Microscopic Damage of Metals Exposed to the Helium Discharges in TRIAM-1M Tokamak and its Impact on Hydrogen Recycling Process

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Abstract. High-energy charge exchange particles bombarding the plasma facing wall may cause not only surface sputtering but also damage inside the materials due to its rather high energy. In the case of burning plasma, we should take into account the effects of helium because it is well known that helium atoms have much stronger effects on material damage than hydrogen atoms. In the present work, therefore, microscopic damage of metals exposed to long pulse discharges of helium plasma in TRIAM-1M was studied and discussed the impact on the hydrogen recycling process by comparing with the helium ion irradiation experiments. Considerably larger amount of dislocation loops and very dense fine bubbles were formed by the irradiation of rather low energy charge exchange neutrals of helium. According to the irradiation experiments with low energy helium ions, formation of dense helium bubbles drastically enhances hydrogen trapping and makes the desorption difficult. The preset result indicates that hydrogen recycling phenomenon during the burning plasma discharge must be quite different from that of the hydrogen plasma discharge experiments.

1. Introduction

The plasma facing vessel walls of fusion devices are bombarded with energetic neutral particles (CX-neutrals), created in charge exchange collisions [1]. The bombardment of the energetic particles cause not only the erosion of the vessel walls and resulting introduction of impurity atoms into plasma, but also cause the radiation damage near the surface and change the material properties [2,3]. As regards hydrogen plasma, microstructural evolution in the metals exposed to tokamak plasma has been carried out in TRIAM-1M [2,4,5,6] and studies focusing on CX neutrals have been also performed in JET [7]. These studies suggested that the CX hydrogen neutrals significantly contribute to the radiation damage and the erosion at vessel walls.

In the case of burning plasma, one should take into account the effects of helium atoms because it is well known that helium atoms in metals have much stronger effects on damage than hydrogen atoms. In the present work, therefore, microscopic damage of metals exposed to long pulse discharges of helium plasma in TRIAM-1M was studied and discussed the impact on the hydrogen behavior by comparing with the helium/hydrogen ion irradiation experiments.

2. Experimental Procedures

TRIAM-1M is an ultra-long discharge tokamak with 3 poloidal limiters and an open divertor made of molybdenum [8]. By attaching a water-cooled collector probe system, plasma irradiation experiments were carried out. The probe head with various metal specimens on it (see Fig.1) was inserted in the scrape-off layer through a horizontal port; 11 mm behind the poloidal limiter surface. The prove head is made of copper plated with gold. In order to collimate the particle incident directions and to avoid the effects of charged particles, some of the specimens were placed in deep holes at the plasma facing side (P-side) [6] . Each hole directs to different directions from the bottom to the top and from the left (electron drift side, E-side) to the right (ion drift side, I-side) of the plasma with semiangle of 14 degrees. Some specimens were directly mounted on the surface of the P-side and the E-side of the probe head.

Pre-thinned vacuum-annealed molybdenum and tungsten disks of 3 mmϕ were used for the damage analysis and bulk copper plates for the analysis of implanted helium. They were exposed to successive long-pulse helium discharges (limiter configuration) sustained by lower hybrid current drive (8.2 GHz). Typical plasma parameters were as follows; T_i~0.25 keV, $\overline{n_e}$ ~$1.6x10^{19}/m^3$, I_p~24kA. The typical duration time of a discharge was about 7s and the total reached 125s by repeating 18 discharges with similar plasma parameters. The temperature of the probe head during discharges was kept at about 24C by circulating cooling water. The actual temperature of the specimens is expected to be comparable with that of the probe head because of tight thermal contact.

After the discharge experiments, the microstructure of the pre-thinned specimens was observed by means of transmission electron microscopy. Retention of helium was measured by thermal desorption spectroscopy (TDS) with the ramping rate at 1K/s.

For more information of damage and helium retention, irradiation experiments were carried out at room temperature with helium ions of 0.2 and 1 keV.

3. Experimental Results

Figure 2 shows radiation-induced defects in the molybdenum specimens placed on the surface at P-side, where bombardment of both CX-neutrals and ions is expected. It is remarkable that large amount of dislocation loops (black images in (a)) and very dense fine bubbles of about 1-2 nm in diameter (white image in (b)) were formed by the exposure to the helium plasma discharges for 125s. Quite similar heavy damage were observed even in heavy tungsten placed on the P-side. Such remarkable formation of bubbles has not been observed in hydrogen plasma discharge experiments in TRIAM-1M.

Figure 3 shows damage in the pre-thinned molybdenum specimens placed in the holes. Because the holes are perpendicular or near perpendicular to the magnetic field, only the CX-neutrals can bombard the specimens. Small defects with black dot images, probably dislocation loops, were observed but not bubbles. It is remarkable that the defects were formed with strong directional dependence. Namely, considerable amount of damage was observed in the specimens directing to the bottom-side and the plasma center while almost no visible damage for that directing to the top-side. Damage also depends on the troidal direction; stronger damage in the specimens directing to the I-side.

Evolution of microstructure in molybdenum at room temperature under 0.2keV-helium ion irradiation is shown in Fig. 4. Small black dot defects appeared at first. By increasing fluence of helium ions they grew and many of them showed a typical image of a dislocation loop. Bubbles became visible above about 10^{20}ions/m^2. The microstructure formed in the specimens in the hole directing to the center of the plasma (Fig.4) and that on P-side surface (Fig.2) are similar to those at 1.5-7.8x10^{19}/m^2 and 9.3-14x10^{20}ions/m^2, respectively.

In order to estimate the amount of helium retained in the specimen, thermal desorption of helium from a copper plate placed on the P-side was measured and the result is plotted in Fig. 5 together with those for 1 keV-helium ion irradiation using ion gun. Though the detail of the spectrum is different from those of the ion-irradiated specimens, it showed typical feature of copper; termination of desorption below 1100K. The total of retained helium was, therefore, estimated to be 3.9x10^{20}He/m^2.

4. Discussion

In general, radiation induced secondary defects such as dislocation loops and voids are formed as the aggregates of point defects (interstitial atoms and vacancies) produced by knock-on processes. If the energy of injected particles is less than the threshold value of displacement damage, no defects are formed. No visible defects, for example, are formed in tungsten irradiated by hydrogen ions below the threshold energy [9]. Because the threshold energy of helium ions for displacement damage in tungsten and molybdenum is about 0.4keV and 0.25keV, respectively, direct formation of vacancies and interstitial atoms by knock-on process is scarcely expected in the present TRIAM-1M experiments (T_i~0.25keV) and ion irradiation experiment (E_i=0.2keV). However, remarkable defect formation occurred in actual as shown in Figs. 1-5. Similar defect formation without knock-on damage process have been observed in tungsten irradiated by low energy helium ions [10] and helium plasma [11]. It should be emphasized that formation of defects such as bubbles by the sub-threshold energy irradiation is very characteristic features of helium irradiation. Though details of formation mechanism of helium bubbles and dislocation loops are under the discussion, it is probable that helium atoms trapped by an impurity atom pushed out a nearby host atom in an interstitial site and form a complex of helium and vacancy, if the number of the trapped helium atoms exceeds a critical value [10]. By repeating this process the aggregate of the helium become a visible size bubble as observed in the preset experiments. Concerning the formation of bubbles, the fact that they are also formed even at high temperatures such 1073K [10], because the binding of helium with vacancy type defects is very strong. [12].

By taking account the facts that the solid angle open to the core plasma is about 30 times larger than that of the specimen in the hole and the fluence estimated from the comparison with the ion irradiation is between 1.5-7.8x10^{19}/m^2, the fluence of the CX-neutrals bombarding the specimen on the P-side (see Fig. 2) is roughly estimated around 10^{21}/m^2. This value agrees with that estimated from the comparison of the microstructure. This result indicates that the damage in the specimen placed on the P-side is mainly caused by the

CX-neutrals of helium. By taking account the result of TDS experiment, the actual fluence of neutral helium contributing to the damage is somewhat smaller than $10^{21}/m^2$. The present results of TRIAM-1M experiments and low energy helium ion irradiation experiments indicate that helium cause very strong material damage in the sub-surface region even at low fluence. One should note that the total discharge time of TRIAM-1M experiment is only 125s.

Anisotropic radiation damage was clearly shown in Fig. 4. Namely, considerable amount of damage was observed in the specimens directing to the lower side and to the plasma center, while almost no damage for those directing to the upper side. Similar up-down asymmetric damage was observed in hydrogen discharges [6]. These results indicate that the CX-neutrals with high energy enough to cause radiation damage were mainly formed in the lower half of the plasma. The most convincing explanation is the effect of the ions trapped in a toroidal ripple. Because high energy ions have lower collision frequency, the energetic ions trapped in a toroidal ripple can easily drift toward the grad-B direction, toward the lower side of the torus in the present case, without strong scattering by collision. Present results showed damage is also asymmetry in toroidal direction (ion drift side and electron drift side). The origin of this anisotropy is under the discussion. The localized formation of the energetic CX-neutrals at the lower side of the plasma indicates stronger sputtering and radiation damage at the bottom of the torus. Such information is valuable for understanding erosion and damage of plasma facing components and also impurity behavior.

Effects of helium ion irradiation on trapping of injected deuterium in tungsten have been studied by TDS technique [13]. Pre-irradiation with helium ions caused remarkable effects on the trapping of injected deuterium. Most of the injected deuterium is desorbed between 400 and 600 K for the case without helium pre-irradiation, while additional large desorption occurs between 600 and 800 K for the helium pre-irradiation case. For example, total amount of the trapped deuterium for irradiations of $2.0 \times 10^{21} He/m^2$ and $1.0 \times 10^{22} D_2/m^2$ is $6.2 \times 10^{20} D_2/m^2$, which is more than three times higher than that in the case of no helium pre-irradiation. Possible trapping sites for the desorption above 600 K is the strong stress field around the high-pressure helium bubbles. In the case where the helium bubbles were noticeably formed, rather weak but dense deuterium trapping sites were also formed. As a result, total amount of the retained deuterium increase drastically. Though it is known that retention of hydrogen isotopes in tungsten is low in general, and this is one of the advantages of this material, these results indicate that synergistic effects of helium bombardment must be taken into account to understand and to evaluate the behavior of hydrogen isotopes in plasma facing materials and total hydrogen recycling process.

5. Summaries and Conclusion

Microscopic damage of metals exposed to long pulse discharges of helium plasma in TRIAM-1M was studied and discussed the impact on the hydrogen recycling process by comparing with the helium ion irradiation experiments. Dislocation loops and dense fine bubbles was formed in tungsten and molybdenum exposed for only 125s. It is considered that thery are formed mainly by the bombardment of low energy CX-neutrals of helium. It was found that the majority of the neutrals contributing to the damage come form the lower half of the plasma. The fact that the helium bubbles are remarkably formed in tungsten and molybdenum even if the energy of the helium is less than the threshold energy for displacement damage is very important for fusion. Formation of dense helium bubbles drastically enhances hydrogen trapping and makes the desorption difficult. These results indicate that hydrogen recycling phenomenon during the burning plasma discharge must be quite different from that of the hydrogen plasma discharge experiments.

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Fig.1. Probe head with various kind of specimens.

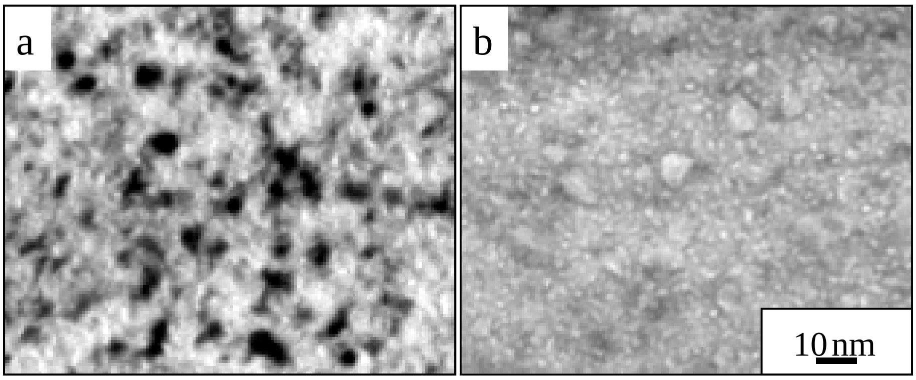

Fig. 2. TEM image of radiation damage in molybdenum placed on the surface at the P-side. (a) an image at small s condition. (b) an image at large s condition.

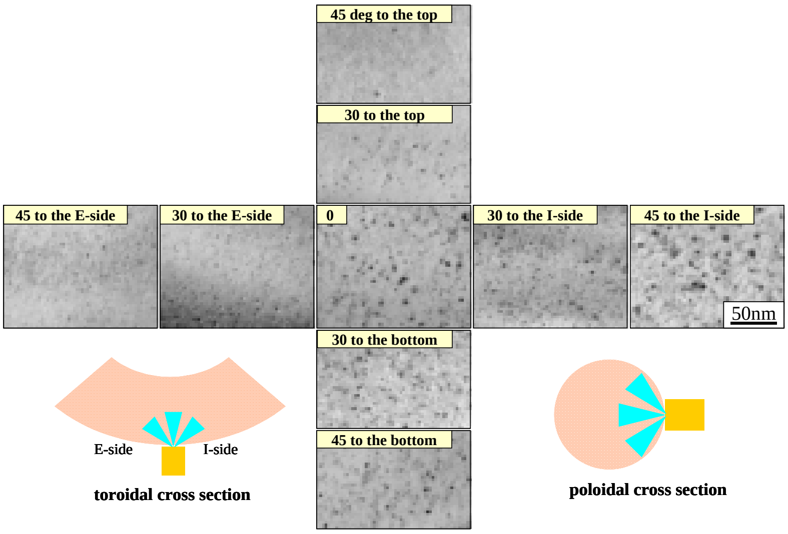

Fig. 3. Directional dependence of damage in molybdenum specimens placed in the deep holes. Direction of each hole is noted in the figure. Only neutral helium can reach the specimens and cause the damage.

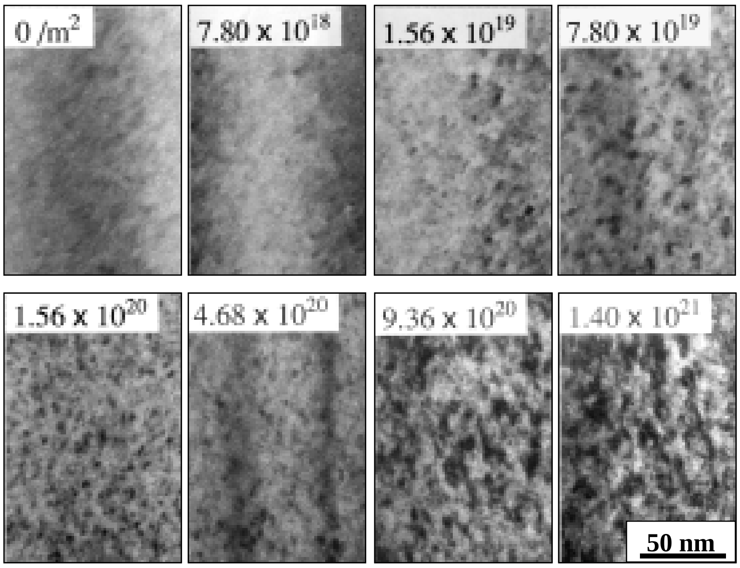

Fig.4. Evolution of microstructure in molybdenum at room temperature under 0.2keV-helium ion irradiation.

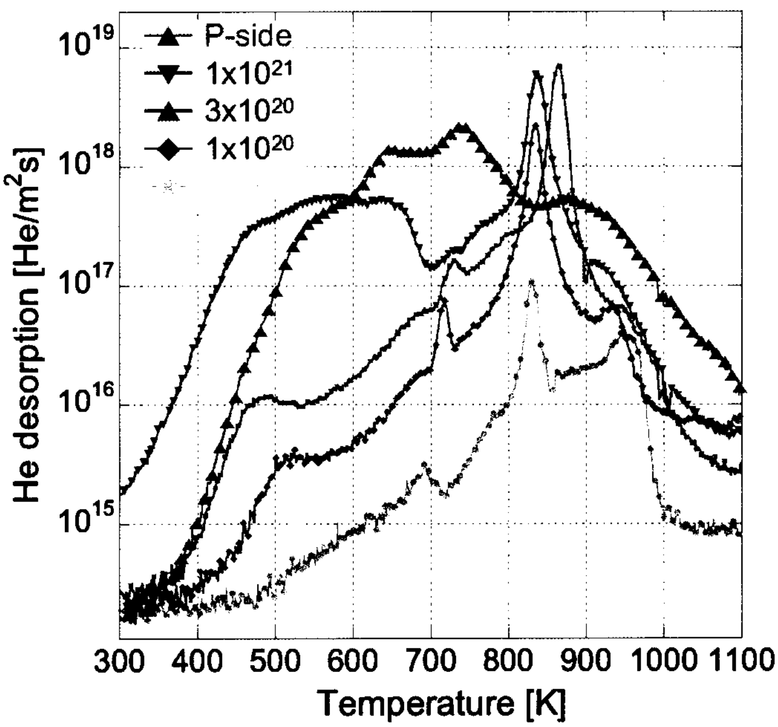

Fig. 5 Thermal desorption of helium from copper exposed to TRIAM-1M discharges and from copper irradiated by 1keV-helium ions. Fluence (ions/m^2) of each data is denoted in the figure.