Journal of Nuclear Materials 390–391 (2009) 635–638

Contents lists available at ScienceDirect

Journal of Nuclear Materials

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

Hydrogen isotopes retention in the outboard first wall tiles of JT-60U

M. Yoshida [a,*], T. Tanabe [a], Y. Nobuta [b], T. Hayashi [c], K. Masaki [c], M. Sato [c]

[a] Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Hakozaki 6-10-1, Higashi-ku, Fukuoka 812-8581, Japan
[b] Division of Quantum Science and Engineering, Hokkaido University, Kita-13, Nishi-8, Kita-ku, Sapporo 060-8628, Japan
[c] Japan Atomic Energy Agency, Mukouyama 801-1, Naka, Ibaraki 311-0193, Japan

ARTICLE INFO

PACS:
52.55.Fa
87.64.Je
92.40.Gc
81.05.Tp

ABSTRACT

We have investigated hydrogen isotopes retention in graphite tiles used as outboard first wall armors of JT-60U by means of SEM, TDS and SIMS. The SEM examination confirmed that these tiles are mostly eroded. Different from graphite divertor tiles, in which H retention was dominant owing to isotopic replacement during HH discharges preformed after DD discharges to remove tritium, deuterium is dominated in hydrogen isotopes retention of the outboard first wall tiles showing deeper penetration. This is attributed to the injection of high energy D and less isotopic replacement due to the lower temperature of the outboard first wall tiles. This type of hydrogen retention could not be avoided for the metallic wall. Although the amount of hydrogen isotopes retained per unit area in the outboard first wall tiles was much less than that for the divertor tiles, the integrated retention over the whole first wall surface could be very large.

1. Introduction

Erosion and redeposition of carbon materials and tritium incorporation in the redeposited layers are main concerns for tritium safety, wall cleaning and the life time of the plasma facing wall in a fusion reactor. Previous studies [1–4,11–14] have focused on the redeposited layers on divertor tiles and remote areas at rather low temperatures. It has been generally accepted that the first wall is eroded and would retain little hydrogen, compared to hydrogen retention in the redeposited layers on the divertor tiles. However, few studies have been done on the first wall tiles of large tokamaks.

In this work, we have examined graphite tiles used as the outboard first wall armors of JT-60U to observe erosion, deposition, and retention characteristics of hydrogen isotopes in the tiles and their poloidal and toroidal differences, by means of SEM, TDS and SIMS. The results are compared with previously obtained results for the divertor tiles; both eroded and redeposited ones [2–5]. Masaki et al. [6] have suggested that most of the first wall tiles were eroded and only those inboard tiles a little above the inner baffle plates were deposited. Some of the inboard tiles of JT-60U were previously analyzed by Oya et al. [7], and were found to be much influenced by boronized layers produced by boronization. In this work, the outboard first wall tiles which had no boronized layers were examined.

2. Experiment

Fig. 1(a) and (b) respectively show vertical and horizontal cross sectional views of the vacuum vessel of JT-60U. In the figures, the locations of the isotropic graphite tiles examined here are indicated. The tiles used as the outboard first wall armor were exposed to neutral beam injection (NBI) heated plasmas of DD and HH which were performed in ~18,000 shots and 2800 shots, respectively, in the experimental campaign of July 1992–November 2004. The total NBI time was $\sim 6.0 \times 10^4$ s; this was used to normalize the hydrogen retention in the examined tiles.

The HH discharges were performed several hundred times before air ventilation to remove tritium produced by the DD discharges and retained in the vessel. The operational temperature of the vacuum vessel was ~573 K. The temperature of the first wall was not exactly measured but might have increased somewhat due to the plasma heat load. Since the hydrogen NBI heating power was about a half of the deuterium NBI heating power in the DD discharges, it is expected that the temperature increment during the HH discharges was less than that during the DD discharges.

The plasma facing surfaces and the cross-sections of the tiles were visually examined to observe signs of redeposition and/or erosion. Retention of hydrogen isotopes (H and D) within $10 \times 10 \times 1$ mm^3 of the plasma facing surface was examined by thermal desorption spectroscopy (TDS) with a heating rate of 0.42 K/s up to 1273 K, and desorbed species were analyzed by a quadrupole mass spectrometer (QMS). The details of the TDS analysis were given elsewhere [3,5]. Depth profiles of hydrogen

* Corresponding author.
E-mail address: yoshida.masafumi@aees.kyushu-u.ac.jp (M. Yoshida).

0022-3115/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.jnucmat.2009.01.177

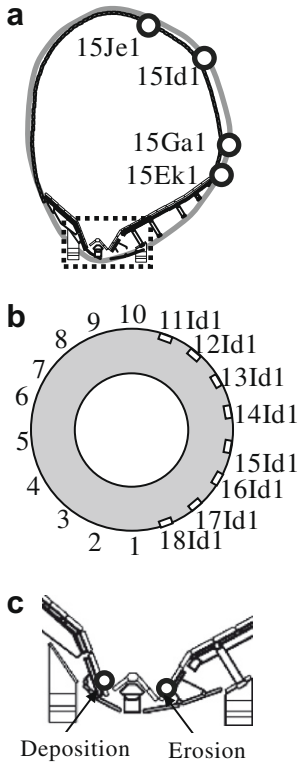

Fig. 1. A schematic view of (a) toroidal and (b) poloidal sections of the JT-60U vacuum vessel and (c) W-shaped divertor. Locations of the first wall tiles examined are indicated in the figure.

isotopes (H and D) in the tiles were determined by secondary ion mass spectroscopy (SIMS).

JT-60U occasionally employed boronization using a gas mixture of $B_{10}H_{14}$ and D_2 resulting in the formation of boronized deposited layers with high deuterium content on some of the first wall tiles [6–8]. In order to avoid the influence of the boronized layers, we have selected the outboard first wall tiles having no boronized layers.

3. Results

The cross sectional SEM image of an outboard first wall tile (15Id1) is given in Fig. 2. The image clearly shows that the tile surface was eroded without any trace of deposition. All tiles analyzed here showed similar structure, i.e., the outboard tiles were mostly eroded irrespective of poloidal and toroidal locations in the torus.

TDS spectra for the outboard first wall tiles are shown in Fig. 3 together with those for eroded and redeposited divertor tiles previously obtained [3,5]. One can clearly see that the desorbed H_2, HD, and D_2 peaks appear in the range 900–1000 K, which is somewhat lower than the temperature (>1000 K) seen for the divertor tiles [3,5]. The total desorbed amount of each first wall tile is comparable to that of the eroded divertor tile, while much smaller than that of the redeposited divertor tiles [3,5]. One also notes that D_2 dominates in the desorbed species for the first wall tiles, while H_2 dominates for the divertor tiles. In particular, the eroded divertor tiles retained only a small amount of D.

In Fig. 4, the total desorbed amounts of hydrogen (H + D) with H and D being separately shown, are compared for all first wall tiles measured here. Also shown are retention values for the eroded and redeposited divertor tiles [3,5]. All retention values in Fig. 4 are normalized to give amount per unit area and integrated NBI time. Although there are some differences depending on the tile locations among the outboard first wall tiles, the total retention amounts in the outboard first wall tiles (H + D = >5 × 10^{17}atoms/m^2/s) are appreciably smaller than those for the redeposited inner divertor tiles (H + D = ~23.0 × 10^{17}atoms/m^2/s) and only little less than that for the eroded outer divertor tile (H + D = ~4.0 × 10^{17}atoms/m^2/s).

Fig. 5 shows the H and D depth profiles for the outboard first wall and divertor tiles [3,5]. For all tiles, D in the near surface regions was mostly replaced by H, resulting in a very high H/C ratio. For the eroded tiles of both the first wall and the divertor, the high H concentration of the near surface regions rapidly decayed with

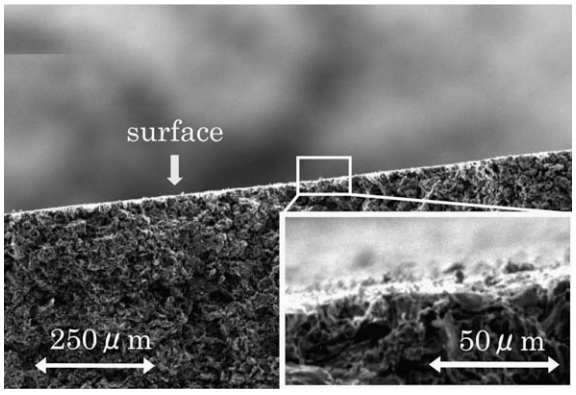

Fig. 2. The cross sectional SEM image of the first wall tile (15Id1).

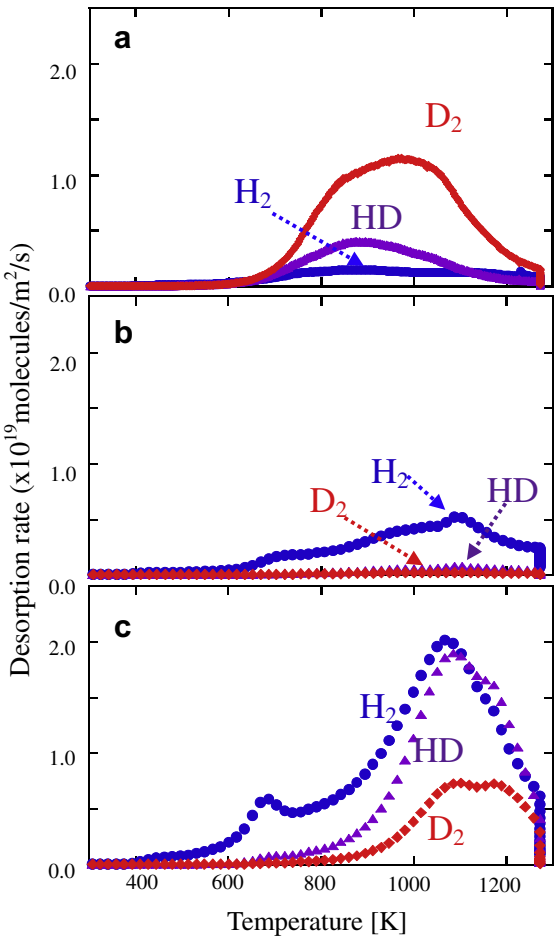

Fig. 3. TDS spectra of a first wall tile (15Ga1), (b) eroded divertor tile, and (c) redeposited divertor tile. ((b) and (c) are from [3,5]).

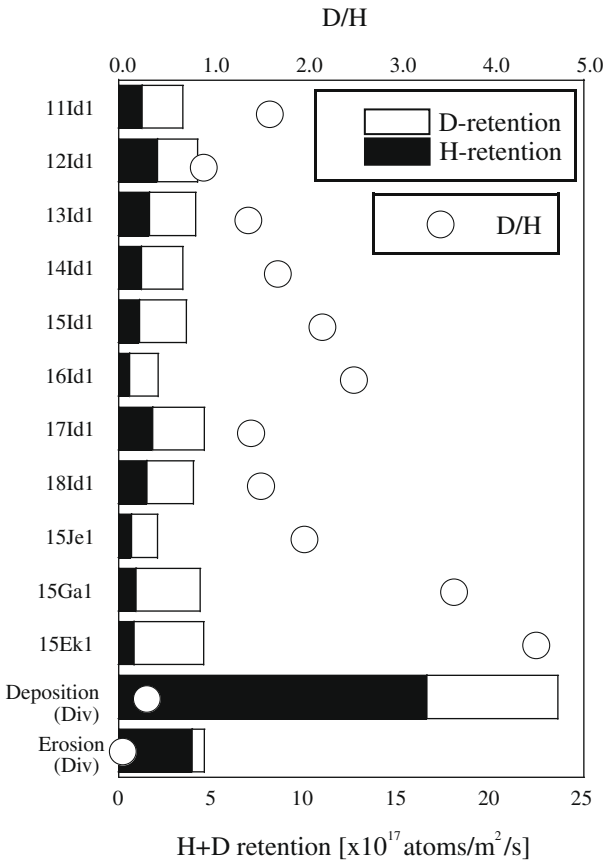

Fig. 4. The total hydrogen isotope retention (H + D) per unit area in the integrated NBI time and the ratio of D and H, of the first wall tiles, together with eroded divertor tiles and re-deposited divertor tiles.

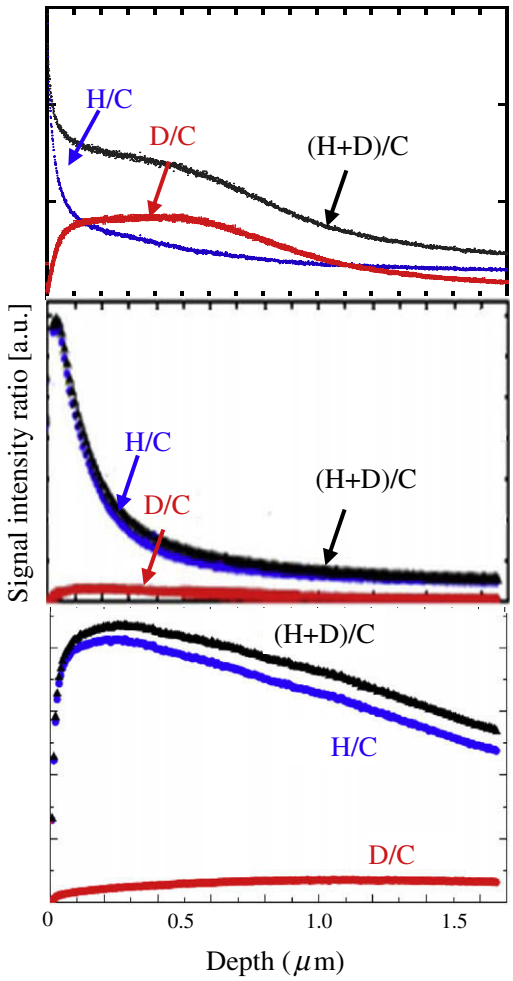

Fig. 5. Depth profiles in H/C and D/C determined by SIMS, (a) for the outboard first wall tile (15Ga1), (b), the eroded divertor tile, and (c) the re-deposited divertor tile ((b) and (c) are from [3,5]).

increasing depth. However, the first wall tile retained a much larger amount of D than the eroded divertor tiles (compare Fig. 5(a) and (b)). The nearly constant concentrations of H and D within a certain depth for the deposited divertor tiles indicate uniform hydrogen distribution throughout the redeposited carbon layers (See Fig. 5 (c)).

4. Discussion

By surface inspection, Maksai et al. [6] have suggested that the outboard first wall tiles are erosion dominated. Fig. 2 is the first clear experimental evidence of the erosion of the outboard first wall tiles in JT-60U. As noted in the experimental section, some of the first wall tiles had boronized layers on their surfaces as reported by Oya et al. [7]. Those tiles with the boronized layers were reexamined and confirmed to be eroded, since there was no carbon dominated redeposited layer on the boronized layers in SEM observations. Also the carbon content in the remaining boronized layers was very small in SIMS analysis (not shown here). Although the analyzed tiles comprised only a very small part of the whole first wall surface and plasma wall interactions would not be homogeneous in toroidal and poloidal directions, the small scatter in the data for the hydrogen retention in the first wall tiles, as seen in Fig. 4, suggests that the inhomogeneity of the plasma wall interaction at the outboard first wall would be small, compared with those at the divertor tiles. Thus, we can conclude that the outboard first wall is mostly eroded as suggested by Gotoh et al. [14].

The different hydrogen retention characteristics among the tiles compared here seem to be controlled by the tile temperature and impinging fluxes. The highest temperature of the eroded divertor surface, which was higher than 1400 K, resulted in the lowest concentration as seen in Fig. 5(b), in spite of the much higher particle flux [2]. During a shot, the temperature increment of the first wall tiles, which was not measured, would have been much less than that of the eroded divertor tiles. Owing to the much higher heat load to the divertor, it is expected that the eroded divertor tiles would have been heated up to a temperature significantly higher than the first wall tiles. Although the lower temperature of the first wall tiles should result in higher retention compared with the eroded divertor tiles, the lower particle flux to the first wall would lead to a similar total retention to that of the eroded divertor tiles. However the similarity in the retention in the eroded first wall tiles and the eroded divertor tiles (see Fig. 4) is most likely a coincidence. One of the possible reasons would be saturation of hydrogen retention in the near surface layers of the eroded tiles.

Furthermore, as already noted in a previous paper [5], D retained at near surface region in the divertor tiles was mostly replaced by H owing to the HH discharges subsequently made after DD discharges. In contrast, the less heating power results in less isotope replace remaining higher D/H in the first wall tiles (See Fig. 5(a) and (b)).

The depth profiles of D (Fig. 5) give additional important information on how D was retained and also replaced by H. The significantly high D concentration in the outboard first wall tiles and its deep penetration could not be caused by simple diffusion. The diffusion coefficient of hydrogen in carbon is too small to allow such

deep penetration of hydrogen, except by pore diffusion. As already suggested [6], such deep penetration is likely to be due to the injection of high energy D (both neutrals and ions) originating from D NBI (50–100 keV). JT-60U was a high ripple loss machine and high energy particles could easily escape to the first wall by the ripple loss mechanism. According to the orbit following Monte Carlo (OFMC) simulation [15], the ripple loss is high at the mid-plane and divertor dome area [9,10]. This is consistent with high D/H observed in the 15Ga1 and 15Ek1 tiles which are located near the mid-plane. In addition, the lower tile temperature of the first wall did not allow the replacement of D by H, resulting in high concentrations of D deeper in the tiles as already noted. Such deep D retention in the fist wall is consistent with T retention previously reported [6], which also supports high energetic implantation due to the ripple loss and/or orbital loss mechanism.

The integrated amount of the retained hydrogen injected rather deep, even if the concentration was smaller, could have significant contribution on the overall tritium retention in tokamak. This contribution would not depend on materials and needs further investigations.

5. Summary

We have investigated erosion/deposition and hydrogen isotopes retention in the outboard first wall tiles by means of SEM, TDS and SIMS.

This work clearly shows that the outboard first wall tiles of JT-60U are mostly eroded. The total retention (H + D) in the eroded first wall tiles and the eroded divertor tiles were nearly the same, in spite of the lower temperature of the first wall. This suggests the saturation of hydrogen retention in the near surface layers.

Different from the hydrogen isotopes retention in the divertor, D retention in the first wall is significantly larger than H retention. This is most probably caused by the injection of high energy deuterons and neutrals originating from NBI by the orbital or ripple loss mechanism. At the outboard first wall tiles, the isotopic replacement, which was appreciable at the divertor tiles, is clearly suppressed due to the lower tile temperatures. Although the flux of the energetic particles onto the first wall must be much smaller than the total particle fluxes to the divertor, the low D concentration in deep regions allows the build-up of hydrogen up to a certain level, resulting in a significant fraction of the total hydrogen retention in the first wall. This type of tritium retention could not be avoided for metallic walls, or even worse, owing to rapid hydrogen diffusion into more deep.

Acknowledgement

This work was partly supported by Grant-in-Aid for Scientific Research, Ministry of Education, Culture and Sports, Priority area 467, 'Tritium Science and Technology for Fusion Reactor' No. 19055008.

References

[1] T. Tanabe, Fus. Eng. Des. 81 (2006) 139.
[2] Y. Hirohata et al., J. Nucl. Mater. 363–365 (2007) 854.
[3] Y. Hirohata et al., J. Nucl. Mater. 367–370 (2007) 1260.
[4] T. Shibahara et al., J. Nucl. Fus. 46 (2006) 841.
[5] T. Shibahara et al., J. Nucl. Mater. 357 (2006) 115.
[6] K. Masaki et al., J. Nucl. Fus. 47 (2007) 1577.
[7] Y. Oya et al., J. Nucl. Mater. 367–370 (2007) 1266.
[8] J. Yagyu et al., J. Nucl. Mater. 421–423 (1997) 579.
[9] K. Masaki et al., J. Nucl. Mater. 313–316 (2003) 514.
[10] K. Tobita et al., Fus. Eng. Des. 65 (2003) 561.
[11] K. Sugiyama et al., J. Nucl. Mater. 367–370 (2007) 1248.
[12] T. Hayashi et al., J. Nucl. Mater. 349 (2006) 6.
[13] Y. Hirohata et al., J. Nucl. Mater. 329–333 (2004) 785.
[14] Y. Gotoh et al., J. Nucl. Mater. 357 (2006) 138.
[15] K. Tani et al., J. Phys. Soc. Jpn. 50 (1981) 1726.