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Influence of carbon-dominated deposition layer on He retention and desorption in tungsten

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ABSTRACT

Pure tungsten (W) samples were respectively installed on the two positions of typical plasma wall interaction area (PI) and erosion dominated position (ER) on the first wall in the Large Helical Device (LHD) at National Institute for Fusion Science (NIFS), Japan. After the experiment campaign in 2014, these samples were picked up and thermal desorption spectroscopy (TDS) were applied to evaluate their desorption behavior of He which was implanted by He discharge. It was found that a carbon-dominated mixed-material layer with impurities, such as Fe, Cr, Mo, O and N, etc., was deposited layer by layer during the plasma exposure on the PI sample. On the other hand, W-C mixed layer was formed on the ER sample. The results showed that a large amount of He was trapped in the samples on both PI and ER, and the total He retention for ER is about twice as large as that of PI. He was trapped in various types of trapping sites in the ER sample and their desorption peaks were located at temperatures of about 425 K, 755 K, 1130 K and 1630 K. For PI sample, most of He was trapped in the carbon-dominated mixed-material layer and the corresponding desorption temperature was limited to be about 600 K, 900 K and 1200 K. The additional 3.0 keV helium ion (He^+) implantation was performed for several samples to investigate the He retention characteristics in these samples and it was found that no additional desorption stage was found. These results suggested that the He discharge history and its deposition on the W plasma facing wall would affect He desorption behavior of W.

1. Introduction

To achieve long pulse discharge with high plasma performance, and high ion temperature, He plasma discharges have been performed in Large Helical Device (LHD) at National Institute for Fusion Science (NIFS), Japan [1–3]. During the He plasma discharges, He recycling affects the plasma performance, and elucidation of He retention behavior in plasma facing materials (PFM) is quite important for the operation with higher plasma performance [4]. Tungsten (W) is considered to be the most likely candidate of PFMs for future fusion reactors, as it possess high energy threshold for sputtering, low ability for hydride formation and low hydrogen solubility level [5,6]. However, He particles would inject into W with various energies during the plasma discharges, which induces the damage introduction and impurity deposition on W plasma facing wall, leading to control the fuel retention in the fusion reactor, degrade W materials' properties and shorten their lifespan [7–9]. Furthermore, in the LHD experiment campaign, a carbon-dominated mixed-material layer with impurities of metals, oxygen and nitrogen, etc. would deposit on the W layer by layer during the experiment because of the usage of graphite in the divertor region [10–12]. Thus, the He retention behavior in the W exposed by LHD plasma experiment campaign extremely becomes complex and has been waiting to be explored.

For the purpose of understanding the He retention behavior in the plasma exposed W at LHD, the polycrystalline W were placed on the plasma facing surfaces in the typical plasma wall interaction positions. One position was the private region at the torus outboard side, where erosion and deposition is dynamically proceeded (PI). Another position was at the torus inboard side, where erosion is dominated (ER). The samples were exposed in long-term plasma throughout the 2014 experiment campaign. Then, the thermal des-

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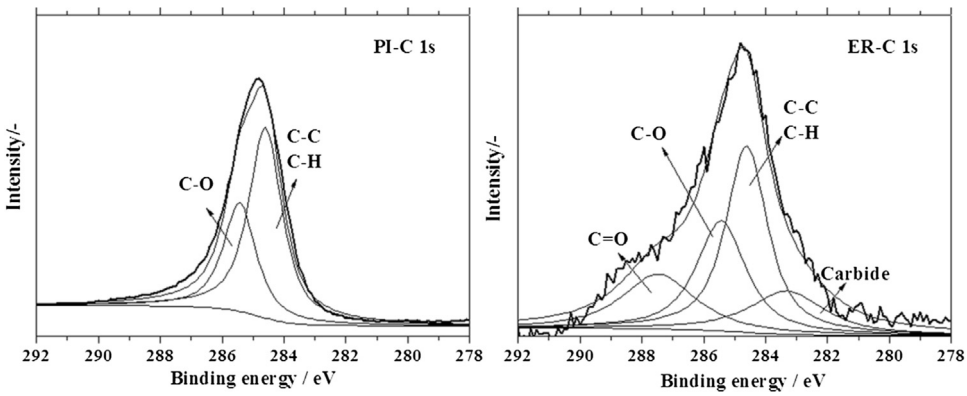

Fig. 1. The C−1s XPS spectra for the top surface of PI and ER samples.

Table 1
Atomic composition on the top surface of samples (%).

	C	O	Fe	Cr	Ni	Mo	B	N	W
PI	84.81	9.05	1.14	0.66	0.19	0.14	2.88	1.12	0
ER	53.03	27.04	0	0	0	0	0.53	0	19.39

orption spectroscopy (TDS) up to a temperature of 1773 K were applied for evaluating the He retention behavior in these samples.

2. Experimental procedures

The stress relieved W samples with size of Φ10 mm × 5 mm were mirror polished and annealed at 1173 K for 30 min under vacuum to remove the residual hydrogen and damages introduced during the fabrication and polishing processes. Then, the samples, namely PI and ER, were placed into the two typical positions on plasma facing wall in LHD. The sample labels mentioned in this work are corresponding to their positions in LHD. The exposure temperature of samples was less than 373 K during the experiment in 2014, and then the samples were picked up and transported to Shizuoka University with air exposure after the plasma discharge experiment. Surface microstructures of the samples were analyzed by scanning electron microscope (SEM) and transmission electron microscope (TEM), and their chemical states were evaluated by X-ray photoelectron spectroscopy (XPS). Their He desorption behaviors were analyzed by TDS up to the temperature of 1773 K at NIFS with high resolution quadrupole mass spectrometer (MKS Microvision 1–6 amu). For some of samples, The 3.0 keV helium ion (He^+) implantation and TDS analysis were additionally performed with the flux of 5.0×10^{17} He^+ m^{-2} s^{-1} and the fluence up to 1.0×10^{21} He^+ m^{-2} to investigate the He retention behaviors on the surface of samples explicitly.

3. Results and discussions

3.1. Chemical compositions and microstructures of the samples

Major chemical compositions except for hydrogen and helium on the top surface and depth of W samples exposed in LHD 2014 experiment campaign were analyzed by XPS. Atomic compositions on the top surface of samples are summarized in Table 1. Their C−1s and W-4f XPS spectra are respectively presented in Figs. 1 and 2. It can be seen that the top surface of PI sample was mainly consisted of carbon (C) and oxygen (O), along with impurities of metals (such as Fe, Cr, Mo), boron (B) and nitrogen (N), etc. Major chemical states of carbon were assigned to be C—C and C—H bonds. No remarkable formation of metal carbide was found. Different from the PI sample, C with O and W were detected on the top surface

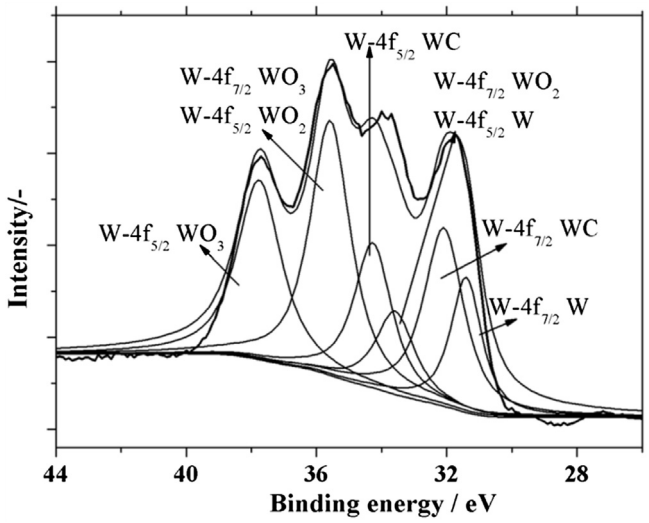

Fig. 2. The W-4f XPS spectra for the top surface of ER sample.

for ER sample. Except for C—C and C—H bonds, the carbide and C—O bonds were respectively found at the binding energies of 283.31 eV and 287.47 eV for ER. Fig. 2 revealed the presence of four kinds of chemical states for W on the ER sample, namely metal W, WC, WO_2 and WO_3. The depth profiles of constituent elements in the samples were further investigated using the combination of Ar^+ sputtering and XPS technique as shown in Fig. 3, indicating that a carbon-dominated mixed-material layer was only deposited on the surface of PI sample, and the thickness of this layer was estimated to be about 0.6 μm while the atomic concentration of W reached 50%. For ER sample, a W-C mixed layer was formed on the top surface. These results coincide with the previous studies, in which most of the positions on the plasma facing wall except for ER were deposition-dominated area [13,14].

Fig. 4(a) and (b) shows surface microstructures of PI sample after plasma exposure experiment with difference magnification. It can be seen that the sample has a smooth surface, and some visible cracks have been observed from the lower magnification view as shown in Fig. 4(b), suggesting that the implantation of energetic particles at erosion region leads to the formation of defects on the surface of PI sample. For ER sample presented in Fig. 5, two kinds of areas with bright and dark colors were found. As mentioned above, ER sample surface consisted of C, W and O. Thus, the dark areas would be the containment of carbon. On the other hand, the dark region with round-shape would be the hole due to the accumulation of helium bubble which was concentrated on the surface of W substrate. More details in the morphology of samples were ana-