ANISOTROPIC RADIATION DAMAGE BY CHARGE EXCHANGE NEUTRALS UNDER THE HIGH ION TEMPERATURE DISCHARGES IN TRIAM-1M

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Abstract

Plasma irradiation experiments have been carried out in TRIAM-1M. Thin foil specimens were exposed to a high ion temperature plasma (hydrogen plasma, limiter configuration) and the microstructural evolution was examined by means of transmission electron microscopy. The anisotropic radiation damage due to charge exchange (CX) hydrogen neutrals was clearly shown. This anisotropy could be explained as the effect of gradient B drift. By the comparison with the areal density obtained from hydrogen beam irradiation experiments, the angular dependence of the CX neutrals fluence was estimated quantitatively. The localized formation of energetic CX neutrals at the lower half of the plasma indicates stronger sputtering and radiation damage at the bottom of the torus.

1. INTRODUCTION

Increasing the stored energy in the core plasma, the interaction between out-flow particles from plasma and plasma facing materials, so called plasma materials interaction, is being a critical issue for thermonuclear fusion devices. The major plasma material interaction takes place at limiters and divertor plates, which are hit directly by the particles and energy flux through the scrape off layer (SOL) plasma [1]. With the introduction of divertors the influx of impurities released at the target plates into the core plasma is largely reduced, especially if a low temperature and high density plasma can be achieved in front of the divertor plates [2,3]. With the reduction of the influence of divertor and limiter, the plasma material interaction at plasma facing walls of blankets and vacuum vessel becomes dominant [4,5].

The plasma facing vessel walls of fusion devices are bombarded with energetic neutral hydrogen atoms, CX neutrals, created in charge exchange collisions [6]. In addition that the bombardment causes the erosion of the vessel walls and the introduction of impurity atoms into plasma, the bombardment causes the radiation damage and the degradation of material properties such as the mechanical property [4,7].

As regards CX neutrals, microstructural evolution of the thin foil specimens that exposed to a tokamak plasma has been carried out in TRIAM-1M [4,8,9] and studies focusing on CX neutrals have been also performed in JET [5]. These studies suggested that the CX neutrals would significantly contribute to the radiation damage and the erosion at vessel walls.

CX neutrals bombard from various directions and the angular distribution of the incident CX neutrals at vessel walls have not been clearly understood. Therefore the angular distribution of the incident CX neutrals must be investigated to estimate the erosion due to sputtering and radiation damage precisely, because it is well recognized that sputtering yield and radiation damage depend on the incident angle [10].

In the present work, behaviour of CX neutrals has been investigated with thin foil specimens mounted on the surface probe system in TRIAM-1M. By observing microstructure in these specimens, the fluence of the CX neutrals bombarding from different directions was estimated quantitatively.

2. EXPERIMENTAL PROCEDURE

TRIAM-1M is an ultra-long discharge tokamak with poloidal limiters and an open divertor made of molybdenum. By installing a water-cooled surface probe system, plasma irradiation experiment was carried out.

The probe head with various probe specimens was inserted in the scrape off layer through a horizontal port; 6mm outside a poloidal limiter surface as schematically shown in Fig. 1. In order to collimate the incident angles, the probe specimens were mounted in holes at the plasma facing side (P-side) as shown in Fig. 2 and covered by slits at the electron drift side (E-side). As shown in Fig. 1(b), the specimen holes at the P-side directed to the five different directions with semi-angle of 14 degrees. The slits at the E-side directed to the plasma edge. Molybdenum and tungsten disks were used as probe specimens. They were annealed in vacuum and shaped to thin foil specimens by electro-polishing before the plasma irradiation. They were exposed to successive high ion temperature plasmas (hydrogen plasma, limiter configuration) sustained by lower hybrid current drive (2.45 GHz)[11]. Typical plasma parameters were as follows; T_i=1.5 - 2.5 keV, $\tilde{n}_e$= ~2x 10^{18} m^{-3}, I_P=20 - 25 kA. The duration time of each discharge was about 1 minute and the total reached 31.5 minutes. The temperature of the probe head during exposing was constant at about 23 .

After the irradiation, the microstructure of those specimens was observed by means of transmission electron microscope (TEM).

Using the same series of molybdenum specimens, irradiation experiments with several keV (1.5, 2, 4, 6, 8 keV) hydrogen beams were carried out as simulation experiments.

3. RESULTS AND DISCUSSION

Figure 3 shows microstructure observed in the molybdenum specimens at the P-side. Sharp white dot images indicate radiation induced defects, so called, dislocation loops. These defects are formed in the following processes; first, incident particles create Frenkel pairs (pairs of an interstitial and a vacancy) if the particles have high enough energy to make atomic displacements, then a part of the interstitials aggregate and form the dislocation loops.

Because the specimens were placed in the holes perpendicular to the magnetic field lines, only the CX neutrals can hit the specimens and result in the radiation damage. Speaking of impurities, the influence could be negligible because of the quite small charge exchange cross section. As a result, the incident particles were CX hydrogen neutrals.

Anisotropic radiation damage was clearly shown in Fig. 3. Namely, a considerable amount of damage was observed in the specimens directing to the lower side (-45, -30 degrees) and to the plasma centre (0 degree), while almost no damage for those directing to the upper side (30, 45 degrees). 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 [11]. High energy ions have lower collision frequency, therefore the energetic ions trapped in a toroidal ripple can easily drift toward the grad-B direction without strong scattering due to collision, the direction in the present experiment is toward the lower side of the torus. In addition to the asymmetry in the poloidal cross section (upper and lower) as discussed above, the asymmetry in the toroidal cross section (ion drift side and electron drift side) could exist in a tokamak plasma. The angular distribution in the toroidal cross section will also be investigated in the future. 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. The present results are important for understanding and assessment of erosion and damage of plasma facing components and also for impurity behaviour.

The comparison between the depth distribution of the dislocation loops and damage estimated by TRIM code [12] is shown in Fig. 4. Suppose the ion temperature is T_i, the depth distribution of damage f_{Ti} can be calculated as following,

$$f_{T_i} = \sum_{j=1,1.5,2,...}^{10} f_{E_j} \times \exp(-E_j / T_i)$$

where the damage distribution of each incident energy (1keV to 10keV) f_{Ej} was calculated as a function of depth and then f_{Ti} was obtained by the convolution of these f_{Ej} taking the existence probability into account. For the existence probability at each energy, Maxwellian distribution like $\exp(-E_j/T_i)$ was assumed and the charge exchange cross section of hydrogen is supposed to be constant in this energy range. Figure 4(a) shows the depth distribution of the dislocation loops formed in the molybdenum specimen directing to the plasma centre, and Fig. 4(b) shows that of damage distribution at the ion temperature 0.5keV, 1.5keV and 2.5keV(high T_i plasma). As can be seen in Fig. 4, the distribution of dislocation loops corresponds well with the calculated damage distribution at ion temperature 2.5keV. This fact means that a large number of CX neutrals have energy of several keV, and is not contradictory to the result of energy spectrum measurement with a neutral particle energy analyzer. Dislocation loops were also observed in tungsten specimen in which dislocation loops were not created unless the incident energy of hydrogen exceeded 2keV[13]. This fact also supports the existence of the high energy component in CX neutrals.

Figure 5 shows the areal density of the dislocation loops in specimens at the P-side. The strong anisotropic radiation damage due to energetic CX neutrals can be estimated quantitatively as areal densities, $4.1\text{x}10^{15}\text{m}^{-2}$ at the direction to the lower side, gradually decreased to $3\text{x}10^{15}\text{m}^{-2}$ at the direction to the plasma centre and fell down to almost zero at the direction to the upper. In order to estimate the fluence of the energetic hydrogen neutrals responsible for the damage formation, the data of the TRIAM-1M experiment were compared with those of simulation experiments with hydrogen ion beam. Because of wide energy spectrum for tokamak plasma it is very difficult to estimate the fluence. But we can roughly estimated the fluence of the neutrals causing radiation damage by the comparison with the data obtained from several keV hydrogen beam irradiation experiments shown in Fig. 6(a). To compare with the areal densities of dislocation loops in the specimens irradiated to the plasma, a convoluted areal density (Fig. 6(c)) was calculated by the convolution of areal densities of hydrogen beam irradiation experiments at each energy with a weighting function shown in Fig. 6(b) into consideration. As a result, the fluence of CX neutrals in the each cone directing to the lower side with the semi-angle 14 degrees, is estimated about $1\text{x}10^{20}\text{m}^{-2}$. In the case of the direction to the upper with the same semi-angle, the fluence would be less than $5\text{x}10^{19}\text{m}^{-2}$ where dislocation loops could not be observed by means of TEM owing to the resolution. The total fluence of the CX neutrals bombarded at the vessel wall will be one-order in magnitude higher than that in the cone because the volume of the cone is about 6 % of the total.

Present results indicate that CX energetic hydrogen neutrals ejected from the plasma cause knock-on damage in the sub-surface region of plasma facing wall and heavy damage is accumulated in a short experimental period. These radiation induced dislocation loops act as good traps for implanted hydrogen. In addition to the dislocation loops, cavities which could be formed at room temperature due to heavy damage ($>1\text{x}10^{22}\ \text{m}^{-2}$) will also act as trap sites for implanted hydrogen. These facts mean that radiation damage at sub-surface region increase hydrogen retention and influence on hydrogen recycling [14-16]. Besides the influence on hydrogen recycling, the dislocation loops cause irradiation induced hardening, concretely, the relative hardness (H_{irr} / H_{unirr}) increased a factor 1.8 by 10keV D^+ irradiation with $2\text{x}10^{21}\ \text{m}^{-2}$[7]. Accordingly plasma facing wall will easily embrittle due to irradiation because the hardening generally corresponds to the embrittlement. Actually the thin edge of tungsten specimen exposed to the plasma in TRIAM-1M was cracked along grain boundaries [4].

These radiation induced effects are not avoidable in any tokamaks because the CX neutrals can not be confined by the magnetic field. However, it would be possible to reduce the effects if the plasma facing components were arranged carefully as taking the less likely incident direction of CX neutrals into account.

4. SUMMARY

Plasma irradiation experiments have been carried out using by thin foil specimens in TRIAM-1M. Anisotropic radiation damage due to CX hydrogen neutrals was shown clearly. Namely, considerable amount of damage was observed only in the specimens directing to the lower side and to the plasma centre. This result indicates that CX neutrals with high enough energy to cause radiation damage were mainly formed in the lower half of the plasma. This result could be explained by gradient B drift of the ions trapped in a toroidal ripple.

The distribution of the dislocation loops corresponds well with the damage distribution at T_i=2.5keV. This fact means that some parts of CX neutrals have energy of several keV and that corresponds well with the result of energy spectrum measurement with the neutral particle energy analyzer

Using the energy spectrum and the data obtained from hydrogen beam irradiation experiments, the fluence of the CX neutrals that bombarded from the cone directing to the lower side and that caused radiation damage, was estimated about $1x10^{20}m^{-2}$. The fluence of the CX neutrals from the upper was estimated less than $5x10^{19}m^{-2}$. The total fluence of the CX neutrals bombarded at the vessel wall will be one-order in magnitude higher than that estimated.

CX neutrals can cause not only erosion but also radiation damage. And it is discussed that radiation damage can influence on hydrogen recycling and degradation of plasma facing materials. These radiation induced effects are not avoidable in any tokamaks because the CX neutrals can not be confined by the magnetic field. However, it would be possible to reduce the effects if the plasma facing components were arranged carefully as taking the less likely incident direction of CX neutrals into account.

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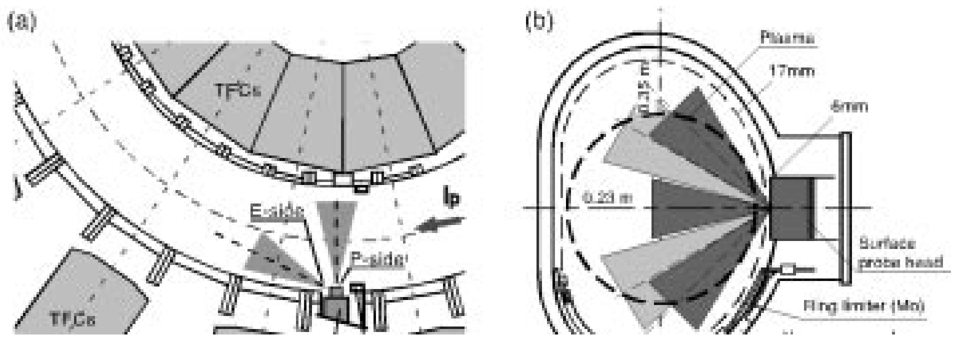

FIG. 1, Schematic views of the experimental set-up in TRIAM-1M. (a) The top view of the torus. The specimens at the P-side direct to the centre, while the specimens at the E-side direct to the plasma edge. (b) The poloidal cross section of the torus. The specimens were irradiated with particles in the cones directing to the five different angles in the poloidal cross section.