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Present status of vanadium alloys for fusion applications

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ABSTRACT

Vanadium alloys are advanced options for low activation structural materials. After more than two decades of research, V–4Cr–4Ti has been emerged as the leading candidate, and technological progress has been made in reducing the number of critical issues for application of vanadium alloys to fusion reactors. Notable progress has been made in fabricating alloy products and weld joints without degradation of properties. Various efforts are also being made to improve high temperature strength and creep-rupture resistance, low temperature ductility after irradiation, and corrosion resistance in blanket conditions.

Future research should focus on clarifying remaining uncertainty in the operating temperature window of V–4Cr–4Ti for application to near to middle term fusion blanket systems, and on further exploration of advanced materials for improved performance for longer-term fusion reactor systems.

1. Introduction

Vanadium alloys are one of the three candidate low activation structural materials for fusion reactors along with Reduced Activation Ferritic/Martensitic (RAFM) steels (including ODS ferritic alloys) and SiC/SiC composites. Of the three candidates, vanadium alloys are the only option that is both non-ferromagnetic and ductile. Thus, they are promising for advanced fusion reactor structural material applications. The three candidate structural materials can be categorized into those for primary option (RAFM) and for advanced options (V-alloy, SiC/SiC, others). Although a large fraction of current research efforts are devoted to development of RAFM for early and sound realization of DEMO, continued efforts are considered to be necessary for the advanced options to mitigate risk and provide potential advancement of the fusion concept in a longer term development strategy.

Research over the past two decades has shown that V–4Cr–4Ti is the leading candidate composition. However, different compositions and/or different fabrication processes have been explored to enhance the performance of vanadium alloys. Overviews of vanadium alloys for fusion reactor applications are available in recent proceedings papers of ICFRM [1–6] and an overview article [7]. This article focuses on the recent progress in the development of vanadium alloys for application to fusion reactors. It should also be noted that vanadium alloys are now also regarded as attractive candidate materials for advanced sodium or gas cooled fast reactors because of its low neutron penalty relative to other higher melting temperature materials [8].

2. Concepts and issues of blankets using vanadium alloys

One advantage of using a vanadium alloy as a structural material is that the blanket operation temperature can be higher than that for RAFM steels. Potential coolants are liquid metals, molten salts or He gas. Table 1 compares blanket development issues associated with several vanadium alloy–coolant combinations. The leading blanket concept for DEMO and commercial reactors with vanadium alloys as a structural material uses liquid lithium for both breeding and cooling functions (self-cooled Li/V blankets) [9,10]. One of the attractive features of this blanket system is that neutron-multiplying materials such as beryllium or lead are, in most cases, not needed for obtaining the required Tritium Breeding Ratio (TBR). Without beryllium, the system is released from the issues specific to beryllium such as handling safety and natural resource limits. Moreover, the blanket replacement frequency will be reduced once long-life structural materials are developed, because the blanket system is freed from the need for periodic replacement due to burning of beryllium. Without beryllium, the blanket can be designed with much simpler structures. However this concept has two major issues, i.e. tritium recovery from liquid lithium and magneto-hydrodynamic (MHD) pressure drop.

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Table 1
Comparison of issues for blankets using vanadium alloys with different coolants.

Coolant	Compatibility	Effects of magnetic field	Tritium leakage	Tritium recovery	Tritium inventory in V-alloy	Technological challenge
Liquid Li	Minor	Critical (MHD pressure drop)	No	Critical	Minor	MHD coating T recovery
Li–Pb	Critical (oxidation, Pb attack)	Critical (MHD pressure drop)	Moderate to critical	Moderate	Moderate to critical	MHD coating Corrosion protection T permeation barrier
FLiBe	Critical (fluoridation, oxidation)	Moderate (thermofluid)	Critical	Moderate	Critical	Corrosion protection T permeation barrier
He	Critical (oxidation, nitriding)	No	No	Critical	Minor	Corrosion protection T recovery

Combinations of vanadium alloys with other coolants have not been well investigated. In all cases other than lithium, compatibility is the key issue.

Because tritium solubility is high, the inventory of tritium in vanadium alloys can be an issue when tritium partial pressure in the system is high. Fig. 1 compares the calculated equilibrium tritium inventory in V–4Cr–4Ti at 1000 K for four different coolant conditions as a function of tritium level in the coolant. The calculation is carried out assuming 700 tons of V–4Cr–4Ti and a Sievert's constant of $0.04/\text{atom}^{0.5}$ [11]. The solubility of tritium was assumed to be $2 \times 10^{-3}/\text{Pa}^{0.5}$ in Li [12] and in $3 \times 10^{-11}/\text{Pa}^{0.5}$ in FLiBe [13]. The solubility in Li–Pb is still controversial. The figure shows two representative cases of (1) low ($2 \times 10^{-8}/\text{Pa}^{0.5}$) [14] and (2) high ($1 \times 10^{-6}/\text{Pa}^{0.5}$) [15] solubility. The calculation for the FLiBe blanket was reported in Ref. [16]. Considering that the typical DEMO reactor tritium inventory limit for in-vessel components is less than 1 kg [17], the figure indicates that the inventory is unacceptably high (10 kg≪) within a reasonable range of tritium level in FLiBe (0.01 appm<). In this case a special effort to reduce the tritium partial pressure is necessary such as TF (Tritium Fluoride) control as proposed in [18] and analyzed in [16]. The tritium inventory in the case of Li–Pb is marginal depending on the solubility data. Only in the case of higher solubility and with a low tritium level in the coolant, the inventory could be within the acceptable range (<0.1 kg).

3. Fabrication and joining/coating technology

Pioneering efforts for fabrication of V–4Cr–4Ti ingots were carried out in the US (US832665, US832864, ingots of 500–1200 kg) in

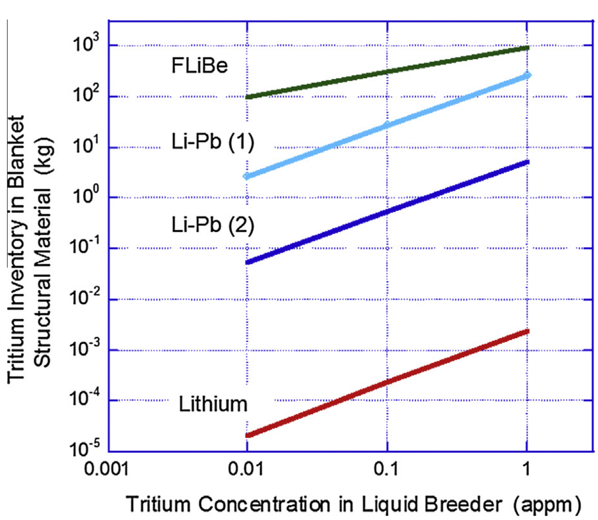

Fig. 1. Equilibrium tritium inventory in V–4Cr–4Ti structural materials at 1000 K for three tritium breeders as a function of tritium level in the breeders assuming self-cooled FFHR reactor [16]. The physical values assumed were shown in the text.

late 1990s [19], followed by Japan (NIFS-HEAT-1, NIFS-HEAT-2, ingots of 30–160 kg) in early 2000s [20,4]. The Japanese ingots had lower oxygen level, which resulted in enhanced workability and weldability. Fabrication efforts were recently made in Russia (RF-VVC-2, VM-DPCh-9, ingots of 30–110 kg) in 2000–2013 [21], in China (SWIP-30, ingots of 30 kg) in 2010 [22], and in France (CEA-J57, ingots of 30 kg) in 2011 [23]. Similar and consistent fundamental properties have been obtained for these materials.

Initial welding research focused on Gas Tungsten Arc (GTA) welding. Weld performance progressed [ductile–brittle transition temperature (DBTT) decreased] by purifying the base metal and the welding atmosphere [24]. Later, use of the high purity NIFS-Heat and ultra-high purity V–4Cr–4Ti filler metal resulted in further improvement by reducing the O level in weld metal [25]. Later, laser and electron beam (EB) welds have been investigated mainly in the Japanese program.

Fig. 2 compares the absorbed Charpy impact energy for GTA [25], laser [26] and EB [27] welds for the same V–4Cr–4Ti alloy. Interestingly, although the absorbed energies of GTA and laser are close to those of the base metal, those of EB welds were much higher. Fig. 2 also shows cross sectional views of the joints and microstructures by SEM. The weld bead is largest in GTA followed by laser and EB. In contrast to coarsened and elongated grains observed in GTA and laser welds, a fine dendritic microstructure was observed in EB welds [27]. Because of narrow bead and low input energy, the cooling rate is higher for the EB welds. This is thought to result in the fine microstructure and high absorbed Charpy energy.

The data in Fig. 2 suggest that post-weld heat treatment (PWHT) to remedy the degraded properties of the joints is unnecessary for structural components. However, weld joints are more sensitive to neutron irradiation than the base metal because Ti-CON precipitates, which trap the interstitial atoms and can act as sinks for radiation-induced defects, are dissolved. Neutron irradiation at 723 K to 8.5 dpa of laser weld joints shows that the DBTT shifts from <134 K to higher than 423 K. But the DBTT can be recovered back to 243 K by post-irradiation annealing at 873 K for 1 h [28]. Research on the effects of PWHT on radiation effects of weld joints is scarce. It was reported that the hardness change of weld metal by irradiation decreased with an increase in the PWHT temperature and became almost zero at a PWHT temperature of 1223 K [29].

Considering that in any blanket concept connection is necessary between in-vessel cooling pipes and out-of-vessel heat exchange or tritium recovery systems, vanadium alloys need to be joined with other out-of vessel materials. Studies on welding of V with steels or other refractory metal are limited, however. EB welding of V with SS316L showed that PWHT over 873 K resulted in the formation of a hard phase (Fe–V sigma phase) [30].

For the use of vanadium alloys as fusion reactor blankets the plasma-facing surfaces need to be protected by armor materials such as W layers. Limited efforts are however available for developing the