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Anisotropic radiation damage by charge exchange neutrals under tokamak discharges in TRIAM-1M

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Abstract

Thin foil specimens were exposed to tokamak discharges in TRIAM-1M. As a result of the microstructural observation, accumulated radiation damage (dislocation loops) due to charge exchange (CX) neutrals were observed only in the specimens pointing to the lower half of plasma and almost no damage in the specimens pointing to the upper side. These results indicate that the lower half of the plasma is the major source for energetic CX neutrals. This anisotropy can be explained by the effect of the gradient B drift of high-energy ions trapped in a toroidal ripple. The mean flux was estimated to 4.2×10^{17} particles m^{-2} s^{-1} sr^{-1} from the lower side by using the areal density (A.D.) of dislocation loops. The depth distribution of the dislocation loops shows a significant contribution of the high-energy CX neutrals. The energetic CX neutrals will give a great impact on material degradations.

Keywords: TRIAM-1M; Charge exchange neutral; Damage

1. Introduction

The vessel walls of a fusion device are bombarded with charge exchange (CX) neutrals created in CX collisions in the plasma [1]. Then radiation damage can be created in the subsurface region. Microstructural observations show that the CX neutrals could cause significant radiation damage [2–4] after exposing to discharges in a superconducting toroidal field tokamak, TRIAM-1M. In addition, the bombardment causes erosion as reported from JET, and it was concluded that CX neutrals greatly contributed to the erosion of the vessel walls [5].

However, studies that imply anisotropy of incident CX neutrals, have not so far been done, although it is well known that both radiation damage and physical sputtering depend on the incident angle [6].

In the present work, radiation damage due to CX neutrals and the anisotropy of the incident particles is shown. Then a reason for the anisotropy is discussed. Compared with the damage structure obtained from hydrogen beam experiments, the mean flux of the CX neutrals can quantitatively be determined. Finally the influence of the energetic CX neutrals on material is discussed.

2. Experimental

TRIAM-1M, a superconducting toroidal field tokamak, can sustain ultra-long discharges over 2 h by means of lower hybrid current drive [7]. The major and minor radii are 0.8 m and 0.12 m × 0.18 m, respectively. In the scrape-off layer, material exposure experiments have been carried out. Annealed thin foil Mo disks that can be observed by transmission electron microscope (TEM) were used as the specimens. The specimens were fixed at the bottom of holes, perpendicular to the magnetic field line, as shown in Fig. 1. The holes were pointing to five different directions in the poloidal cross-section (Fig. 2). Each hole defined the cone-shape incident volume with semi-angle of 14°. The specimens

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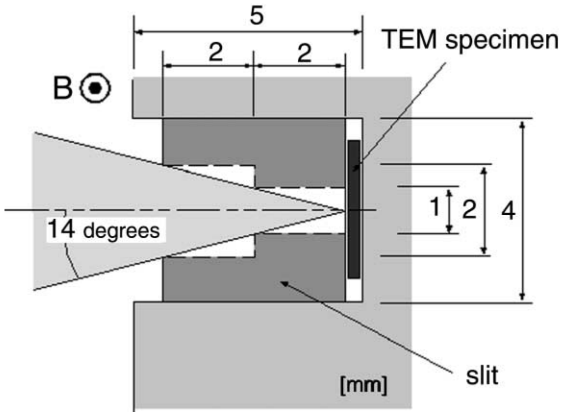

Fig. 1. Cross-section of the slit and TEM specimen.

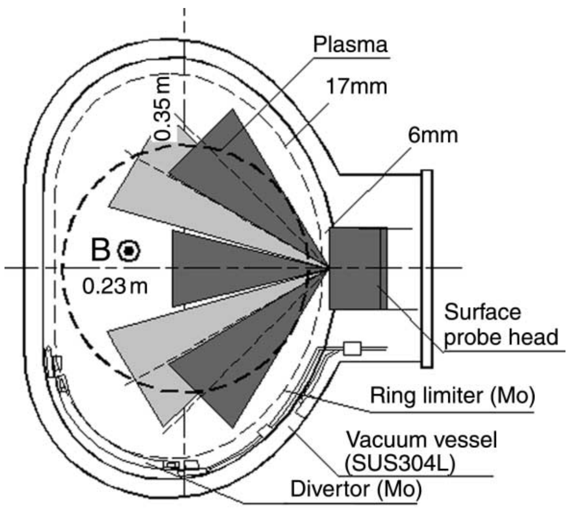

Fig. 2. Schematic views of the poloidal cross-section of TRIAM-1M. The specimens were irradiated with particles in cones pointing to five different directions.

mounted at the plasma facing side (P-side) on the probe head were inserted up to 6 mm outside the last closed flux surface (LCFS). The LCFS was defined by poloidal limiters. The head was actively cooled and the temperature was kept constant at 23°C during the discharges. The specimens were exposed to successive high ion temperature discharges [8] (hydrogen plasma, limiter configuration) with the typical parameters: $T_i = 1.5–2.5$ keV, $\tilde{n}_e = \sim 2 \times 10^{18}$ m^{-3}, $I_P = 20–25$ kA. The duration of each discharge was about 1 min and the total exposure time was 31.5 min. After exposure, the microstructure of the specimens were investigated by TEM.

For comparison of the damage structures of specimens irradiation experiments have been carried out with hydrogen beams from 1.5, 2, 4, 6 up to 8 keV.

3. Results and discussion

3.1. Radiation damage by CX neutrals from the local source

Fig. 3 shows dark field images of the microstructure observed in the Mo specimens. Sharp white dots observed in the images of the specimen pointing to the lower half, indicate a radiation-induced defect, the so-called interstitial type dislocation loop [2]. The density is related to the incident fluence. The dependence on the fluence will be discussed in the next section.

The radiation damage can be created by hydrogen and impurities as well. As impurities, O and Mo have to be considered in TRIAM-1M. Mo is sputtered from limiters and divertor plates made of Mo. However, the ions could not hit the specimens, since the holes were perpendicular to the magnetic field line and the Larmor radii are much shorter than the depth of the holes (5 mm). For example, the largest radius for Mo^+ is 0.91 mm ($T_e = 15$ eV, $n_e = 10^{17}$ m^{-3}, $B_t = 6$ T). Consequently only neutrals can hit the specimens. In addition, it is well known that CX hydrogen neutrals are the dominant component in neutral particles ejected from tokamak plasma [9]. Therefore, the observed damage was most likely caused by CX neutrals.

The anisotropy of the radiation damage is with respect to poloidal direction shown in Fig. 3. A considerable amount of damage was observed only in the specimens pointing to the lower half (−45°, −30°, 0°). Fig. 4 shows the measured areal density of the dislocation loops. The densities of the dislocation loops have a maximum value of 4.1×10^{15} m^{-2} in the specimen pointing to the lower side. This suggests that the CX neutrals with high-energy were created especially in the lower half of the plasma. A most convincing explanation of this phenomenon is the effect of the gradient B drift of ions trapped in a toroidal ripple [8]. The high-energy ions have a lower collision frequency, and the ions trapped in a toroidal ripple can easily drift in the gradient B drift direction without strong scattering and accumulate in the direction. The accumulation of high-energy ions due to grad-B drift had been confirmed by the asymmetry of ion temperature [8]. This direction is towards the lower side in the present experiments. There the formation of the energetic CX neutrals is enhanced and causes the radiation damage at the bottom side of the torus. The present results are important for the degradation of plasma facing components as well as for impurity generation.

3.2. Estimation of the mean flux of CX neutrals

In order to estimate the fluence of the energetic CX neutrals responsible for the formation of dislocation loop, the results of the experiments were compared with

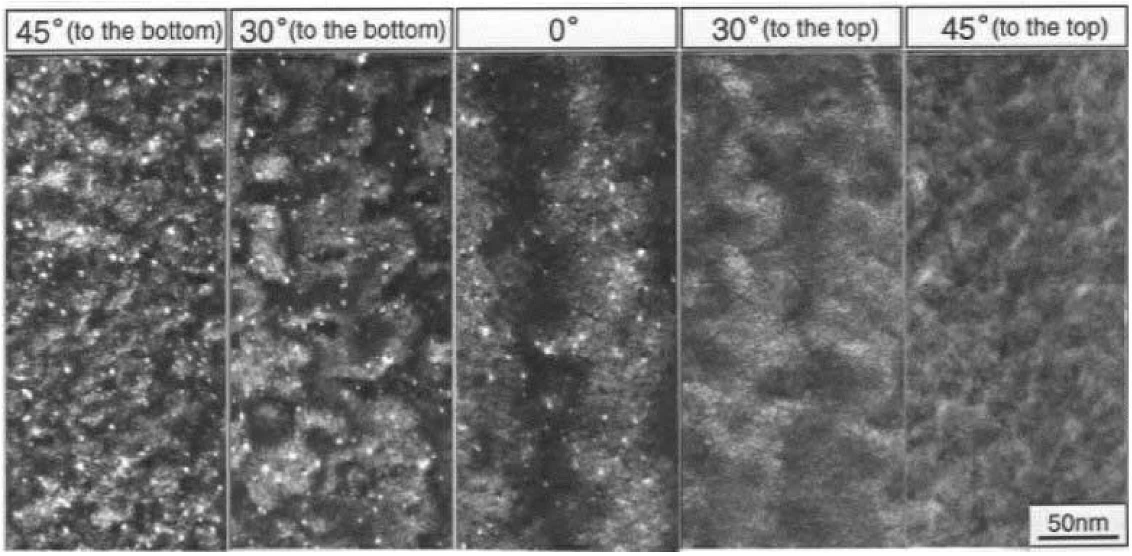

Fig. 3. Dark field images of the microstructures observed in Mo specimens (TEM micrograph).

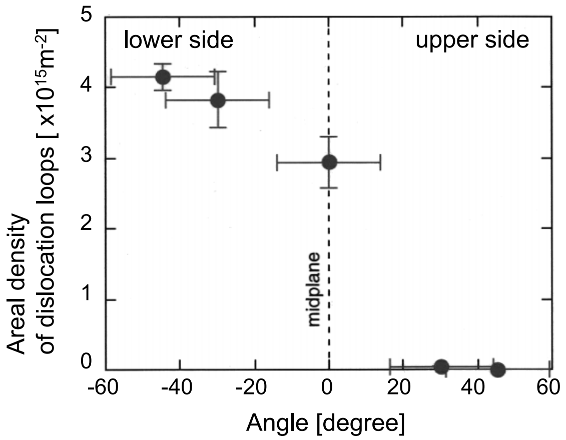

Fig. 4. Areal density of dislocation loops in the Mo specimens.

the results of hydrogen beam irradiation experiments. It is difficult to determine the fluence of the CX neutrals because of the wide energy spectrum of tokamak plasma. But we can roughly estimate the fluence using the convoluted areal density (A.D.) of dislocation loops and taking into account a weighing function as shown in Fig. 5(a). The areal density (shown in Fig. 5(b)) were calculated by the convolution of areal density of dislocation loops as measured in hydrogen beam irradiation experiments by means of the equation:

$$(\text{Convoluted A.D.})_{T_i=2.5\ \text{keV}} = \sum_{j=1.5,2,4,6,8} (\text{A.D.})_{E_j} \times f(A_i). \qquad (1)$$

One may point out the linearity of summation on the convolution. In fact, the linearity has been confirmed by experiments at low fluence range ($<2 \times 10^{20}$ particles m^{-2}). Using the convoluted areal density as a parameter, the fluence of CX neutrals can be estimated to about 1×10^{20} particles m^{-2} from the lower side. From the upper side where dislocation loops cannot be observed, the value is less than 5×10^{19} particles m^{-2}. The mean flux can be calculated by dividing the fluence by the solid angle of the cone and by the total discharge duration. As a result, the mean flux of CX neutrals would be 3×10^{17} particles m^{-2} s^{-1} sr^{-1} from the lower side and less than 1.5×10^{17} particles m^{-2} s^{-1} sr^{-1} from the upper side. Note that the estimated flux corresponds to the fraction only which can create radiation damage in Mo specimens, i.e., the energy of the particles exceed the minimum energy to introduce damage. The minimum energy E_{min} can be calculated by the following equation [10]:

$$E_{min} > \frac{(M_1 + M_2)^2}{4M_1M_2} E_d, \qquad (2)$$

where M_1 and M_2 are the masses of the incident particle (H: 1 amu) and the target atom (Mo: 96 amu), respectively. With the threshold energy for atomic displacements of $E_d = 35$ eV as quoted from literature [11], hydrogen particle of more than 850 eV is required to cause damage. Provided the energy distribution can be extrapolated to the lower energy (<850 eV), the mean flux including the lower energy components can be estimated about 4.2×10^{17} particles m^{-2} s^{-1} sr^{-1} from the lower side.

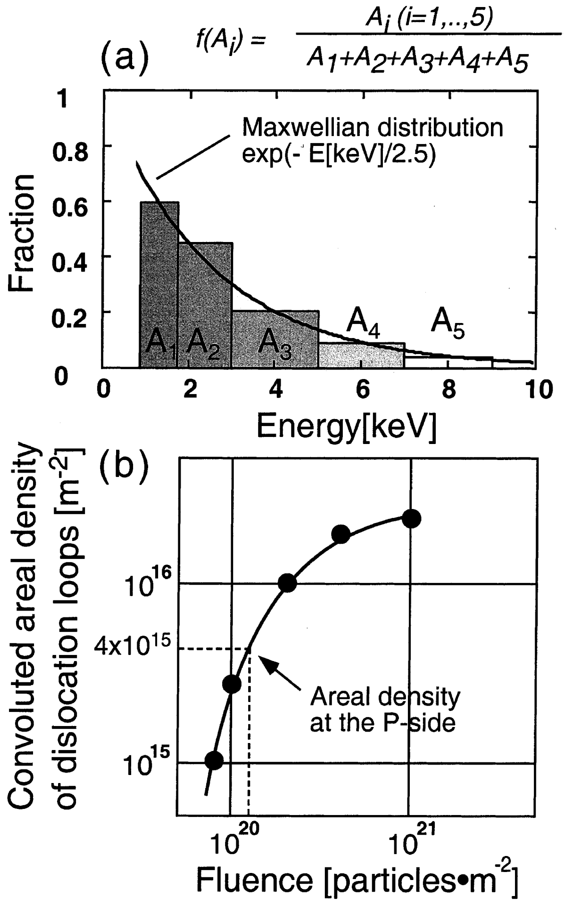

Fig. 5. (a) Weighing function based on Maxwellian distribution at $T_i = 2.5$ keV. (b) Fluence dependence of convoluted areal density (A.D.) of dislocation loops.

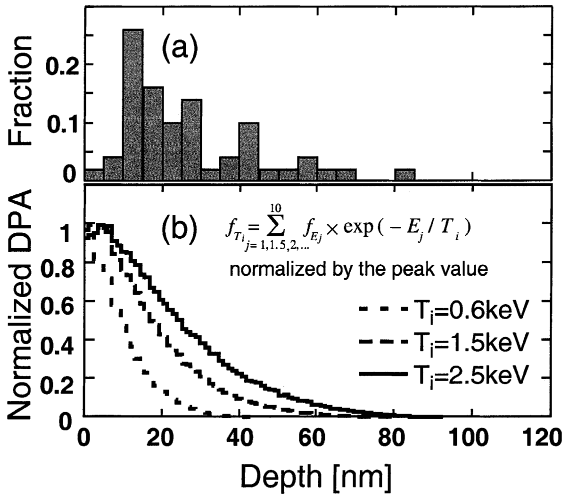

Fig. 6. (a) Depth distribution of dislocation loops in Mo specimen. (b) Depth distribution of damage (DPA: displacement per atom) in Mo calculated with TRIM-code at $T_i = 0.6$, 1.5, 2.5 keV.

3.3. Radiation damage by energetic CX neutrals

A comparison between the depth distribution of the dislocation loops and damage distribution calculated by the TRIM code [12] is shown in Fig. 6. Fig. 6(a) shows the measured depth distribution of the dislocation loops, while Fig. 6(b) shows the damage distribution in the low ion temperature discharges (0.6 keV) and high ion temperature (1.5 and 2.5 keV). As shown in Fig. 6(a) the dislocation loops are distributed until 80 nm in depth. The widespread depth distribution would be attributed to the high-energy components of CX neutrals. Suppose the ion temperature is T_i, the energy spectra can be written by $\exp(-E_i/T_i)$. Taking into account this Maxwellian distribution, the convolution of the distribution for each incident energy (f_{E_j}) yields

$$f_{T_i} = \sum_{j=1,1.5,2,\ldots}^{10} f_{E_j} \times \exp(-E_j/T_i) \quad (3)$$

as the convoluted damage distribution (f_{T_i}) at T_i. The figure shows the normalized distribution. As can be seen in Fig. 6, the measured distribution of the dislocation loops corresponds well to the calculated damage distribution for ion temperatures from 1.5 to 2.5 keV. The result indicates that the impact of the high-energy components cannot be neglected, even though the fraction is small. Dislocation loops were also observed in a tungsten specimen (not shown here). In the tungsten specimen, dislocation loops would be created if the incident energy of hydrogen exceeded 2 keV [13]. This result also shows the bombardment with the high-energy component of the CX neutrals.

The present results also indicate that energetic CX hydrogen neutrals ejected from the plasma, cause knock-on damage in the subsurface region of the plasma facing wall. Consequently, a considerable amount of damage is accumulated in a short experimental period. The radiation-induced dislocation loops can also act as good traps for the implanted hydrogen. Furthermore, cavities which will be formed due to high fluence ($>1 \times 10^{22}$ m^{-2}) will also act as trap sites for the implanted hydrogen [14]. These facts mean that radiation damage increase the hydrogen retention and then influence by hydrogen recycling [14,15]. Moreover, the radiation damage causes irradiation-induced hardening and embrittlement. It was reported that the edge of a tungsten specimen exposed to the discharges in TRIAM-1M was cracked along grain boundaries [4]. In addition, it was shown that the relative hardness (H_{irr}/H_{unirr}) increased by a factor 1.8 due to 10 keV D^+ irradiation with 2×10^{21} m^{-2} [16]. These works indicate that the plasma facing wall will easily brittle due to the bombardment.

4. Summary and conclusion

Material exposure experiments have been carried out in TRIAM-1M. As a result of microstructural observation of the specimens, accumulated radiation damage (dislocation loops) due to CX neutrals were observed only in the specimens pointing to the lower half of plasma. This anisotropy can be understood by the gradient B drift of high-energy ions trapped in a toroidal ripple.

The mean flux of the CX neutrals was estimated to be about 3×10^{17} particles m^{-2} s^{-1} sr^{-1} from the lower and less than 1.5×10^{17} particles m^{-2} s^{-1} sr^{-1} from the upper side. The mean flux including the low energy components from the lower side is estimated to be 4.2×10^{17} particles m^{-2} s^{-1} sr^{-1}.

It was shown that the high-energy components (several keV) of CX neutrals significantly contributed to the radiation damage. It is well known that radiation-induced defects play as trapping sites for implanted hydrogen. Accordingly, the amount of retained hydrogen in a material will be increased. In addition, defects can cause hardening and embrittlement of the materials.

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