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Energy and fluence dependences of helium retention in stainless steel

Y. Nobuta [a,*], Y. Yamauchi [a], Y. Hirohata [a], T. Hino [a], N. Ashikawa [b], K. Nishimura [b], A. Sagara [b], S. Masuzaki [b], T. Ozaki [b], N. Noda [b], A. Komori [b], O. Motojima [b], LHD Experimental Group[b]

[a] *Department of Nuclear Engineering, Laboratory of Plasma Physics Engineering, Hokkaido University, Kita-ku 13, Sapporo 608-8628, Japan*
[b] *National Institute for Fusion Science, Toki-shi, Gifu-ken 509-5292, Japan*

Abstract

Helium retention behavior of 316L stainless steel (316L SS) used for the first wall of the large helical device (LHD) was investigated by using an ECR plasma/ion apparatus and thermal desorption spectros copy. Samples of 316L SS were irradiated by helium ions with different energy. After helium ion irradiation with 100s eV energy, the desorption temperature of the retained helium was below 800 K. As increasing ion energy, the fraction of helium desorbed temperatures >800 K gradually increased. The retained amount of helium saturated for ion fluences above 1.0×10^{17} He/cm^2. The retained amount of He was similar to that observed in other plasma facing materials. For irradiation fluences $>1.0 \times 10^{17}$ He/cm^2, blister formation was observed. The present results are consistent with the desorption behavior of 316L SS samples exposed to LHD plasmas.

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Keywords: LHD; Helium; Ion irradiation; Stainless steel; Desorption

1. Introduction

In fusion devices, plasma facing materials are exposed to helium ash produced by fusion reactions and helium ions during helium glow discharge conditioning. Then the helium accumulates in the plasma facing walls. If the helium releases into the core plasma, the conditions of plasma energy balance and plasma heating change. Thus, it is necessary to evaluate the behavior of helium retention in the plasma facing material.

In the large helical device (LHD), 316L stainless steel (316L SS) has been used for the first wall with area of 1000 m^2, and graphite tiles in the divertor trace region with area of 34 m^2 [1]. The main plasma discharge experiments have been conducted by using hydrogen or helium gas. As the wall conditioning technique, glow discharges using helium or hydrogen gas were conducted

* Corresponding author.
E-mail address: nobuta@apollo.qe.eng.hokudai.ac.jp (Y. Nobuta).

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[2]. It was found that a large amount of helium has been retained in the plasma facing wall [3,4]. In addition, the release of helium has been observed in the subsequent hydrogen main discharge. The presence of helium changes the ICRF heating condition and dilutes the hydrogen plasma [2].

In the present study, we examined the desorption behavior of helium retained in 316L SS after helium ion irradiation using an ECR plasma/ion apparatus at Hokkaido University [5,6]. After the helium ion irradiation, the helium desorption rate was measured by using thermal desorption spectroscopy (TDS). In particular, we examined the dependence of the desorption spectrum on the helium ion energy. Based on the present results, the desorption behavior of helium retained in 316L SS samples exposed to LHD plasma discharges is discussed.

2. Experimental

The same 316L SS material as used for the LHD first wall was used in the present experiments. The sample was mechanically polished using alumina powder and rinsed by ethanol in an ultrasonic bath. After this pretreatment, the sample was degassed at a temperature of 473 K for 60 min in vacuum.

Helium ion irradiation was performed with an ECR plasma apparatus and an ECR ion apparatus; see Fig. 1. For further details of these apparatus see Refs. [5,6]. In the ECR plasma apparatus, the discharge pressure was kept at 6.5 Pa, and a negative bias voltage ranging from −200 V to −1400 V was applied to the sample in order to adjust the energy of implanted helium ions. This bias voltage roughly corresponded to the energy of implanted helium ions. In the ECR ion apparatus, implantations were performed for helium ion energy of 3 keV. During the implantation, the sample was biased at +20 V to suppress secondary electrons. In both cases, the irradiation temperature was room temperature. The helium ion fluence was measured by the current collected on the sample. After irradiation, the sample was transferred into the TDS apparatus [7], and then linearly heated from room temperature to 1273 K with a heating rate of 0.5 K/s. During heating, the desorption rate of helium was measured with a quadrupole mass spectrometer (QMS).

In the fourth experimental campaign of LHD [8], 316L SS samples exposed to only main discharges or only glow discharges were prepared. In this campaign, the total number of shots of main discharges using helium gas was approximately 4500. Helium glow discharge cleaning was employed for wall conditioning. In the helium glow discharge, the anode voltage was approximately 300 V and the total discharge time was 1600 h. The samples were placed at the port of toroidal sector #7 [8]. After the fourth experimental campaign,

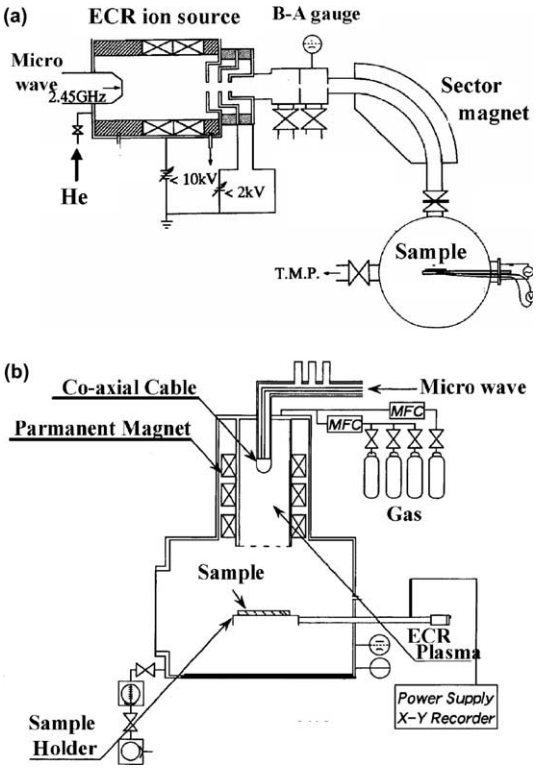

Fig. 1. (a) ECR ion apparatus; (b) and ECR plasma apparatus.

the desorption behavior of helium retained in the sample was examined using thermal desorption spectroscopy.

3. Results and discussion

3.1. Helium ion irradiation experiments

Fig. 2(a) shows thermal desorption spectra of helium for samples irradiated with different He ion energies at a fluence of 1.0×10^{16} He/cm^2 in the ECR plasma apparatus. Several desorption peaks were observed. These desorption peaks may be classified into two regimes: (i) desorption in the lower temperature region (<800 K), and (ii) desorption at temperatures >800 K. When the bias voltage was low, −200 V, the desorption amount of helium in the low temperature region was significantly large. By increasing the negative bias voltage, i.e., increasing the ion energy, the desorption peak around 1000 K became dominant. Fig. 2(b) shows the fraction of desorbed helium for the temperature regions below and above 800 K. Again, it is evident that at low bias voltages, the fraction of desorbed helium is dominant in the lower temperature region. As the bias voltage increases, the fraction of desorbed helium decreases in the low-temperature region and increases in

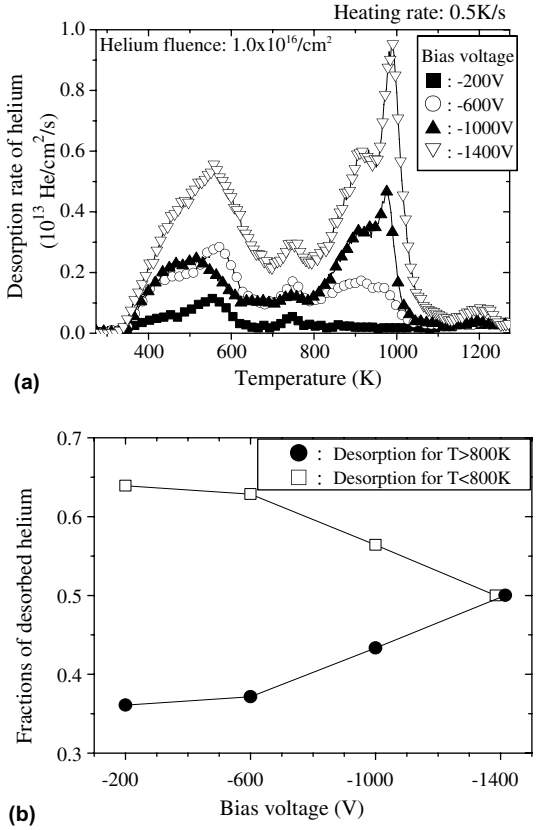

Fig. 2. (a) Thermal desorption spectra of helium for 316L SS samples after helium ion irradiation with different ion energy at a fluence of 1.0×10^{16} He/cm^2 by using an ECR plasma apparatus. (b) Fraction of desorbed helium at temperatures >800 K; and at temperatures <800 K.

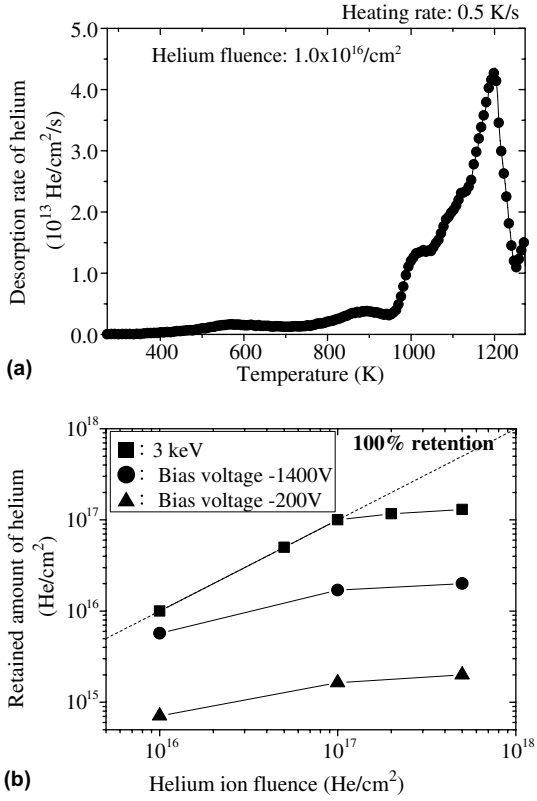

Fig. 3. (a) Thermal desorption spectra of helium for 316L SS sample after helium ion irradiation at a fluence of 1.0×10^{16} He/cm^2 by using an ECR ion apparatus. (b) Retained amounts of helium versus helium ion fluence in the case of 3 keV (ECR ion apparatus), bias voltage of 1.4 kV and 0.2 kV (ECR plasma apparatus).

the high-temperature region. In the ECR plasma apparatus, the highest ion energy corresponds to the sum of the bias voltage and sheath potential, and the helium ions with energy less than the highest energy seemed to exist due to collisions with neutral helium particles. This may be a possible reason for the appearance of desorption peaks at both the low- and high-temperature regions with the ECR plasma apparatus.

Fig. 3(a) shows the thermal desorption spectrum of helium for the sample irradiated with helium ions of 3 keV energy and 1.0×10^{16} He/cm^2 fluence using the ECR ion apparatus. The spectrum showed a sharp peak at around 1200 K, and there was little amount of helium desorbed in the low temperature region. This behavior is similar to that observed for other materials such as Cu and Ni [9,10].

In the case of the 3 keV ion irradiation, the energetic ions produce atomic displacement damage and create a large number of vacancies, where most of the helium atoms appear to be trapped by vacancies and their clusters. For low helium ion energies, where atomic displacements do not occur, the implanted helium atoms are likely to be trapped in inherent trap-sites, such as impurities and precipitates [11].

Fig. 3(b) shows the retained amounts of helium versus helium ion fluence in the case of 3 keV (ECR ion apparatus), bias voltage of 1.4 kV and 0.2 kV (ECR plasma apparatus). The retained amount of helium is seen to increase with increasing helium ion energy. For fluences greater that $\sim 1.0 \times 10^{17}$ He/cm^2, a saturation trend is observed. For 3 keV He ions, the saturation value is $\sim 1.3 \times 10^{17}$ He/cm^2, which is similar to the values published for W, B_4C, graphite and SiC [12].

Subsequent to He ion irradiation, the change of surface morphology was examined with the use of an atomic force microscope (AFM). Blisters were observed for irradiations with fluences higher than $\sim 1.0 \times 10^{17}$ He/cm^2. When the ion energy was in the range of 200–1400 eV, the lateral size and height of the blisters were ~50 nm and several nm, respectively. In the case

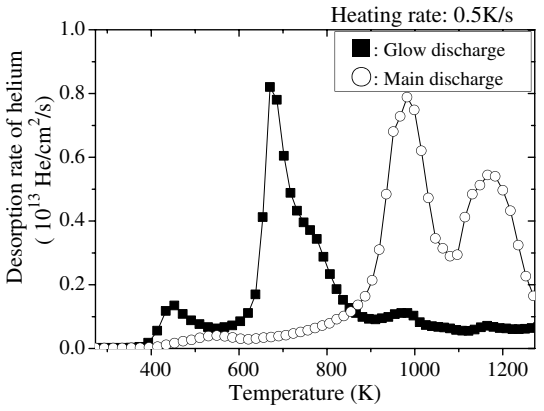

Fig. 4. Thermal desorption spectra of helium for 316L SS samples exposed to *only main discharges* and to *only glow discharges* in the LHD.

of 3 keV, the average size and height of blisters were larger, 100 nm and 5 nm. The areal number density of the blisters was 3.0×10^{10}/cm^2 at ~200 eV, and 1.6×10^{10}/cm^2 at 3 keV.

3.2. LHD samples

Fig. 4 shows the thermal desorption spectra for 316L SS samples exposed to only main discharges and only glow discharges in the LHD. The temperature of these plasma exposed samples was kept below 368 K. The amounts of desorbed helium in the sample exposed to *only main discharges* and to *only glow discharges* were 5.7×10^{15} He/cm^2 and 3.3×10^{15} He/cm^2, respectively. In the sample exposed to only helium main discharges, the retained helium desorbed mainly in the temperature region higher than ~800 K. This desorption behavior is similar to the case of helium ion irradiation with 3 keV energy. Thus, the helium desorbed from the sample exposed to main LHD discharges is regarded as charge-exchanged helium with several keV energy. On the other hand, in the sample exposed to only glow discharges, the amount of helium desorbed in the temperature region lower than 800 K was large. Since the anode voltage was 300 V, the ions with energy lower than 300 eV were implanted. This result corresponds to the case of ion irradiation with energy of several hundreds eV in the ECR plasma apparatus.

4. Conclusion

The desorption behavior of retained helium in 316L SS was examined after the ion irradiation in an ECR plasma apparatus. The thermal desorption spectra significantly depended on the helium ion energy. When the helium energy was several hundreds eV, desorption at temperatures <800 K dominated. For higher helium ion energies, the fraction of desorbed helium at temperatures >800 K also became significant. In the ECR ion apparatus, with 3 keV helium ion irradiation, the retained helium desorbed mainly at temperatures >800 K region. The retained amount of helium was seen to increase with increasing helium ion energy and tended to saturate for fluences $>1.0 \times 10^{17}$ He/cm^2. The change of surface morphology after the ion irradiation was examined. The formation of blisters with a size of 50–100 nm was observed.

In the sample exposed to *only main discharges* in the LHD, the retained helium desorbed mainly at temperatures >800 K. This result indicates that charge-exchanged helium with several keV energy were implanted into the sample. On the other hand, in the sample exposed to *only glow discharges* in the LHD, desorption at <800 K dominant. This result corresponds to ion irradiation with energy of several hundreds eV in the ECR plasma apparatus.

Acknowledgment

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