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Plasma exposure behavior of re-deposited tungsten on structural materials of fusion reactors

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ABSTRACT

To evaluate the effects of re-deposited tungsten (W) on the surface modification and hydrogen isotope retention behavior of fusion structural materials, the plasma exposure behavior of re-deposited W samples prepared by magnetron sputtering on the F82H steel, the V-5Cr-5Ti alloy as well as bare substrate samples was investigated. All the samples were exposed to 367 shots of deuterium plasmas in the 2015 spring EAST campaign. After the plasma exposure, large area of W layer was exfoliated, while big blisters were found at the interface between the remaining W layer and the substrate materials. The deuterium retention behavior of the samples with re-deposited W layer was characterized by thermal desorption spectroscopy and compared with the bare substrate samples.

1. Introduction

Tungsten (W) has a high melting point, low sputtering yield and low tritium retention, thus in the design of future fusion reactors, it is currently a leading material choice for plasma facing materials (PFMs) of the divertor [1,2]. For plasma facing components (PFCs) with relatively small particle fluxes such as the first wall (FW), a thin layer of tungsten (W) armor on structural materials is supposed to be the PFM in most scenarios. However, considering the fact that the W armor could bring issues such as reduction of tritium breeding ratio (TBR), higher cost and technological challenge in bonding W with structural materials, bare structural materials such as reduced activation ferritic/martensitic (RAFM) steels and V-(3–5)Cr-(3–5)Ti alloys have been proposed as the FW PFMs in many blanket concepts for DEMO and commercial reactors [3]. W eroded in the divertor may transport and deposit onto the FW surface, which will change the surface conditions and meanwhile influence the retention behavior of hydrogen isotopes in the FW. Previous investigations have shown that the amount of retained hydrogen isotope in re-deposited W on W substrate is huge [4–6]. However, the plasma exposure behavior of re-deposited W on structural materials of fusion reactors has not yet been clarified sufficiently, especially for re-deposited W at the initial stage with a small thickness.

This work aims to experimentally study (a) surface modification of re-deposited W on structural materials after exposure to deuterium plasmas in the EAST tokamak and (b) deuterium retention of re-deposited W on structural materials compared with bare structural materials after exposure to deuterium plasmas in the EAST tokamak. As in the real tokamak devices, the FW will be continuously eroded by charge exchange particles, co-deposition of eroded PFM of the FW with W could be formed. In this study, we have focused on the re-deposition of W.

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2. Experimental

2.1. Preparation of re-deposited W specimen

Two kinds of structural materials were used in this work, including a vanadium alloy, the V-5Cr-5Ti manufactured by the General Research Institute for Nonferrous Metals and a reduced activation ferritic/martensitic (RAFM) steel, the F82H steel. Samples with dimensions of 10 mm × 10 mm × 1 mm were cut and mechanically polished to a mirror finish. Then the F82H steel samples were electro-polished in 10 wt.% $HClO_4$ alcoholic solution at ~253 K. The surface morphology of the F82H steel sample is shown in Fig. 1a. Re-deposited W layer was prepared on the F82H steel and V-5Cr-5Ti samples using a magnetron sputtering device. The morphology of re-deposited W layer is shown in Fig. 1b. Deposition was performed in argon atmosphere at 1 Pa. During W deposition, the DC power applied to the W sputtering target was kept constant at 120 W. All samples were re-deposited in one turn with a total deposition time of 2 min. The deposition rate of W in the magnetron sputtering device with certain DC power and argon atmosphere pressure has been calibrated by TEM, and the thickness of the W layer ~10 nm is obtained by calibrated deposition rate multiplied by deposition time.

2.2. Deuterium plasmas exposure experiments in EAST

During the 2015 spring EAST campaign, re-deposited W samples and bare substrate samples were exposed to 367 shots of deuterium plasmas employing the material and plasma evaluation system (MAPES) at the mid-plane of EAST. The samples were irradiated with a total plasma exposure time ~2000 s. The sample surface is 5 mm behind the limiter and the local electron temperature and density are measured to be $T_e = 5–10$ eV and $n_e = \sim 1 \times 10^{18}$ m^{-3} by a Langmuir probe. The temperature varies from 323 to 623 K due to the heat from plasmas measured by thermocouples attached to the backside of the samples. Detailed description of MAPES can be found in a previous paper [7], and detailed description of the MAPES experiments during 2015 spring EAST campaign can be found in a previous paper [8].

2.3. Characterization techniques

Before and after the plasma experiments, surface morphology of the samples was examined by a field emission gun scanning electron microscope (SEM). The chemical composition was identified by means of an energy dispersive spectrometer (EDS) coupled to the SEM instrument. Thermal desorption spectra (TDS) experiments were performed to characterize the deuterium retention behavior. Samples were heated up to 1273 K with a heating rate of 10 K/min. Desorption signals were monitored with a quadrupole mass spectrometer, which was calibrated with a standard leak.

3. Results and discussion

Shown in Fig. 2 are the SEM images of re-deposited W layer on the F82H steel and the V-5Cr-5Ti samples after exposure to EAST deuterium plasmas. Large area of exfoliation and blisters could be seen on both samples. To further confirm the position of blisters in the cross-section direction, EDS line scan experiments are performed on a rupture blister on the F82H steel sample with W layer, as shown in Fig. 3. The W signal increases when the distance goes from ~13 to 17 μm, and decrease to the background with the signal of Fe increasing when the distance goes from 17 to 27 μm. The increase of the W signal is owing to the height difference, which shows that the layer exfoliated is mainly W. In addition, the W signal is close to the zero with the relatively high Fe and Cr signal where the bubble dome is off, which shows that the layer exfoliated is W. Similar phenomenon has been observed on the V-5Cr-5Ti sample, too. It can be concluded that the blisters are located at the interface between the W layer and the structural materials. Despite that, it can be inferred that the exfoliation of the W layer is mainly induced by the bursting of the blisters. The heat cycle shot by shot giving thermal expansion can not be the main reason for the exfoliated W layer. Because on one hand, the change of temperature between shots is limited in a range blow 200 °C, on the other hand, if the heat cycles are the main reason, there should be long cracks not blisters, and the surface morphology of the W layer on the F82H steel should be almost the same as the one on the V-5Cr-5Ti.

In Fig. 2, the exfoliation of W layer on V-5Cr-5Ti sample is relatively more serious with relatively less remaining W layer compared to the F82H steel sample. Two important points should be noted. One is that at the initial stage of the formation of re-deposited W layer when the thickness of the W layer is small, the plasmas in the tokamak may crack the uniform surface, leading to exfoliation of the W layer. Thus, it may be not suitable to use thick (micron or larger) W layer to simulate the re-deposited W layer on RAFM steels or vanadium alloys. Meantime, considering that many works have been done using micron sputtering W layer on bulk W samples to simulate the re-deposited W [4–6,9], more work should be done to confirm if this simulation is adaptable. The other important point is that the exfoliation of the W layer leads to the formation of W dust in the tokamak [10]. As W is a high-Z material,

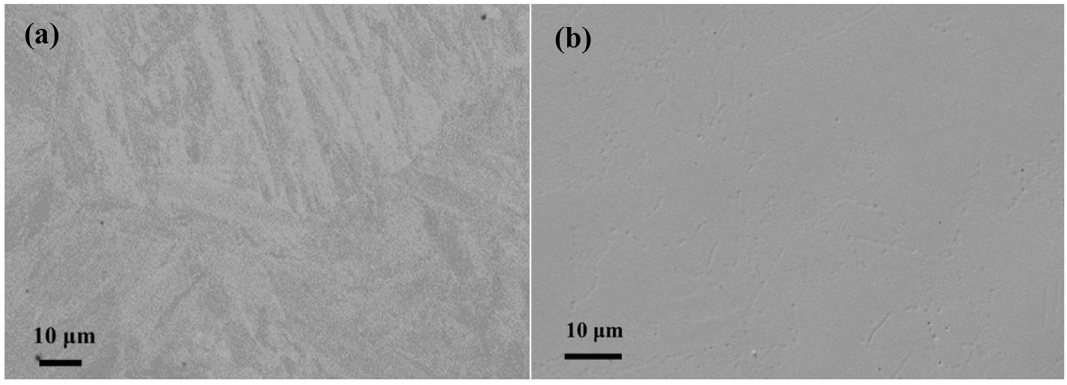

Fig. 1. (a) Surface morphology of bare F82H steel samples after mechanical-polish to a mirror finish and electro-polish in 10 wt.% $HClO_4$ alcoholic solution at ~253 K; (b) surface morphology of re-deposited W layer prepared by magnetron sputtering.