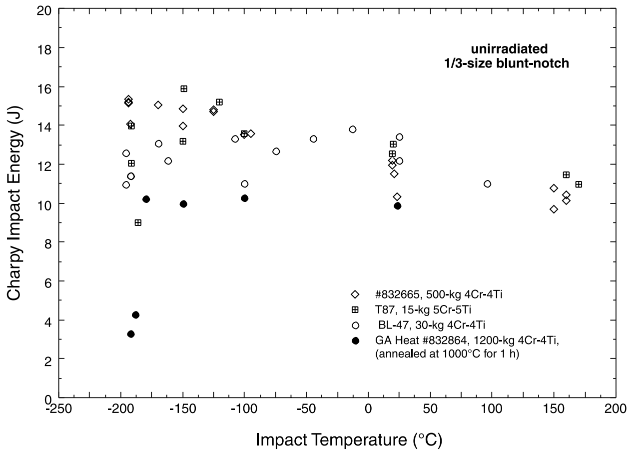

Fig. 9. Charpy Impact properties of four heats of V–(4–5)Cr–(4–5)Ti alloys.

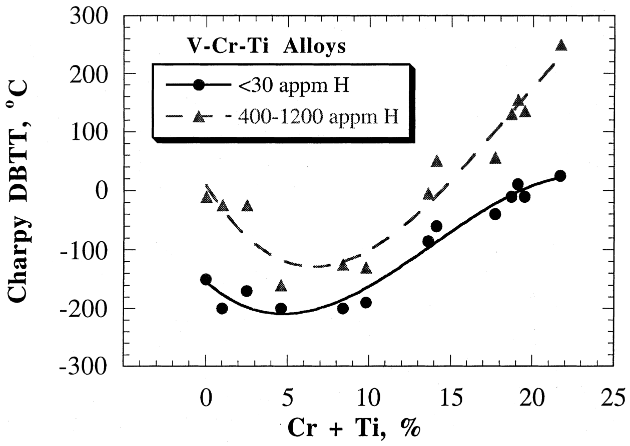

Fig. 10. DBTT (Charpy) as a function of composition for V–Cr–Ti alloys.

creep properties of vanadium alloys can be substantially modified by variations in composition, both substitutional and nonmetallic elements. Schirra [41] has compiled results from an extensive creep evaluation of approximately forty alloy compositions. Trends from these data indicate that V–(10–15) Nb–3Ti–1Si exhibited the highest creep strength, alloys with 10–15% Cr and 1–3% Ti or Zr also exhibited good creep strength. The creep strength of V–Ti binary alloys decreased with an increase in Ti concentration above ∼3%, and oxygen additions in the range 700–1500 wppm significantly increased the creep strength of some of the vanadium alloys. The oxygen concentrations in most of these tests were 700 wppm or greater. Gold and Bajaj [42] have investigated the effects of oxygen on the creep response of selected vanadium alloys at lower concentrations. Recent investigations have focused on the creep properties of V–4Cr–4Ti with low oxygen concentrations (300–400 wppm). Creep rupture results obtained by both uniaxial and biaxial tests [43,44] are presented in Fig. 11 as a function of the Larson–Miller (LM) parameter, which correlates the time and temperature dependence with rupture stress. For reference, a LM parameter of 21 corresponds to a 10,000 h rupture life at 600°C. Characteristic curves for the V–15Cr–5Ti alloy and austenitic and ferritic steels are shown for comparison. These results illustrate the superior creep properties of the vanadium alloys compared to those of the steels.

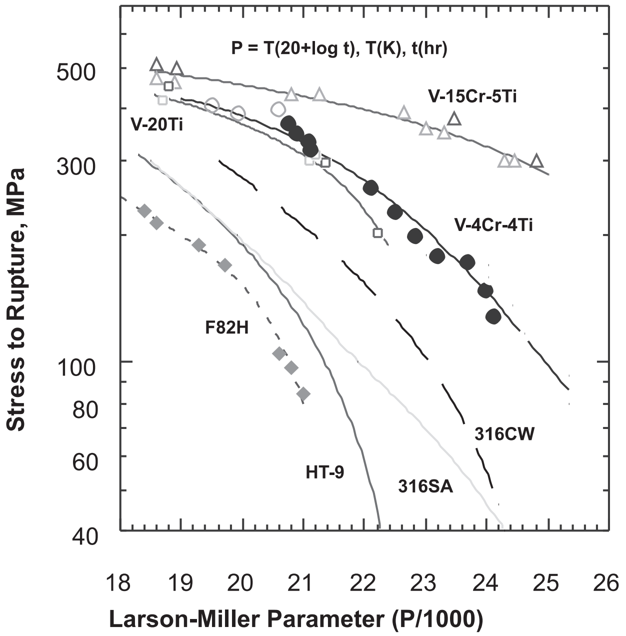

Fig. 11. LM correlation of creep-rupture stress for vanadium alloys and steels.

Only limited fatigue data have been generated for the vanadium alloys [45–47]. Fig. 12 presents room temperature fatigue data for two vanadium alloys tested in high vacuum at room temperature along with typical data for type 316 austenitic steel. The vanadium alloys exhibit superior fatigue properties; however, it has also been shown that oxygen contamination can severely degrade the fatigue properties of vanadium alloys at elevated temperature [46].

7. Corrosion/compatibility

Interactions with the chemical environment are important considerations for the application of vanadium alloys at elevated temperatures. In general vanadium alloys are sensitive to oxidation, they exhibit relatively high solubility and permeability for hydrogen, and they are relatively resistant to corrosion by most liquid metals.

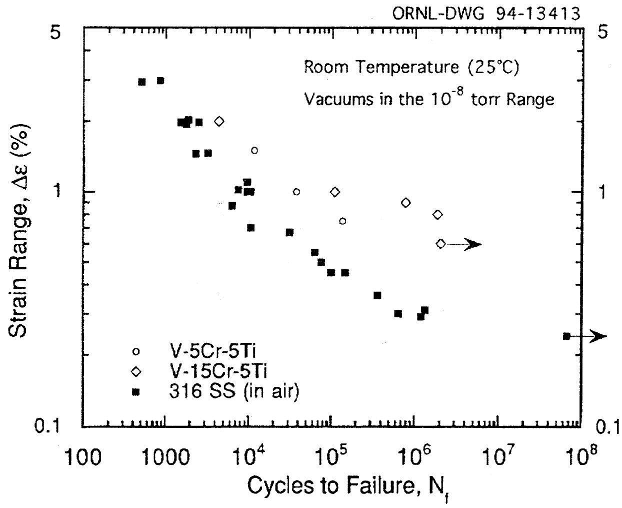

Fig. 12. Fatigue data for V–Cr–Ti alloys compared with values for stainless steel.

The solubility of hydrogen in vanadium has been well established in several fundamental studies [48,49]. The Seiverts' constant for the hydrogen solubility in vanadium is given by:

$$\ln K_{S(V)} = -8.093 + 3490/T,$$

where K is at.% $Pa^{-1/2}$, and T is Temperature (K). Titanium additions to vanadium tend to increase the hydrogen solubility while chromium tends to decrease the solubility. Limited data for the V–4Cr–4Ti alloy indicate that the hydrogen solubility is slightly lower than that for pure vanadium [50,51]. An important consideration for fusion is the compatibility with the D–T plasma, which typically corresponds to a hydrogen pressure of 10^{-3}–10^{-1} Pa in the chamber. The solubility of hydrogen in vanadium at 500°C at these pressures corresponds to 10–100 appm H (0.2–2 wppm H), which is acceptable. The effects of hydrogen in V–4Cr–4Ti on the tensile properties has been evaluated by room temperature tensile tests after exposure to hydrogen environments at elevated temperatures [52,53]. As shown in Fig. 13 the tensile ductility of this alloy is not affected for hydrogen concentrations below about 300 wppm (~15,000 appm). The effects of hydrogen on the Charpy impact properties of two V–Cr–Ti alloys is illustrated in Fig. 10 [54]. Hydrogen concentrations of 700–1200 appm produce a significant increase in the DBTT; however, the DBTT for the V–4Cr–4Ti alloy remains far below room temperature.

Vanadium alloys are known to be susceptible to oxidation even at very low oxygen partial pressures. Thermodynamic analyses indicate that the oxygen potential required to form vanadium oxides is extremely low. The effects of time, temperature and oxygen partial pressure in the exposure environment on oxygen uptake, scaling kinetics and scale microstructure of V–(4–5)Cr–(4–5)Ti alloys have been investigated for oxygen pressures in the range 10^{-4}–10^5 Pa and for temperatures of 500–700°C [31,55]. The oxidation process and oxygen uptake of these alloys followed parabolic kinetics as shown in Fig. 14. Adherent oxide scales, predominantly VO_2, formed on the surface after exposure to oxygen pressures of 8×10^{-2} to 10 Pa.

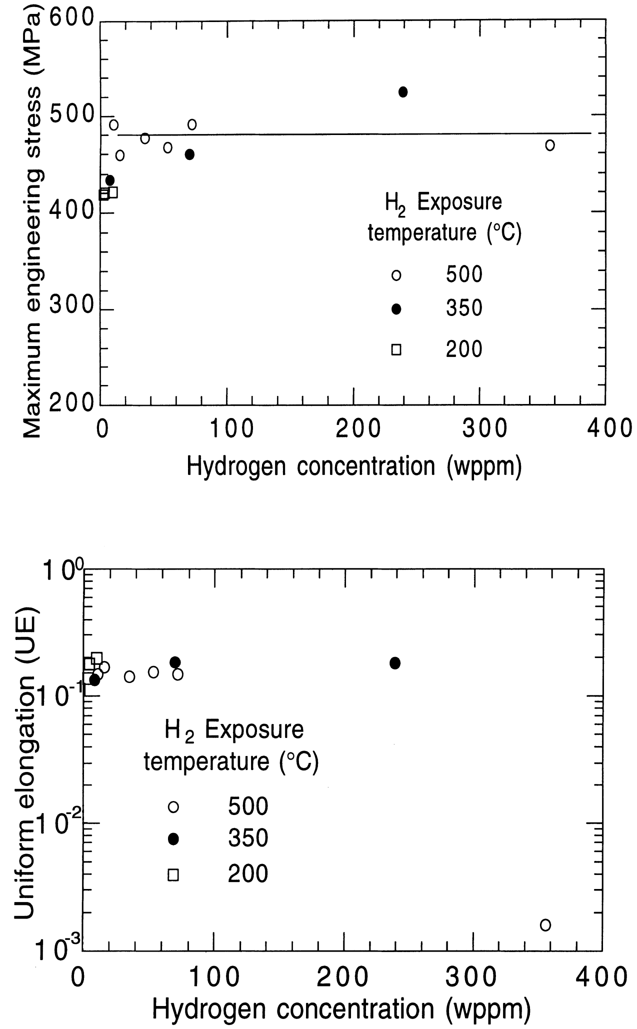

Fig. 13. Effects of hydrogen on tensile strength and uniform elongation of V–4Cr–4Ti alloy.

8. Effects of irradiation on properties

Candidate vanadium alloys generally exhibit good resistance to irradiation damage at temperatures of interest and offer a potential for long operating lifetime. As shown in Table 1, vanadium alloys exhibit favorable neutronic characteristics particularly with respect to lower He and H transmutation rates compared to those

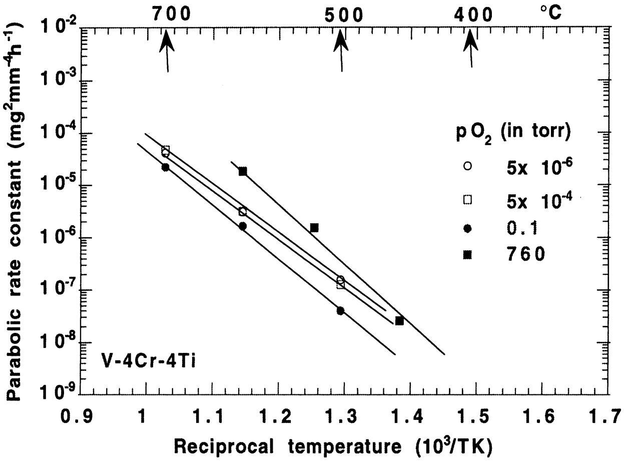

Fig. 14. Temperature dependence of parabolic rate constant for oxygen uptake in V–4Cr–4Ti alloy for a range of oxygen pressures.

of the steels and SiC. However, the effects of helium transmutation produced by the high-energy neutrons remains one of the major concerns regarding the performance limits of materials in a fusion environment. The helium generation rate in the vanadium alloys is a factor of 2–3 lower than those for the steels and a factor of 25 lower than that for SiC. The hydrogen transmutation rate and nuclear heating are also significantly lower than those for the other candidate materials. The neutronic properties of vanadium alloys have significant advantages for fusion applications. A major issue in the development of materials for fusion is the lack of a high-flux neutron source with a fusion relevant spectrum. Fission reactors are used to provide most of the irradiation effects data; however, the transmutation rates for helium and hydrogen produced in most materials exposed to a fission neutron spectrum are orders of magnitude lower than transmutation rates for materials exposed to a 14 MeV neutron spectrum. Because of its unique properties with respect to hydrogen solubility, a dynamic helium charging experimental (DHCE) method developed for vanadium alloys provides a unique approach for investigating the effects of fusion-relevant helium generation rates during neutron irradiation in a fusion reactor spectrum [56].

Vanadium alloys that contain a few percent titanium additions are shown to be resistant to irradiation induced swelling under either neutron or ion irradiation [10,11,57]. Both binary V–(1–20)Ti alloys and V–Cr–Ti alloys with 3–7% Ti exhibit good swelling resistance, in some cases for damage rates in neutron irradiations of 80–115 dpa. The V–Fe–Ti alloys have also exhibited good swelling resistance [58]. An important issue associated with swelling involves the effect of the high helium generation rate in a fusion neutron spectrum. Preliminary experiments have been conducted with the DHCE to investigate the effects of simultaneous helium generation with displacement damage [57]. Results obtained on several alloy compositions indicate significantly different microstructural changes for specimens with higher helium concentrations [57–68]. Microstructural evaluations indicate no significant cavity formation in alloys with titanium; however, substantial uniform cavity formation has been observed in alloys, which do not contain titanium. Additional investigations using the DHCE approach are recommended to further evaluate the swelling phenomenon in candidate alloys.

The V–4Cr–4Ti alloy shows good resistance to irradiation induced embrittlement at both low strain rates (normal tensile tests) and at very high strain rates (Charpy impact tests) after irradiation at high temperatures of primary interest for fusion power applications. At temperatures in the range 420–600°C most solution annealed V–Cr–Ti alloys exhibit some degree of radiation hardening as indicated by increases in the yield strength (see Fig. 15) [11,13,17,36]. The radiation hardening tends to saturate at ~10–30 dpa and the extent of hardening decreases significantly with temperature in the range 430–600°C. At temperatures above 430°C, several vanadium alloys including V–4Cr–4Ti retain substantial tensile ductility as measured by total elongation. The total elongation of V–4Cr–4Ti alloy remains above ~5% at temperatures above ~300°C and damage levels of 4–33 dpa as shown in Fig. 16 [16,17,70,71]. The measured reduction in area also remains high, typically >50%. Only limited data have been reported at temperatures above 600°C. V–5Ti and V–3Ti–1Si alloys irradiated to 6 dpa at 700°C exhibited high tensile ductility as shown in Fig. 17 [69]. However, most vanadium alloys investigated exhibit a transition to less ductile behavior at about 400°C, even at relatively low fluences as indicated in Fig. 18. At temperatures

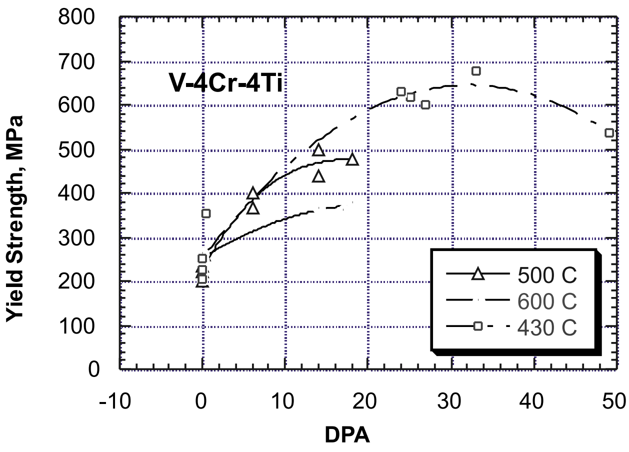

Fig. 15. Irradiation hardening of vanadium alloys as a function of temperature.

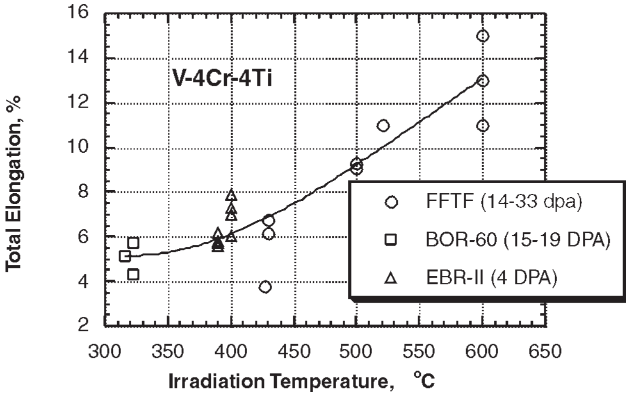

Fig. 16. Total elongation as a function of temperature for V–4Cr–4Ti alloys irradiated in fast breeder reactors.

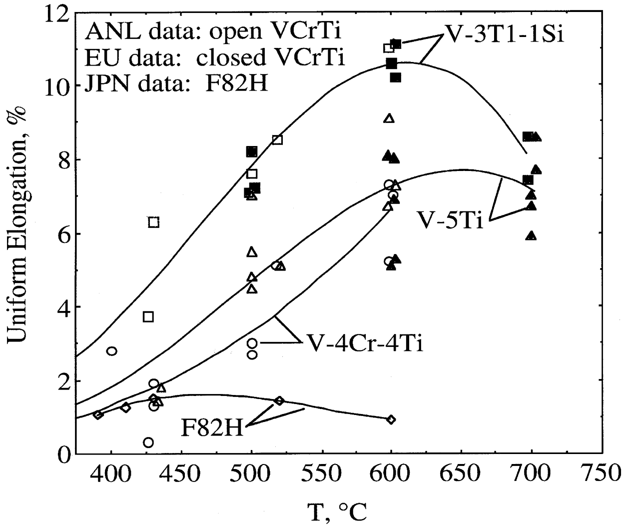

Fig. 17. Uniform elongation of vanadium alloys irradiated to temperatures of 700°C.

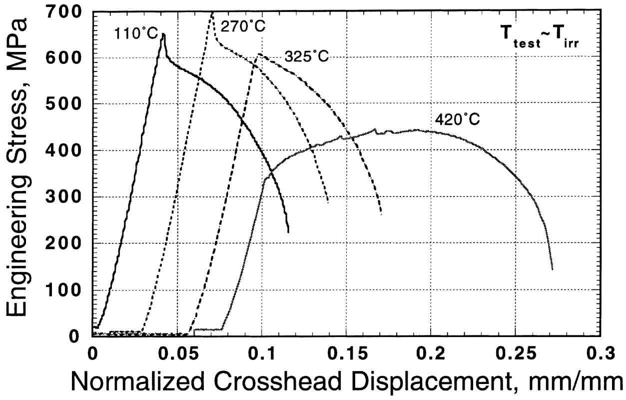

Fig. 18. Effects of low-dose irradiation on tensile properties of V–4Cr–4Ti alloy.

below ~400°C, the uniform elongation typically decreases to <1%; however, the total elongation remains above 5% as indicated in Fig. 16. Related investigations have been conducted on V–(4–5)Cr–(4–5)Ti alloys with small additions (0.1–1%) yttrium, silicon and/or aluminum [64,72]. These alloys appear to exhibit tensile ductilities comparable to those for the reference V–4Cr–4Ti alloy. Further research on the effects of nonmetallic element (O, N, C) concentrations on the tensile properties of selected vanadium alloys is warranted.

The fracture behavior of several vanadium alloys after irradiation has been evaluated by Charpy impact tests. Most of the data for the temperature range of primary interest, 400–750°C, have been obtained from fast reactor irradiations. The Charpy impact energy curves (1/3 size Charpy specimens) for V–4Cr–4Ti after irradiation at 425–600°C to damage levels of ~30 dpa are illustrated in Fig. 19 [34,57,73]. The DBTT for this alloy remains far below room temperature. The dip in the curve for the 427°C irradiation, which has also been observed for other alloys, e.g., V–5Ti and V–3Ti–1Si, is tentatively attributed to an effect of hydrogen. However, at irradiation temperatures below 400°C, the DBTT of this alloy shifts to temperatures approaching 0°C as indicated in Fig. 20 [16,17,74]. General observations from these experiments indicate that vanadium alloys with Cr + Ti <10% exhibit low DBTT's both before and after irradiation at temperatures above 400°C. The alloys with higher concentrations of Cr and of Ti exhibit higher DBTT's as illustrated in Fig. 21. Unfortunately, the effects of simultaneous helium generation and displacement damage on the impact properties of neutron-irradiated alloys have not been investigated. Further investigations on helium effects are recommended.

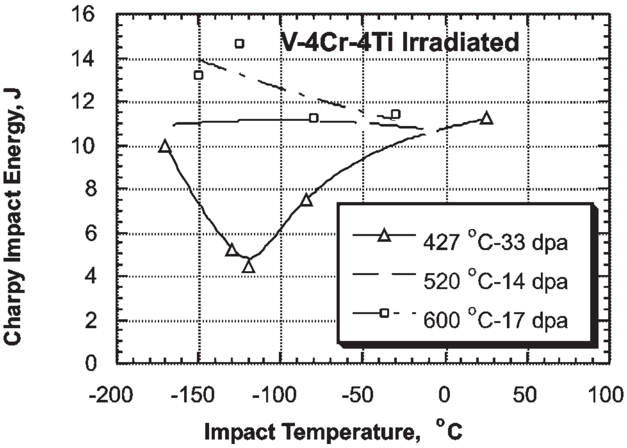

Fig. 19. Charpy impact energy as a function of temperature for V–4Cr–4Ti irradiated at 427–600°C to 14–33 dpa.

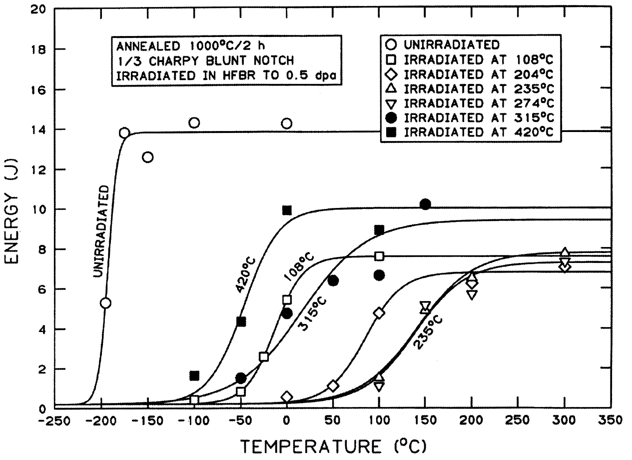

Fig. 20. Charpy impact energy as a function of temperature for V–4Cr–4Ti irradiated to 0.5 dpa at temperatures of 108–420°C.

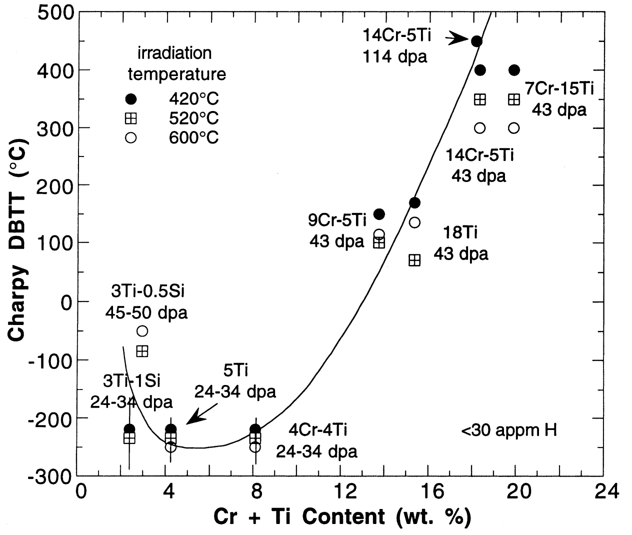

Fig. 21. DBTT of irradiated vanadium alloys as a function of Cr and Ti concentration.

9. Conclusions

The vanadium–chromium–titanium alloys provide an attractive structural material option for a first-wall/blanket of a fusion system. A V–4Cr–4Ti alloy appears to be a near optimum composition, although further development and optimization is required to evaluate effects of nonmetallic elements and other alloying additions on the properties.

Results obtained to date indicate that vanadium alloys offer the following features that can enhance the attractiveness of fusion as an energy source:

- Vanadium alloys are readily fabricable and can be welded.
- Vanadium alloys can operate at high temperatures and accommodate high-surface heat fluxes.
- Vanadium alloys provide safety and environmental advantages associated with low-activation characteristics, high-temperature properties, and low-decay heat-generation rate.
- Vanadium alloys are resistant to irradiation-induced swelling and embrittlement over a wide temperature range.

The primary issues that require further research involve effects of high helium concentrations on the properties of neutron-irradiated alloys, effects of nonmetallic element concentrations on properties, and weld development including the effects of irradiation on weldments. In addition, electrically insulating coatings for lithium-cooled systems require further development.

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