Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Nuclear Materials 337–339 (2005) 436–440
journal of nuclear materials
www.elsevier.com/locate/jnucmat

The effect of co-deposition of hydrogen and metals on wall pumping in long duration plasma in TRIAM-1M

M. Miyamoto [a,*,1], M. Tokitani [a], K. Tokunaga [a], T. Fujiwara [a], N. Yoshida [a], M. Sakamoto [a], H. Zushi [a], S. Nagata [b], K. Ono [c], TRIAM group [a]

[a] *Research Institute for Applied Mechanics, Kyushu University, Japan*
[b] *Institute for Materials Research, Tohoku University, Japan*
[c] *Department of Material Science, Interdisciplinary Faculty of Science and Engineering, Shimane University, Japan*

Abstract

The effect of co-deposition on recycling and wall pumping during long duration plasmas in TRIAM-1M has been studied. To examine the hydrogen retention on the all metal walls, material exposure experiments were carried out using an ultra-long discharge for about 72 min. After exposure to the plasma, the surface modification and hydrogen retention of the specimens were examined quantitatively by means of ion beam analysis techniques and transmission electron microscopy (TEM). Large amount of retained hydrogen were detected in the specimen exposed to the long duration discharge in TRIAM-1M. This amount was sufficient to explain the wall pumping in TRIAM-1M. A correlation was also observed between the thicknesses of the deposits and the amount of retained hydrogen. These results mean that the metallic deposited layer can trap a large amount of hydrogen and has a strong influence on hydrogen recycling similar to a carbon deposit.

PACS: 81.15.Jj; 52.40.Hf; 28.52.Cx; 52.25.Vy
Keywords: Erosion and deposition; Hydrogen inventory; Surface analysis; TRIAM-1M; Wall pumping

1. Introduction

The understanding of plasma fuel recycling properties of the first wall is one of the most critical issues for plasma confinement devices from the viewpoint of plasma density control. In TRIAM-1M, especially, recycling and wall pumping have a large impact on control of plasma density in steady state operation. Hirooka et al. reported that wall pumping is probably necessary from the particle control point of view, based on model calculations of global particle balance [1]. Actually, strong continuous wall pumping and temporary reduction of wall exhaust capability in ultra-long discharges have been reported [2]. On the other hand, strong hydrogen retention has been confirmed in even metallic deposits by using Mo films specimens simulating the deposits in TRIAM-1M [3,4]. Therefore, a relation between deposits and wall pumping is expected. In the present work, the effect of co-deposition on recycling and wall pumping during ultra-long duration plasmas in TRIAM-1M has been studied.

* Corresponding author. Tel.: +81 852 32 6448; fax: +81 852 32 6409.
E-mail address: miyamoto@riko.shimane-u.ac.jp (M. Miyamoto).
[1] Present address: 1060 Nishikawatsu, Matsue, Shimane 690-8504, Japan.

0022-3115/$ - see front matter © 2004 Published by Elsevier B.V.
doi:10.1016/j.jnucmat.2004.08.019

2. Experimental

2.1. Probe experiment and sample preparation

TRIAM-1M ($R_0 = 0.8\,\mathrm{m}$, $a \times b = 0.12\,\mathrm{m} \times 0.18\,\mathrm{m}$) is a superconducting high field tokamak [5]. The vacuum vessel consists of 304SS, while three poloidal limiters and an open divertor are made of Mo. Non-metallic materials such as graphite have not been used for in-vessel components. To examine the effect of surface modification on wall pumping, various specimens mounted on the surface probe system [6] were exposed to an ultra-long discharge for about 72 min (hydrogen plasma, limiter configuration) at the plasma facing side (P-side) and the electron drift side (E-side) in the scrape-off layer (SOL). Typical plasma parameters were: $I_p \sim 15\,\mathrm{kA}$, $n_e \sim 1 \times 10^{18}\,\mathrm{m}^{-3}$, $T_i \sim 0.6\,\mathrm{keV}$. The plasma was sustained with 2.45 GHz lower hybrid current drive (LHCD), and the RF power was <20 kW. Fig. 1 shows a schematic view of the collector probe experiment and the probe head. The specimens on the P-side were located 5 mm behind the poloidal limiter surface. Bulk W specimens were used for this probe experiment after vacuum annealing for degassing. Electro-polished pre-vacuum-annealed stainless steel (SUS316L) and Mo disks of 3 mm diameter were also used for transmission electron microscopy (TEM) investigation. In order to collimate the particle incident direction and to avoid the effects of charged particles, some of the specimens were placed at the bottom of holes with depth of 6 mm and diameter of 3 mm at the P-side. The temperature of the probe head during discharges was almost constant at about 25 °C.

2.2. Analysis of exposed specimens

After exposure to the discharge, the bulk specimens were taken out in air to transfer to the ion beam analysis chamber. The surface layer composition including hydrogen in the W specimen was analyzed quantitatively by ion beam techniques, using a 1.7 MV tandem accelerator [7]. The chemical composition and thickness of deposits were measured by means of Rutherford backscattering spectroscopy (RBS) with an He^+ ion probe beam of 2 MeV. The concentration of hydrogen retained in the deposit was measured by means of the elastic recoil detection (ERD) technique with an He^+ ion probe beam of 2.8 MeV. In the case of ERD, the analysis beam fluence was simultaneously monitored by means of RBS. In addition, the microstructure of specimens was observed by means of TEM.

To obtain more information on the deposits and hydrogen retention, thermal desorption spectroscopy was used.

3. Results and discussion

3.1. Deposited impurities

After the exposure, deposited impurities, which mainly consisted of Mo, were formed. Fig. 2 shows the distribution of the thickness of deposited Mo on W specimens placed at P-side and E-side, as measured by RBS. The amount of deposited Mo at the E-side depended on the distance from the plasma. The mean deposition rate of Mo at the E-side, 7 mm behind the limiter surface, where the thickest deposit was formed, was estimated as $3.9 \times 10^{17}\,\mathrm{atoms/m^2 s}$. At the P-side, the deposition rate was 6.4×10^{16} and smaller than at the E-side. This small net deposition of impurities at the P-side seems to result from the lower sticking rate and higher sputtering rate, because ionized particles drift along the magnetic field parallel to the P-side. In addition to Mo, Fe and/or Cr were also detected as deposited metallic elements by RBS, but concentrations were less than several at.%.

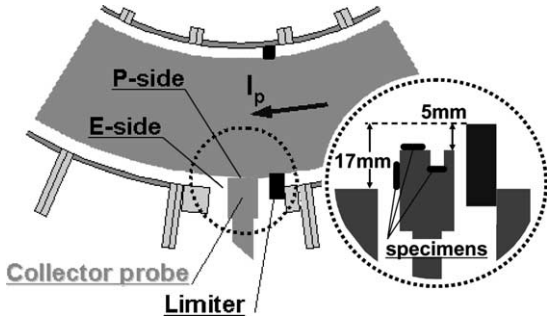

Fig. 1. A schematic view of the experimental set-up in TRIAM-1M.

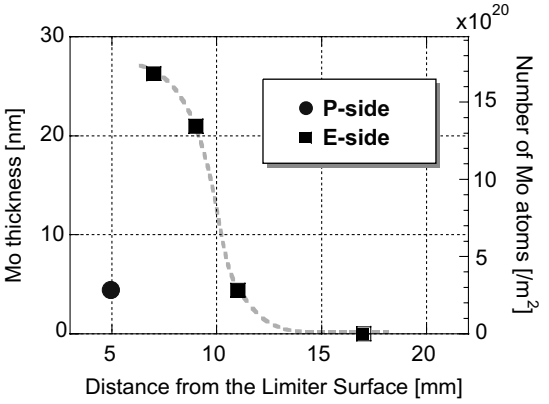

Fig. 2. The distribution of the thickness of deposited Mo.

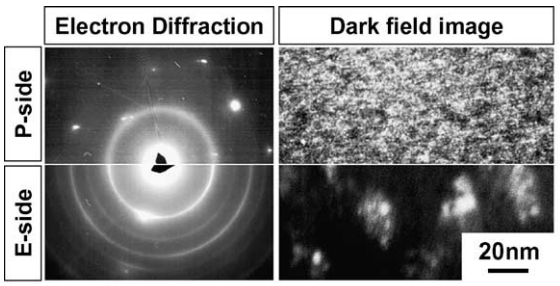

Fig. 3. Electron diffraction patterns and microstructures of the deposit.

Fig. 3 shows the dark field images and the corresponding electron diffraction pattern of the deposits formed on a SUS316L specimen at P-side and E-side. The images were obtained from a part of the first broad diffraction ring. Under this imaging condition, only the crystal grains satisfying the Bragg condition show up in white contrast. These images show that the impurity deposits have different structures in each position. The deposit at the P-side consisted of fine grains only, around 1nm in diameter, and had no distinct structure, while that at E-side was bcc polycrystalline of lattice constant 0.31 nm, with a larger grain size of about 10–20 nm in diameter. These properties indicate the deposit at the E-side has similar structure to bulk Mo. On the other hand, the deposits at the E-side formed in relatively short pulse plasma consisted of fine grains [3] such as that obtained at the P-side in the present experiment. As reported in Refs. [3,8], residual oxygen strongly affects these differences of the structures. The oxygen atoms, co-deposited with Mo atoms during the discharge and between discharges, seems to suppress free migration and crystallization of the deposited Mo atoms.

3.2. Wall pumping caused by deposition

Fig. 4 shows dark field images for the SUS316L specimen at the P-side and E-side, and the Mo specimen placed in the hole at the P-side. The radiation-induced dislocation loops with white contrast were formed in these specimens. In general, radiation induced secondary defects are formed as aggregates of point defects produced by knock-on processes. Since the threshold energies of hydrogen for displacement damage in SUS316 and Mo are about 0.36 keV and 0.85 keV, respectively, these defects indicate the existence of high energy incident particles. One can note that the damage also formed in Mo specimen placed in the deep hole where only bombardment by charge exchange neutrals is expected. These high energy particles, which may be mainly CX-neutrals, are implanted in plasma facing materials, and seem to affect the wall pumping. According to Ref. [9], the flux of energetic CX neutrals has been estimated to be of order 10^{17} atoms/m^2 s. A similar order of flux was roughly estimated in this experiment from the material damage. Therefore, it is appropriate to conclude that a part of the CX-neutrals contribute to wall pumping in TRIAM-1M.

Fig. 5 shows the amount of retained hydrogen in W specimens placed at P-side and E-side as a function of the thickness of the deposits. Data for the un-exposed bulk W specimens are also plotted in the figure for comparison. As shown in this figure, the hydrogen was detected even in the un-exposed W specimen. Some of hydrogen seems to be adsorbed on specimen surface as water during exposure to air for transfer and other processes. Subtracting the amount of this hydrogen as background from the total amount of retained hydrogen, a clear correlation was observed between the retained

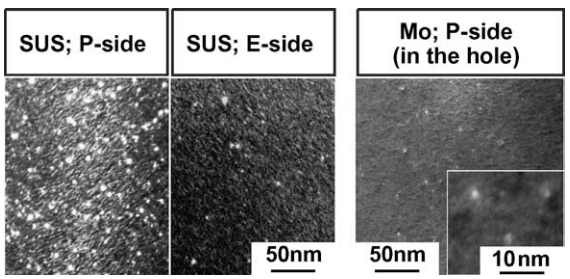

Fig. 4. Dark field images of the microstructure in SUS316L at P-side and E-side, and Mo placed in the hole at P-side.

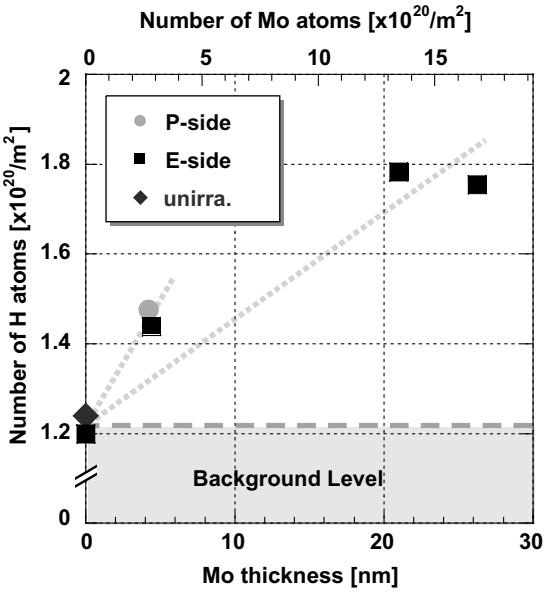

Fig. 5. The amount of retained hydrogen is dependent on the thickness of deposited Mo.

hydrogen and the thickness of the deposits. Since no correlation was observed between the position of specimens and the amount of retained hydrogen, the amount of hydrogen seemed to depend only on the thicknesses of the deposit. Examples for both the P-side and E-side are shown in the figure. This means that the co-deposition of hydrogen with Mo had occurred in TRIAM-1M. Evaluating the amount of hydrogen which trapped in the deposition layer aside from the hydrogen adsorbed during exposure to air, the wall pumping rates caused by depositions at P-side and E-side are estimated to be about 6.4×10^{15} and 1.3×10^{16} atoms/m^{2}s, respectively. On the other hand, the averaged wall pumping rate in a similar ultra-long discharge for 70 min was evaluated at about $\sim 1.5 \times 10^{16}$ atoms/m^{2}s from the point of view of plasma density control in TRIAM-1M [2]. This value is larger than that obtained from this experiment. However, taking account that some of hydrogen retained in the specimens was desorbed because the interval between the probe experiment and the sample analysis was more than a month, it seems that the deposit contributed to the wall pumping. In fact, it has confirmed that the retained hydrogen isotopes in W and Mo decrease to about 1/2 after a week even at room temperature [10]. In addition, it is thought that the persistence of the wall pumping in TRIAM-1M is evidence for the contribution of the deposit formed continuously under the long discharge. One should note that metallic deposits play an important role in hydrogen recycling as well as carbon deposition.

3.3. The effects of microstructure of deposits on wall pumping

The hydrogen concentration, H/Mo, in thin and thick deposits was evaluated to be 0.10 and 0.04, respectively, from Fig. 5. The difference may be caused by the difference of the microstructure of the deposits. As shown in Fig. 2, the thin deposits had a very defective structure while thick deposit had bulk-like structure. To examine the hydrogen properties of these deposits, thermal desorption experiments were carried out using a simulated specimen of each deposit. Fig. 6 shows thermal desorption spectra of D_2 from the Mo deposits and the bulk Mo implanted with 6 keV-D_3^+ at room temperature to a fluence of 1×10^{21} D/m^2. As shown in Fig. 6, the structure of deposits has a large influence on deuterium retention. With the grains becoming smaller, larger and stronger retention occurred. Especially in the Mo deposit with fine grains, very large desorption occurred and the total amount of retained deuterium was about 10 times higher than that in bulk Mo, and about 3 times higher than that of Mo deposits with large grains. This result is consistent with the difference of the ratio of H/Mo observed in the deposits of TRIAM-1M, and

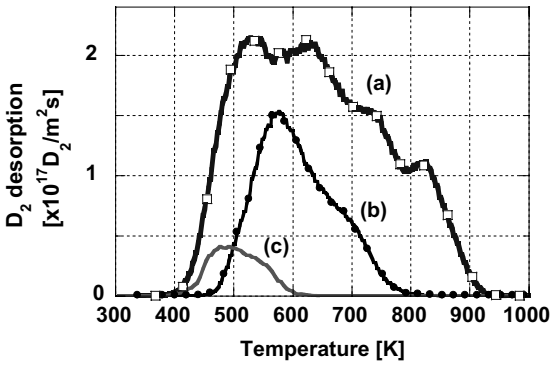

Fig. 6. Thermal desorption spectra of D_2 obtained from the Mo deposit with fine grains (a) and with large grains (b) and bulk Mo (c) implanted with 6 keV-D_3^+ at room temperature to a fluence of 1×10^{21} D/m^2.

indicates that larger wall pumping could be expected in the case of formation of defective deposits. Actually, in high ($\sim 10^{19}$ m^{-3}) density plasmas in TRIAM-1M, a larger wall pumping rate of about $\sim 4 \times 10^{17}$ atoms/m^{2}s on average was observed. In our previous experiments [4], since the thick deposits with defective structure formed, it can be concluded that the deposits have also influenced the strong wall pumping.

Similar large hydrogen retention properties were observed in W deposits formed in RF hydrogen plasmas [11]. These results indicate that deposition has a strong influence on hydrogen recycling in metallic tokamaks as well as in carbon tokamaks. Furthermore, because deposit properties vary with plasma conditions, a more quantitative analysis should be undertaken using various plasmas to examine the effects of the deposits on wall pumping.

4. Summary

The effect of impurity deposition on recycling and wall pumping during ultra-long duration plasmas in the all-metal machine TRIAM-1M has been studied. As a result of the material probe experiment, a correlation was observed between the thicknesses of the deposits and the amount of retained hydrogen. The wall pumping rates caused by deposits at P-side and E-side were estimated to be about 6.4×10^{15} and 1.3×10^{16} atoms/m^{2}s, respectively, and are sufficient to explain the wall pumping in TRIAM-1M. In addition, it was also confirmed that the wall pumping is influenced not only by the deposition rate but also by the microstructure of the deposits.

These results indicate that the co-deposition of impurities with hydrogen is a significant problem even in metallic plasma confinement devices.

References

[1] Y. Hirooka et al., J. Nucl. Mater. 313–316 (2003) 588.
[2] M. Sakamoto et al., Nucl. Fus. 42 (2002) 165.
[3] T. Hirai et al., J. Nucl. Mater. 283–287 (2000) 1177.
[4] M. Miyamoto et al., J. Nucl. Mater. 313–316 (2003) 82.
[5] S. Itoh et al., Nucl. Fus. 39 (1999) 1257.
[6] T. Hirai T. Fujiwara, K. Tokunaga, N. Yoshida, S. Itoh, TRIAM group, in: Proceedings of the 17th International Conference, Yokohama, 1998, Fus. Energy, IAEA-CN-69/EXP2/16.
[7] S. Nagata, K. Takahiro, J. Nucl. Mater. 290–293 (2001) 135.
[8] T. Hirai, M. Miyamoto, T. Fujiwara, K. Tokunaga, N. Yoshida, A. Komori, O. Motojima, S. Itoh, J. Plasma-TRIAM group, Fus. Res. Ser. 3 (2000) 284.
[9] T. Hirai et al., J. Nucl. Mater. 290–293 (2001) 94.
[10] R. Sakamoto et al., J. Nucl. Mater. 233–237 (1996) 776.
[11] M. Nishikawa, K. Katayama, private communication.