Erosion and Carbon Deposition on Boron Exposed to Plasmas

OHYA Kaoru and SAJI Nobuyasu
Faculty of Engineering, The University of Tokushima, Tokushima 770-8506, Japan

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Abstract

Erosion of boron exposed to deuterium plasmas containing carbon impurity is investigated using a Monte Carlo simulation model for ion-solid interactions which takes dynamic composition change in the surface layer into account. The calculated results are compared with an erosion experiment of a boronized graphite test piece in TEXTOR-94. The implantation of carbon impurities strongly decreases the boron sputtering yield as a result of the formation of a thick carbon containing layer near the surface. These calculations can explain the experimental observations of surface erosion near the plasma edge and deposition of carbon at the surface location far from it. However, non-linear change of the observed thickness of boronized layer with time is not reproduced by the simulation. Furthermore, the carbon depth profile observed after the plasma exposure broadens inside the layer, deeper than the calculated profile.

Keywords: plasma-material interaction, boron erosion, carbon deposition, Monte Carlo simulation, boronization, TEXTOR

1. Introduction

The main erosion process for wall materials exposed in fusion plasma experiments is physical sputtering, except for carbon under certain conditions. The wall materials are simultaneously bombarded with ions of various species and charge states which impinge on the surface with a certain energy and angular distribution. The plasma impurity ions such as carbon are deposited and alter the surface composition and therefore also the sputtering yield of the wall materials. Despite the erosion due to the impact of plasma deuterium ions, therefore, the surface layer is partly reformed by the deposition of impurities eroded at the other locations of the wall and transported away along the magnetic field lines in the scrape-off layer (SOL) plasma. As a result, the life time of the walls depends on the balance of the rates for erosion and deposition [1].

Thin boron containing coating, "Boronization", of the walls has led to a large success in the present large tokamaks, due to reduced energy loss of plasma by radiation and its gettering of oxygen; as well as its protection for the chemical erosion of carbon walls [2]. Recently, the erosion of a boronized graphite test piece exposed in the SOL plasma of TEXTOR-94 has been observed [3,4]. It suggested that the gradual change of the composition due to implanted carbon can prolong the life time of protecting coatings when the coating became eroded under simultaneous carbon ion flux and deposition.

This paper presents computer simulations of the erosion-deposition process on boron due to simultaneous bombardment with deuterium and carbon ions in plasmas, by means of a dynamic Monte Carlo code. The code takes the composition change in the surface layer due to carbon deposition into account, so that it can simulate erosion due to sputtering of the modified multicomponent materials. The calculated results are also compared with some observations (change in the thickness of the boron coatings and carbon depth profile in the coatings) in TEXTOR-94.

corresponding author's e-mail: ohya@ee.tokushima-u.ac.jp
2. Simulation Model and Its Application to Erosion-Deposition on Boron Exposed to TEXTOR-94 Edge Plasmas

2.1 Simulation model

Projectile reflection and physical sputtering from solid surfaces under ion bombardment are simulated using the binary collision approximation under the assumptions of an amorphous medium, constant free flight path for elastic collision and continuous slowing down due to inelastic interaction in the solid, according to the Monte Carlo method [5]. The simulation model calculates trajectories of a projectile ion and recoiling solid atoms which are generated through elastic collisions of the ion with ionic cores in the solid. The motions of the ions and recoil atoms are treated in the same way: each particle moves along a free flight path

\[ L = N^{1/2} \cdot \tan(\theta/2) \]

before it encounters the next collision partner with an impact parameter \( P \) between 0 and \( \pi^{1/2}N^{1/3} \), including simultaneous weak collisions with more distant atoms with larger impact parameter; \( N \) is the atomic density of the solid and \( \theta \) is the scattering angle in the center-of-mass system. The impact parameter, which is chosen by using a random number, is related to the scattering angle by an approximate analytical formula for Ziegler-Biersack-Littmark potential [6], and the azimuthal angle is determined between 0 and 2\( \pi \) by another random number. The inelastic energy loss in the paths between elastic collisions is calculated using empirical formulae derived by Ziegler et al. [7], while the energy loss during each elastic collision is calculated from the scattering angle, according to the classical collision theory; a new recoil atom is generated. Some of the projectile ions escape from the surface, after migration within the solid, as reflected particles. The recoiling atoms which reach the surface with kinetic energy greater than the surface binding energy of the solid, leave it as sputtered particles.

The ion bombardment induces composition changes near the solid surface due to both implantation of the projectile ion and collisional transport of the projectile ion and recoil atoms. The dynamic composition change of the solid are simulated using the same Monte Carlo model as in the TRIDYN code [8]. The model is based on the assumption that each projectile ion represents a differential ion fluence \( \Delta \Phi = \Phi/N \) where \( \Phi \) and \( N \) are real ion fluence and the number of projectiles simulating \( \Phi \), respectively. The surface layer of the solid is divided into \( k \) slabs of initially constant thickness \( \Delta x \); in this study, \( N = 10^9 \), \( k = 400 \) and \( \Delta x = 2 \) nm. The physical processes associated with the collisional transport of the projectile ion and recoil atoms, such as ion implantation, reflection, physical sputtering and atomic relocation, cause removal or deposition of particles in different layers. Each particle removed from (or deposited in) a layer causes a change in the partial atomic density of the component atoms, including the projectile ion, in that layer. After termination of each collision process induced by a projectile, the fractional compositions are recalculated for each layer and the total atomic density in each layer relaxes to the sum of the constant atomic densities of pure components weighted by the fractional composition. This relaxation results in an altered thickness of the layer due to the lack of or excess densities of component atoms. Before following the collision process of a new ion, the change in total thickness of the surface layer, i.e., the surface erosion (or deposition), is calculated, and then the in-equidistant layer thicknesses are converted into the original thickness \( \Delta x \) by interpolation. As a result, surface composition and the depth distributions of the component atoms are calculated as a function of the fluence of the projectile ions, which is proportional to time. The surface binding energy of the multicomponent solid is assumed to be the sum of each sublimation energy \( E_s \) weighted by the surface atomic concentration; in this study, \( E_s \) is taken to be 5.77 eV for boron and 7.37 eV for carbon [9]. In this dynamic simulation, diffusion and segregation processes are not taken into account. These effects may not play a role, at least, at low temperatures of the solids.

2.2 Application to erosion-deposition process on boron exposed to plasmas

The simulation code is applied to calculate erosion and carbon deposition on a boronized layer exposed to a scrape-off layer (SOL) plasma in TEXTOR-94. In the experiment [3,4], a boronized (between 95 and 110 nm a-B:D) on an Al interlayer of \( \sim 300 \) nm graphite test piece is brought into the SOL and exposed during 22 discharges (121 s). As shown in Fig. 1, because its plane surface (60 mm \( \times \) 63 mm) is tilted to the toroidal direction (20.8°), the different surface locations correspond to different radial distances from the last closed flux surface (LCFS: \( r = 46.0 \) cm) and covered the radial range of 47.2 - 49.5 cm. Most of the Ohmic heated (OH) discharges (\( \sim 7 \) s duration) are auxiliary heated for \( \sim 2 \) s by neutral beam injection (NBI). This increased, about by a factor of two, not only the electron density and temperature in the SOL but also the D and C ion fluxes along the magnetic field lines. Parameters used in this calculation are listed in Table 1. The electron density and temperature in the SOL measured
by Li- and He-beam diagnostics were fitted to exponential functions; not all discharges were measured, but in the average they were fitted. The D ion flux at the LCFS and its decay length in the SOL for the NBI phase was estimated experimentally [3,4], whereas the C ion flux, which was not measured, was estimated from the fact that it has to be consistent with the observed carbon deposits on an Al plate at $r = 49.8$ cm [3,4], assuming the decay length to be 2 cm [10]. For the OH phase, furthermore, the fluxes are taken to be half the values for NBI phase and the decay lengths are assumed to be unchanged. The mean charge state of bombarding carbon ions was calculated [11], which also was consistent with experiments [12]. The total exposure times in the OH and NBI phases during 22 discharges were 95 s and 26 s, respectively.

In this simulation, because of different plasma conditions between OH and NBI phases, the erosion-deposition process in each phase is separately calculated during each exposure time. The two ion species are chosen randomly according to their fluxes at different surface locations, so that simultaneous incidences of fuel D$^+$ ions and impurity C$^{4+}$ ions are taken into account. As found in Fig. 1, furthermore, the values of their ion fluxes hitting the inclined surface are weighted by $\sin 20.8^\circ$. The velocity distributions of the bombarding ions are assumed to be Maxwellian with an ion temperature $T_i$ in front of the surface location, which may be somewhat higher than the electron temperature $T_e$, e.g., by a factor of 2 - 4, which depends on the discharge conditions [12]. Therefore, $T_i = 1.5 T_e$ and $T_i = 4 T_e$ are tentatively chosen for this simulation. The ions bombard each surface location after sheath acceleration, where the sheath acceleration voltage is $-2.48 T_e$ [13]. In the simulation, a pure boron surface with an atomic density of $1.0 \times 10^{23}$ cm$^{-3}$ is assumed to be exposed to the SOL plasma. The D retention in boron (also in deposited C) is not taken into account. Furthermore, it is assumed that the Al interlayer and graphite test piece do not influence the erosion-deposition process of the boron layer (initially 100 nm), whose thickness is much thicker than the implantation depth (or ion projected range $\sim 10$ nm) of incident ions. This assumption is not justified when the thickness becomes comparable to or smaller than the ion range as a result of strong erosion.

Table 1 Plasma parameters used in the calculation.

<table>
<thead>
<tr>
<th>Discharge condition</th>
<th>OH phase</th>
<th>NBI phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron density at the LCFS, $n_{LCFS}$ (cm$^{-3}$)</td>
<td>$2.4 \times 10^{12}$</td>
<td>$6.2 \times 10^{12}$</td>
</tr>
<tr>
<td>Electron temperature at the LCFS, $T_{e,LCFS}$ (eV)</td>
<td>25</td>
<td>44</td>
</tr>
<tr>
<td>Density decay length in the SOL, $\lambda_D$ (cm)</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Temperature decay length in the SOL, $\lambda_T$ (cm)</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Ion fluxes at LCFS, $F_{i,LCFS}$ (cm$^{-2}$s$^{-1}$)</td>
<td>$0.77 \times 10^{19}$</td>
<td>$1.53 \times 10^{19}$</td>
</tr>
<tr>
<td>$F_{i',LCFS}$ (cm$^{-2}$s$^{-1}$)</td>
<td>$3.75 \times 10^{16}$</td>
<td>$7.50 \times 10^{16}$</td>
</tr>
<tr>
<td>Flux decay lengths in the SOL, $\lambda_i$ (cm)</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Carbon charge states, $q$</td>
<td>+4</td>
<td>+4</td>
</tr>
<tr>
<td>Time of exposure, $t$ (s)</td>
<td>95</td>
<td>26</td>
</tr>
</tbody>
</table>
3. Calculation Results and Comparison with Experiments

3.1 Boron and carbon sputtering yields
Since the calculated carbon reflection coefficient is 0.009 - 0.025, most of incident C ions are implanted in the boron film. The carbon implantation causes the sputtering yield of B to decrease with the exposure time in both the OH and NBI phases, whereas an additional sputtering of implanted C appears, as shown in Figs. 2 and 3. Due to the fact of the ion temperature (bombarding energy) being lower for the OH phase than for the NBI phase, the sputtering yield of B in the OH phase is smaller, e.g., by a factor of two or more for the case of $T_i = 1.5 T_e$, than that in the NBI phase. Due to the formation of thick carbon layer (as described in the next section), furthermore, there is a strong decrease in the sputtering yield of B with the exposure time, in particular, at the surface location corresponding to large radial distances ($r = 48.7$ cm). On the other hand, at small radial distance ($r = 47.3$ cm), the sputtering yield of B is approximately constant after sudden decrease at the early stage of exposure. As seen in Figs. 3(a) and 3(b), the sputtering yield of implanted C increases with the exposure time. In spite of the formation of the thick carbon layer, however, the sputtering yield of C in the OH phase with $T_i = 1.5 T_e$ (Fig. 3(a)) decreases with...
increasing radial distance due to the decrease in the ion temperature. With increasing the ion temperature \( T_i = 4 T_e \), however, the thickness of the carbon layer decreases due to strong sputtering of implanted C, and as a result, the sputtering yield of C decreases at the top edge of the test piece \( r = 47.3 \text{ cm} \). At \( r = 47.3 \text{ cm} \), furthermore, the sputtering yield of C is dominated by the amount of carbon deposits (not by the ion temperature), therefore, the change in the sputtering yield of C with the exposure time is similar to each other in both the OH and NBI phases, in particular, for \( T_i = 1.5 T_e \). In contrast with the OH phase \( T_i = 1.5 T_e \), due to dominant effect of increasing the amount of carbon deposits, the sputtering yield of C in the NBI phase with \( T_i = 4 T_e \) increases with increasing radial distance, except at the early stage of exposure.

In Figs. 4(a) and 4(b), the sputtering yields of B and C at the end of exposure in the OH and NBI phases are shown as a function of the radial distance of the surface location from the plasma center. The distances of \( r = 47.2 \text{ cm} \) and \( r = 49.5 \text{ cm} \) correspond to the top edge and bottom edge of the test piece (Fig. 1), respectively. At small distances where the ion temperature is high, strong sputtering of B is obtained, in particular, for the NBI phase and \( T_i = 4 T_e \). With decreasing ion temperature and also increasing ratio of C ion flux to total bombarding ion flux \( (D+C) \), the B yield is steeply decreased at large distances; for both OH and NBI phases, the ratio \( \Gamma_C/(\Gamma_D + \Gamma_C) \) is 0.008 at \( r = 47.3 \text{ cm} \) and 0.017 at \( r = 49.1 \text{ cm} \). This decrease in the B yield is accompanied with the increase in the C yield at small distances. At large distances, however, the increase in the C yield is suppressed due to the decrease in the temperature (energy) of bombarding ions. For the OH phase with \( T_i = 1.5 T_e \) where the ion temperature is lowest in this calculations, the C yield decreases even at small distances \( (r = 47.3 \text{ cm}) \). At \( r = 47.3 \text{ cm} \), furthermore, the C yields in all the cases (OH and NBI phases with \( T_i = 1.5 T_e \) and \( T_i = 4 T_e \)) are approximately equal to each other due to dominant effect of the amount of carbon deposits, mentioned before.

### 3.2 Carbon depth profile in boron

Figures 5(a) and 5(b) show the calculated depth profiles after the exposures in the OH and NBI phases, respectively, at different surface locations (radial distances). The implantation depth (or projected range) of incident C\(^{4+} \) ions is very shallow and comparable to or less than 10 nm in the average at such low energy. With increasing radial distance \( r \), the energy (temperature) of C ions bombarding the boron surface decreases, which results not only in the decrease in the implantation depth but also in the decrease in the sputtering yield of implanted C, in particular, for the case of the OH phase. The former produces shallow depth profiles of implanted C whereas the latter produces thick carbon deposition profiles. Despite relatively small change in the sputtering yield of C as well as the decrease in the implantation depth, the increase in the ratio of C ion flux to total ion flux \( (D+C) \) causes the depth profiles in the NBI phase to broaden gradually with increasing radial distance. The depth profiles \( (r < 48.1 \text{ cm}) \) in the OH phase with \( T_i = 4 T_e \) shows the same trend as in the NBI phase. However, the depth profiles in the OH phase with \( T_i = 1.5 T_e \) indicate the formation of the
3.3 Boron erosion and carbon deposition

Both the changes in the sputtering yield of B and C (Figs. 2 and 3) and the depth profile of C (Fig. 5) substantially influence the erosion process of boron during the exposure of SOL plasmas. As a result, the question of whether surface erosion or deposition occurs depends strongly upon the SOL plasma conditions (ion and electron temperature and density, impurity concentration in the plasma). Figures 7(a) and 7(b) show the change in the thickness of boron with time during the OH phase (95 s) and the NBI phase (26 s), respectively, at different radial distances. In the OH phase with \( T_i = 1.5 T_e \), it is clearly found that erosion of the boron surface occurs at small distance \( (r = 47.3 \text{ cm}) \), whereas deposition of the impurity C occurs at large distances \( (r = 48.1 \text{ cm and } r = 48.7 \text{ cm}) \). For \( T_i = 4 T_e \), however, an erosion of the boron surface is found at all of the distances. The transition from erosion to deposition with \( T_i = 1.5 T_e \) due to the increase in the distance of the surface location from the plasma center is due to decreasing sputtering yield of B and the formation of thick C layer. In the NBI phase, due to high temperature of bombarding ions, an erosion of the boron surface is found at most of the distances.
although at \( r = 48.7 \text{ cm} \), the surface thickness is approximately unchanged with time, due to the balance of erosion due to sputtering and carbon deposition. For both OH and NBI phases with \( T_i = 4 T_e \), the boronized layer (initially \( \sim 100 \text{ nm} \)) at the top edge of the test piece (\( r = 47.3 \text{ cm} \)) disappear after a time shorter than the exposure time of 96 s (OH) and 26 s (NBI). Nevertheless, the deposition of C in the OH phase with \( T_i = 1.5 T_e \) may suppress the erosion of the boronized layer in the NBI phase, in particular, at the radial distances of \( r < 48.1 \text{ cm} \).

In Fig. 8, the changes in the observed thickness of the boronized layer with time at different radial distances [4] are compared with the calculated thickness which is evaluated from the sum of the thickness changes in the OH and NBI phases (Fig. 7). The calculated thickness is in reasonable agreement with the observation. At small distances, e.g., \( r = 47.3 \text{ cm} \), the boron surface is clearly eroded due to strong sputtering of B by impact of high-fluence and high-temperature D ions, in spite of simultaneous implantation of incident C ions. On the other hand, at large distances, e.g., \( r = 48.7 \text{ cm} \), since the C concentration in the bombarding ion flux is about 0.015 and the sputtering yield of implanted C is less than 0.0075 for \( T_i = 1.5 T_e \), more than half of the bombarding C ions are continuously implanted during the exposure. As a result, the deposition of C is dominant and thick carbon containing layer is clearly formed as obtained experimentally, which decreases the sputtering yield of B as well. At \( r = 48.4 \text{ cm} \) (not shown here), the observed thickness is approximately unchanged with time, whereas by the simulation, the unchanged thickness is calculated at the radial distance of \( \sim 48.2 \text{ cm} \) for \( T_i = 1.5 T_e \); for \( T_i = 4 T_e \) only the surface erosion is calculated at all the distances.

4. Discussion
In the erosion zone (\( r = 47.3 \text{ cm} \) and \( r = 48.1 \text{ cm} \)), the observed thickness decreases slowly at first and later it largely drops (Fig. 8). After the large decrease in thickness the erosion rate is reduced again and becomes comparable to the values at the beginning. The calculated change in the thickness strongly depends on the ion temperature which is in this study assumed to be \( T_i = 1.5 T_e \) and \( T_i = 4 T_e \). The change in the
thickness between $T_1 = 1.5 T_e$ and $T_1 = 4 T_e$ is larger than the observed non-linear change in the thickness with time. However, the observed non-linear change is not reproduced by this simulation. The erosion process calculated by our simulation is the physical sputtering due to impact of D and C ions. The thick carbon layer near the boron surface may be also subject to chemical sputtering, producing hydrocarbons such as CD$_4$, by D ion impact. However, the chemical sputtering will be suppressed by the presence of B atoms in the carbon layer [14]. One of the origins for the observed non-linear change may be morphological changes on the surface, which are accompanied with the island-like non-uniform deposition of C mentioned before. Since, for impact of D ions with the energies of less than 1 keV, the sputtering yield of C is smaller than the yield of B, the surface location where deposition of C occurs is less eroded, whereas the carbon-free areas are more eroded. The non-uniform erosion initially causes the development of surface topographies, such as cone or pyramids [15], and as a result, the top of the cones where the C atoms deposit is slowly eroded. With further exposure to plasma ions, the cones shrink and disappear due to dominant erosion of inclined surfaces; the cones are steeply eroded due to the increase in the sputtering yield with oblique angles of incidence. As a result, the nearly flat surface is reformed again. In recent experiments [12], the non-uniform carbon deposition with typical dimensions of 10 - 30 μm was found even in the net erosion zones, by electron probe micro-analysis.

Neutral C and B atoms sputtered from the surface are ionized upon entering the SOL. As a result, the ionized atoms gyrate due to the Lorentz force and are guided along the magnetic field lines, and move away from the surface, or return near the sputtered area or to the area where the magnetic field lines intersect at a small angle with the surface. Upon returning to the surface the ions are deposited or reflected, and if the sheath potential accelerates the ions before incidence enough to overcome the sputtering threshold energy the ions may also cause further sputtering. These prompt redeposition and self-sputtering process are important if the ionization length of the sputtered atoms in the SOL is comparable to or less than the gyroradius of the ionized atoms. We have developed a computer simulation code which combines the TRIDYN-type dynamic simulation code with a simple model of multiple ionizations of sputtered atoms and gyromotion of the resulting ions in the SOL [16]. A tentative calculation with the plasma parameters in Table 1 shows small contribution of the prompt redeposition to the erosion-deposition process on boron; only 4.6% - 2.2% of sputtered C and B are redeposited on the surface. This is because the ionization length is much longer than the gyroradius, e.g. by a factor of 10, resulting from low density and low temperature of the SOL and low-Z atoms (C and B).

If the surface composition change is not taken into account, then we can linearly add the erosion due to sputtering by impact of D and C ions with the deposition due to implantation of C ions to roughly estimate the net erosion/deposition on the boron surface [1]. This leads to the simple equation for the erosion (deposition) thickness per unit time at different surface locations,

$$\frac{dT}{dt} = -\left[ Y_{D-B} \Gamma_D^{LCFS} \exp \left(-x/\lambda_D^C\right) \sin \delta \right] + Y_{C-B} \Gamma_C^{LCFS} \exp \left(-x/\lambda_C^C\right) \sin \delta/N_b$$

$$+ \left[ \Gamma_C^{LCFS} \exp \left(-x/\lambda_C^C\right) \sin \delta/N_b \right],$$

where $Y_{D-B}$ and $Y_{C-B}$ are the sputtering yields of boron due to impacts of D and C ions, respectively, and $N_b$ and $N_c$ are the atomic densities of pure boron and carbon. $\delta$ is the inclination angle of the surface against the magnetic field lines (Fig. 1), and $x$ is the radial distance of the surface location from the LCFS. As listed in Table 1, $\Gamma_D^{LCFS}$ and $\Gamma_C^{LCFS}$ are the D and C ion fluxes at the LCFS, respectively, and $\lambda_D^D$ and $\lambda_C^C$ are their decay lengths. The sputtering yields $Y_{D-B}$ and $Y_{C-B}$ due to impact of the ions with the Maxwellian velocity distribution with the ion temperature at the surface location, including the sheath acceleration, are calculated using our simulation code without the surface composition change.

Results for this simple method of the net erosion/deposition thickness are shown in Fig. 9, for different radial distances with $T_1 = 1.5 T_e$ and $T_1 = 4 T_e$; where the boron thickness is evaluated from the sum of the thickness changes in the OH and NBI phases, in the same manner as in Fig. 8. In the figure, the deposition due to implantation of C ions without erosion due to sputtering is also shown (thick dotted line). In comparison with the result taking the surface composition change into account (Fig. 8), the carbon deposition at $r = 48.7$ cm is suppressed for $T_1 = 1.5 T_e$, and the boron erosion at $r = 48.1$ cm and $r = 47.3$ cm are enhanced. As a result, it is found that the dynamic composition change in boron due to implantation of C ions causes the increase in the deposition rate of carbon and the decrease in the erosion rate of boron. This is because the physical sputtering yield of carbon due to impact of
D ions is smaller than that of boron at the ion energies of less than 1 keV [17], due to higher surface binding energy $E_b$ (higher threshold energy $E_{th}$ for physical sputtering).

We are aware of the fact that, in this study, the simulation represents the erosion-deposition of the boronized film by only two exposures in the OH phase (95 s) and the NBI phase (26 s), whereas the experiment was performed with 22 exposures, each of which is shaped by both the OH and NBI phases. Moreover, each discharge used for the exposure is not identical in plasma parameters and discharge time. There were also 5 discharges that disrupted during exposure. For more detailed discussion on the erosion-deposition of the boronized film, therefore, these real exposure conditions with 22 discharges may be simulated, in addition to the physical and chemical processes which are not included in this study, such as surface topography change and deuterium retention in the film.

5. Conclusion

In this work, a dynamic simulation which calculates implantation of incident ions and collisional transport of solid atoms has been performed for studying erosion of boron and deposition of carbon impurities by simultaneous bombardment with deuterium and carbon ions in the TEXTOR-94 edge plasma. The dynamic composition change due to the implantation of carbon impurities near the surface causes strong decrease in the boron sputtering yield and an additional sputtering of implanted carbon, as a result of the formation of a carbon containing layer. These can explain the experimental observations of a lowering of the surface erosion near the plasma edge and a deposition of carbon at the surface location far from it. However, non-linear change of the observed thickness with time is not reproduced by the simulation. One of the possible origins for this discrepancy may be morphological changes on the surface due to non-uniform carbon deposition. Furthermore, the carbon depth profile observed after the exposure broadens inside the boron layer, in comparison with the profile calculated, assuming ideally flat surface.

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