Fusion Engineering and Design 107 (2016) 25–31

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Deuterium blistering in tungsten and tungsten vanadium alloys

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ARTICLE INFO

Article history:
Received 12 November 2015
Received in revised form 14 March 2016
Accepted 28 March 2016
Available online 14 April 2016

PACS:
(53.40.Hf.81.05.Bx)

Keywords:
Tungsten-vanadium alloy
Deuterium plasma
Blistering

ABSTRACT

In order to evaluate D blistering behavior in W based plasma facing materials, rolled W and different grades of W-V targets were exposed to high flux of 1.2×10^{24} m^{-2} s^{-1}, low energy (38 eV) D plasma at two different surface temperatures. The blistering behavior was investigated by means of scanning electron microscopy, accompanied by electron back-scattering diffraction. Highest numbers of blisters were observed on the surface of rolled tungsten. The addition of V precursor to W suppressed D blister formation. In the case of W-V alloys, comparatively submicron V-containing materials have shown high tendency but small size blisters formation than micron V-containing samples. A high density of blisters was observed near the (111) plane on the surface of both V-containing alloys. Nano-sized blisters were also observed on V enriched surface.

1. Introduction

One of the main challenges for the development and viable operation of a fusion power reactor is the development of plasma facing materials (PFMs). W due to its durability and favorable physical properties at elevated temperatures is considered as a choice for PFMs in an advanced fusion reactor [1–5].

Indeed, W will be used in ITER as the PFMs in the divertor, where it will face high heat fluxes of up to 10 MWm^{-2} and high particle fluxes, helium (He) and hydrogen isotopes (H)of up to 10^{24} m^{-2} s^{-1}, while loads at other plasma-facing walls can be orders of magnitude smaller [6]. These loads on W change the morphology of the surfaces and possibly degrade its physical and mechanical properties. This issue calls for the development of new W based alloys with improved ductility and better structural properties for fusion environment. A lot of research is going on to develop and characterize W based materials with improved properties and microstructures, which can withstand the intense environment of fusion reactor [7–16].

A limited number of elements form solid solution and have significant solubility in W at room temperature. Only few of them do not form brittle intermetallic compounds with W. Ta, V, Nb and Mo have full range solubility in W, while Ti and Re have limited solubility and maximum contents of about 12 and 27%, respectively, due to the formation of intermetallic σ- and χ-phases [17,18]. Re is the only known alloying metal used for ductilization of W by solid solution [19]. The other mentioned metals also form solid solution but cannot reduce the ductile-brittle transition temperature of W based materials. For PFMs, Re addition to W is to be avoided due to its activation and the formation of brittle phases due to transmutation of Re into Os [20]. Similarly, applicability of Nb and Mo for fusion applications is doubted because they transmute to very long-lived radioactive isotopes [21]; this leaves Ta, V, and Ti as possible alloying elements for W based materials. Recent studies of W-Ti alloys, fabricated by different routes, failed to promote promising results [22,23]. The formation of metastable Ti phases is responsible for poor mechanical properties of W–Ti alloys. The fracture toughness of the W-Ta alloys decreases with the increase of Ta concentration [24].

From our recent studies it is suggests that the addition of V in W constrains the grain growth and improves the densification and mechanical properties [25]. Fine-grained W materials have shown attractive properties in terms of reduction in brittleness and improvement in toughness and strength [26,27]. The fracture toughness of the alloys is gradually increased with the increase of V concentration [25]. Furthermore, the V precursor powder size

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http://dx.doi.org/10.1016/j.fusengdes.2016.03.072
0920-3796/

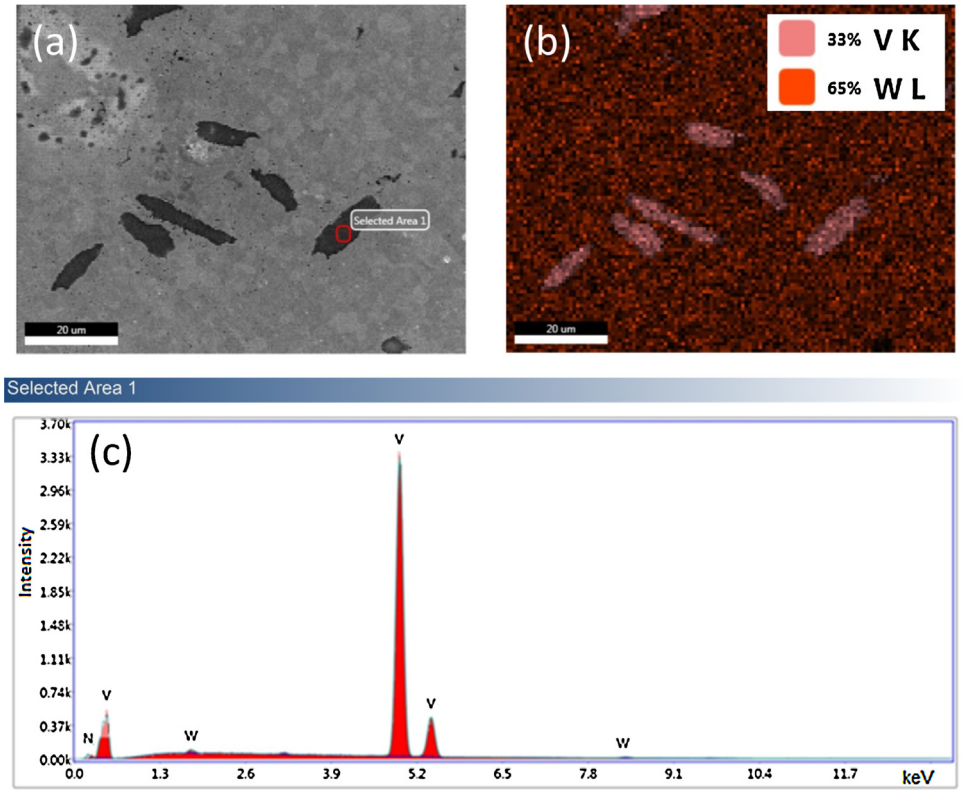

Fig. 1. Phase analysis of the unexposed WVm sample (a) SEM image, (b) elemental map distribution of the same area and (c) EDS of V enriched phase respectively.

also plays an important role in the grain refinement and improvement of mechanical properties of the fabricated W-V alloys [28]. The addition of submicron V precursor highly improved mechanical properties including micro-hardness and fracture toughness of W based alloys as compared to micron V precursor. Similarly a large refinement of W grains can be achieved by adding submicron V precursor [28]. The mechanical properties of W at high temperatures (higher than the recrystallization temperature) are also highly deteriorated [26,27], where V addition also enhances the thermal stability of the microstructures and mechanical properties of W-based materials [29]. Moreover, V shows high stability against activation and transmutation under neutron irradiation as compared to W, Re, Ta etc. [30].

Change of the material microstructures and composition due to neutron transmutation can influence hydrogen trapping in W. V addition provides stability to W microstructures and reduces its degradation against neutron. Until now, there is no experimental study available on the subject of D implantation in different grades of W-V alloys. The present work is performed to obtain important information about the influence of different V precursor admixture in W on the D-induced morphology changes.

2. Experimental procedure

2.1. Target materials

Spark plasma sintering (SPS) fabricated W-V alloys with different V precursor particle size, micron-size (WVm) and submicron size (WVs) at 5 wt.% of V were mixed with W in a planetary ball miller. The average precursor particle size of micron and submicron V powder was 48 μm and 0.8 μm respectively, where 2 μm powder size was used for W. The powders were mechanically milled in a planetary ball miller and sintered by SPS at 1873 K for 3 min [25]. During the start of the sintering process a uniform 20 MPa pressure was applied to press the samples and rose to 50 MPa after 1773 K. Commercially available rolled W samples were also tested for comparison. The surface of each sample was mechanically polished to a mirror finish. Due to short dwell time of 3 min at peak sintering temperature of 1873 K, relative low grain growth took place and the average grain size of WVm and WVs was ~2.4 μm and 1.8 μm respectively.

2.2. Experimental setup

The Pilot-PSI linear plasma generator at FOM Institute DIFFER (Netherlands) was used for this investigation. It is capable of delivering low energy, high flux D plasma to simulate ITER like conditions [31]. The detailed design and parameters of Pilot-PSI for D irradiation has been reported by Hoen et al. [32]. The plasma beam distribution on the target surface has been discussed by Zayachuk et al. [14]. The incident D plasma energy and flux were set to 38 eV and $\sim 1.2 \times 10^{24}\ m^{-2}\ s^{-1}$ respectively, with the fluence in the order of $10^{26}\ m^{-2}$. The predominant ion species was D^+. Two different surface temperatures 453 K and 573 K were used for comparison, and were measured by an infrared camera. The irradiation parameters of the target samples such as deuterium fluence, irradiated temperature and blistering at different W based targets are tabulated in Table 1. The morphology of the exposed samples and occurrence of blistering were analyzed with scanning electron microscopy (SEM), electron back-scattering diffraction (EBSD) and energy-dispersive X-ray spectroscopy (EDS).

3. Results

3.1. Phase analysis

To identify W and V phases of WVm alloy, the phase analysis of unexposed sample were performed. Fig. 1 The SEM images