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Compatibility of vanadium alloys and its weld joints in homogeneous and heterogeneous liquid lithium systems

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Abstract

The self-cooled liquid lithium fusion reactor blanket concept has considerable attractions. Liquid lithium compatible structure materials working at high temperature and under liquid metal flow conditions are needed for realization of the concept. On the basis of the corrosion tests of vanadium-based alloys and vanadium alloys together with 316Ti type SS, some conclusions and recommendations are given for the optimization of liquid metal blanket operating conditions, alloys composition, lithium purity and material choice.

1. Introduction

At present the most promising and advanced concept of self-cooled Li–Li blanket for a prototype fusion reactor is based on liquid lithium as a tritium breeder and as a coolant at the same time, and on low-activated vanadium alloy system, V–Ti–Cr, as a structural material with AIN based electrical insulating coating [1–4]. The V–4Ti–4Cr alloy and, probably, a V–10Ti–5Cr alloy will be used as structural materials operating at 700°C. External lithium systems operating at <700°C would be fabricated of type 316 austenitic steel or, more preferably, of 9% chromium steel. All the above-mentioned materials need to be compatible with lithium beyond other requirements of the blanket and its external system operating conditions.

2. Corrosion and compatibility of vanadium-based alloys with lithium

The corrosion behaviour of vanadium-based alloys depends substantially on the temperature, lithium purity and presence of dissimilar materials in the liquid metal system. The mass transfer rate of vanadium alloys in lithium flow is low due to the low equilibrium solubility of vanadium in high-purity lithium which depends on temperature as [5]

$$\ln C(\text{at.frac.}) = 5.69\text{–}22050/T. \quad (1)$$

A monometallic loop facility has been fabricated of V–4Ti–4Cr alloy [6] to develop the technology of vanadium alloy constructions and to study their behaviour in lithium. Tests of V–4Ti–4Cr and V–10Ti–5Cr alloys conducted in lithium flow with <70 wppm of nitrogen at velocities up to 1 m/s and temperatures up to 700°C during 1000 h [7] have shown (Fig. 1) that in these conditions the minor absorption of nitrogen impurity by alloys from lithium is a predominant process. The capacity to pick up nitrogen increased with an increase of titanium content in the alloy and it was higher for those specimens which had weld joints. Mechanical properties of specimens have been practically unchanged after exposure in lithium.

The corrosion effect of lithium in homogeneous conditions has resulted in slight etching of grain boundaries of specimen surface and in the solution of carbides on the surface in the weld zone (Fig. 2). At 450–550°C the character of the nitrogen impurity influence in thermal convention lithium flow on the vanadium alloy mass transfer rate may be assessed. The available data (Fig. 3) show the vanadium alloy solution rate to be non-monotonic as a function of nitrogen concentration in lithium flow. The solution rate has a minimum at ~200 wppm of nitrogen content in lithium flow ~450°C, as seen in Fig. 3.

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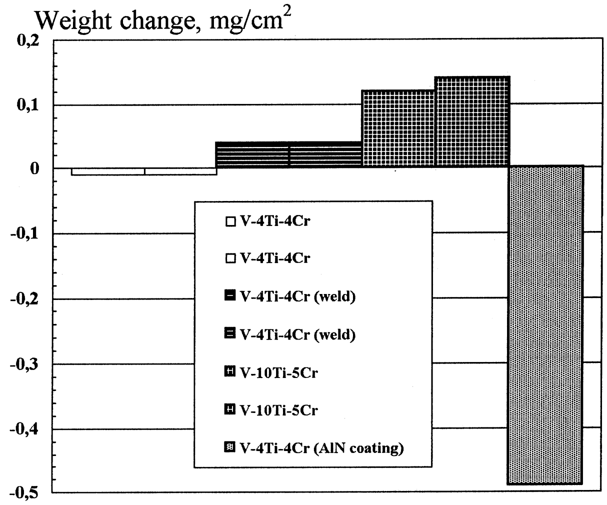

Fig. 1. Weight change of specimen after 1000 h test in a vanadium-lithium loop.

This is likely to result from the nitride film formation on the vanadium alloy surface, the solubility of which in lithium is low, on one hand, and from a certain increase in film component solubility in lithium for higher nitrogen concentrations, on the other hand. The vanadium alloys have by far the advantage of mass transfer in lithium flow with nitrogen impurity over chromium and chromium-nickel stainless steels [8], as seen in Fig. 4.

A peculiar case of corrosion interaction may take place in a lithium system in the vanadium alloy-steel weld zone. In this case steel is the source of carbon impurity for vanadium. Pure vanadium can be embrittled completely under these conditions [9]. To study the resistance of V–Ti–Cr alloys to lithium in heterogeneous conditions, simultaneous tests of V–4Ti–4Cr, V–9Ti–4Cr and V–15Ti–7Cr together with type 304Ti steel have been conducted under static conditions at 700°C. These tests were made in ampules of V–8Cr alloy for over 1040 h. The vanadium to steel surface ratio of specimens was $S_V/S_{Steel} = 3.4$. Lithium initially contained 150 wppm of nitrogen impurity and <30 wppm of aluminum impurity. The self-heading effect of AIN-based insulating coating on vanadium alloy was simulated by the introduction of nitrogen into lithium up to 500 wppm and ∼3 wt% of aluminium.

In this case the nature of mass transfer was changed and Fe rather than Ni is mainly transferred to vanadium alloy in lithium with an elevated content of nitrogen and aluminum (see Table 1). It is necessary for this to be taken into account in the development of a technology of coating for application in heterogeneous lithium systems. The observed transfer of steel components to vanadium alloy was suppressed by the introduction of nitrogen and aluminium additions to lithium (Fig. 5). As seen from the data given in Fig. 6, the decrease of V–4Ti–4Cr alloy plastic properties without fracture mode change and increase of steel plasticity are evident in heterogeneous conditions.

The microhardness distribution in vanadium alloy cross sections (Fig. 7) shows the formation of a hard surface layer of ∼90 μm thick on V–4Ti–4Cr and V–9Ti–5Cr alloys at the heterogeneous test condition. An increase of titanium concentration in vanadium alloys or an introduction of aluminum impurity into lithium eliminate the mechanical properties change under test conditions (see Figs. 6 and 7). Thus, the elevated content of nitrogen and aluminum impurities in lithium, which is essential a priori for AIN coating stability in a lithium environment, has a favorable effect on corrosion resistance of vanadium alloys under homogeneous and heterogeneous conditions.

3. Effect of oxygen and hydrogen impurities on corrosion process

The oxygen impurity in lithium has no important effect on the corrosion behaviour of materials under consideration and its content in lithium is limited from technology considerations. Hydrogen affects negligibly the solubility of metals in lithium [10–14] and is not responsible for their embrittlement. However, this impurity activates substantially other nonmetallic impurities (C,N) in a heterogeneous lithium system [2]. This phenomenon has been noted at 100–200 appm hydrogen concentrations. The hydrogen impurity contribution to corrosion in lithium systems should be defined more exactly. This is of special importance in the case of

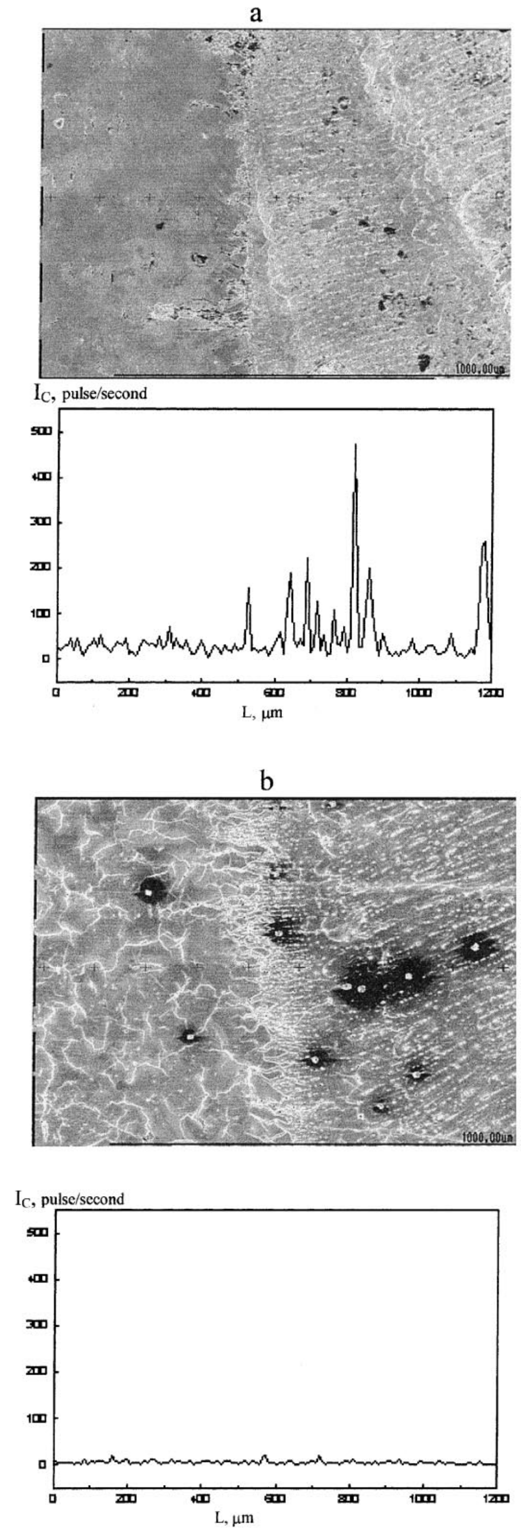

Fig. 2. SEM micrographs of the V–10Ti–5Cr specimen weld zone surface and carbon line intensity I_c distribution before (a) and after (b) exposure in Li flow.

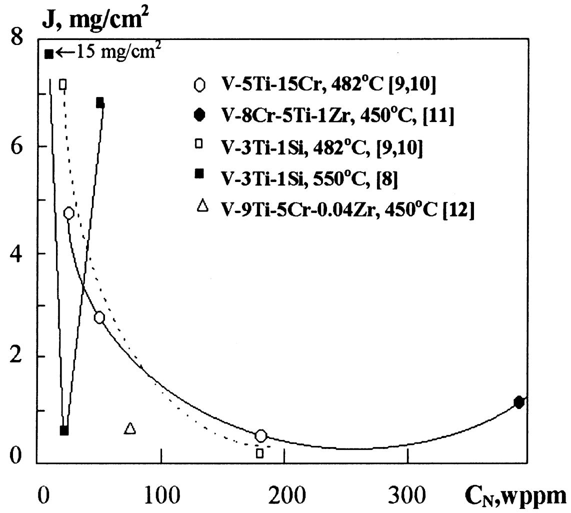

Fig. 3. The effect of nitrogen concentration in Li flow on the dissolution rate of V-base alloys.

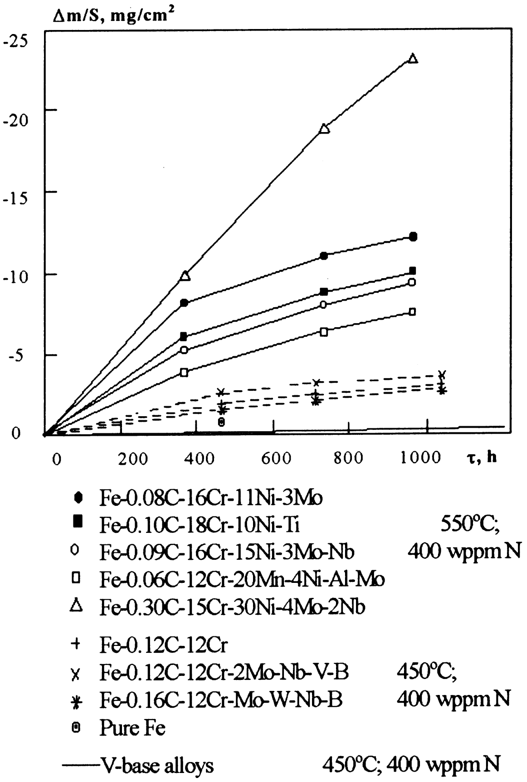

Fig. 4. Weight loss of SS and V-alloys in Li flow.

protium introduction provided by the technology of tritium extraction from lithium. The effect of irradiation on lithium system compatibility has been investigated extremely poorly and presents a particular problem.

Table 1
Surface chemical composition of V–4Ti–4Cr alloy after test in static lithium at 700°C, 1040 h

Test condition/initial impurity concentration in lithium (wppm)	Concentration of element (wt%)				
	Fe	Cr	Ni	Ti	Al
Homogeneous/150 N, $\leqslant 30$ Al	<0.2	3.1	<0.1	4.9	<0.3
Heterogeneous/150 N, $\leqslant 30$ Al	8.4	15.8	22.8	16.2	0.5
Heterogeneous/500 N, $\sim 3.10^4$ Al	48.2	3.4	5.9	10.4	11.5

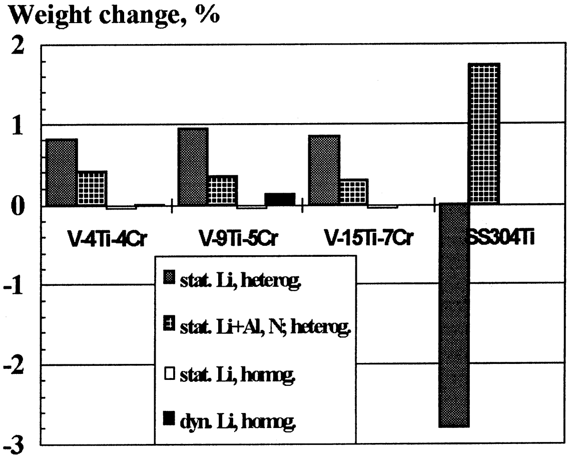

Fig. 5. Weight change of V alloys and SS specimens after 1040 h test in static lithium at 700°C.

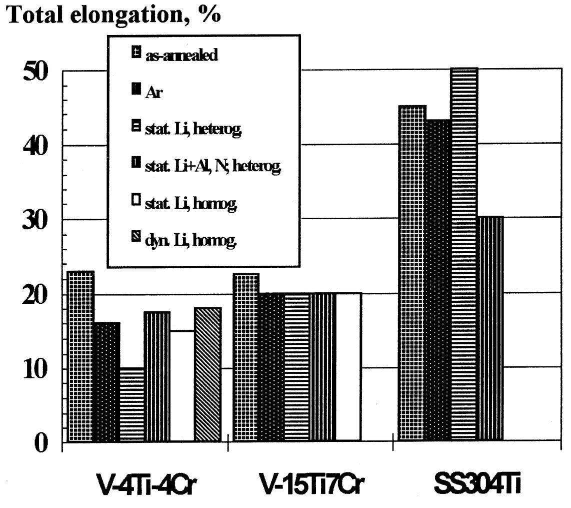

Fig. 6. Total elongation of V alloys and SS specimens after 1040 h test in static lithium at 700°C.

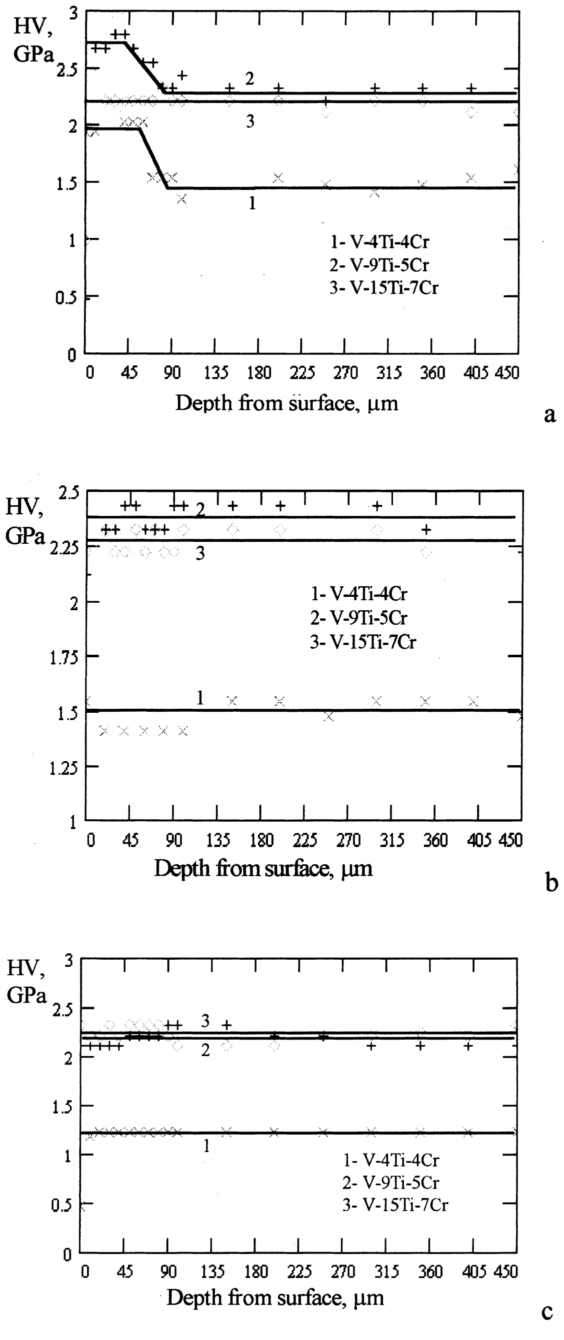

Fig. 7. Microhardness distribution in cross section of vanadium alloys after 1040 h tests at 700°C in Li + 0.02%N with 304Ti SS, (a) Li + 0.02%N, (b) Li + 0.05%N + 3%Al with 304Ti SS (C).

4. Conclusions

The high corrosion resistance of vanadium alloys of the V–Ti–Cr system has been experimentally confirmed for blanket operating conditions. The corrosion resistance of vanadium alloys to lithium and their compatibility with stainless steels increased with increasing titanium concentration in alloy and adding Al and N impurity to lithium which provide for the stability of an electrically insulating coating on vanadium alloy.

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