

# Effects of carbon impurity in fusion plasmas on erosion of RAF first wall

Y. Ueda<sup>\*</sup>, T. Funabiki, T. Shimada, R. Kawakami<sup>1</sup>, M. Nishikawa

*Department of Electronic, Information Systems, and Energy Engineering, Graduate School of Engineering, Osaka University, 2-1 Yamadaoka, Suita, Osaka 565-0871, Japan*

## Abstract

Sputtering erosion of RAF (reduced-activation ferritic/martensitic steel) was studied under hydrogen and carbon mixed ion beam irradiation. Ion beam energy, flux, and fluence were 1 keV  $H_3^+$  (dominant species),  $\sim 1.5 \times 10^{20}$  H/m<sup>2</sup> s and  $\sim 5 \times 10^{24}$  H/m<sup>2</sup>, respectively. Erosion yields of RAF irradiated by the mixed ion beams are found to be temperature dependent. For carbon concentration in the beam of 0.84% (1.3%), an effective erosion yield at 453 K is lower than that at 773 K by 18% (34%). For 0.8% C in the beam, the surface carbon composition at 453 K is about 20%, while at 773 K it is very low ( $\sim 3\%$ ), which suggests swift carbon diffusion into the bulk. This experimental surface carbon concentration agrees with simulation results by the EDDY code. The change in the effective erosion yield with temperature is consistent with the change in surface carbon concentration.

© 2004 Elsevier B.V. All rights reserved.

## 1. Introduction

Reduced-activation ferritic/martensitic steel (RAF) is one of the strongest candidates for structural materials of blankets for DEMO reactors [1]. Its sputtering erosion, however, could be an important issue for the use of RAF as a plasma-facing wall material. Although putting an armor material such as tungsten on the first wall can reduce sputtering yield significantly, the use of tungsten would increase radioactive dust and complicate fabrication processes of the blankets. Therefore, the use of RAF as a plasma-facing wall still remains as an attractive option. Estimation of erosion rates of RAF wall, however, is not easy when impurity ions are included in the plasma. Effective sputtering yield increases with volatile impurity ions (eg. inert gas) in the DT plasma, while non-volatile impurity ions such as carbon ions

remain in the material after implantation and reduce erosion of base materials. These implanted carbon atoms diffuse at elevated temperatures, which makes erosion processes more complicated. Therefore, the behavior of carbon ions in RAF and its effect on sputtering erosion needs to be studied for reliable blanket design. However, no useful experimental results nor reliable simulation has yet been reported.

In this study, RAF (F82H) samples were irradiated with a high flux ( $>10^{20}$  m<sup>-2</sup> s<sup>-1</sup>) hydrogen ion beam with small amounts of carbon ions (0.8–1.3%) to obtain erosion yield of RAF under simultaneous bombardment of hydrogen and carbon. Erosion rates were estimated by weight loss and erosion depth. In addition, dynamic simulation by the EDDY code [2] was also done.

## 2. Experimental

In this study, an ion beam irradiation device Hi-FIT was employed for hydrogen and carbon mixed ion beam irradiation. Although the details of this ion source were described elsewhere [3,4], a brief

<sup>\*</sup> Corresponding author. Tel.: +81-6 6879 7236; fax: +81-6 6879 7867/7236.

E-mail address: [yueda@eie.eng.osaka-u.ac.jp](mailto:yueda@eie.eng.osaka-u.ac.jp) (Y. Ueda).

<sup>1</sup> Faculty of Engineering, The University of Tokushima, Tokushima 770-8506, Japan.

description is given here. In the HiFIT, an ECR ion source powered by 2.45 GHz microwave (5 kW at maximum) equipped with spherical electrodes (effective diameter was 150 mm) geometrically focused the broad ion beams onto the samples to obtain a high-flux beam. In the experiments, hydrogen ion beams consisting of mainly  $H_3^+$  as well as  $H_2^+$  and  $H^+$  were used with energy of 1 keV. Energies per an atom for these species are 333, 500, and 1 keV, respectively. Atom species ratio (333 eV H:500 eV H:1 keV H) is about  $\sim 0.7:\sim 0.2:\sim 0.1$ . Irradiation flux and fluence were  $\sim 1.5 \times 10^{20}$  H/m<sup>2</sup> s and  $\sim 5 \times 10^{24}$  H/m<sup>2</sup>, respectively.

Carbon impurity in hydrogen ion beams was added by putting carbon plates in the ion source chamber. Carbon impurity concentration was changed from  $\sim 0.1\%$  to  $\sim 1.3\%$ , depending on the size of carbon plates in the ion source. Oxygen impurity in the ion beam of about 0.05% was always present. The other impurity concentrations are less than the detection limit ( $\sim 0.01\%$ ). Carbon impurity ions in the beam appeared as hydrocarbon molecular ions such as  $CH_x^+$  and  $C_2H_x^+$ . Carbon concentration in the ion beams was measured by a magnetic deflection mass analyzer. Details of estimation of impurity concentrations in ion beams were described in Ref. [5].

RAF used in the experiments is F82H steel, which contains 7.65 wt% Cr, 2 wt% W, and Mo, Mn, V, Ta, Ti, Si and C below 1 wt% in sum total, and Fe for the balance [6]. Sample materials were the same as those used for compatibility studies of F82H with tokamak plasma in JFT-2M [7,8]. Heat treatment at 623 K for 10 h in vacuum was done before ion beam irradiation to desorb contained gas. Sample size was  $10 \times 20 \times 1$  mm<sup>3</sup> with surfaces polished to a mirror finish, with roughness of an order of 10 nm. The ion irradiation area was defined by a 5 mm diameter aperture in front of the samples. Samples were heated up to 773 K with an IR-heater and the sample temperature was measured using a thermocouple embedded in the copper holder, which was attached to the irradiation samples. In the case of about 470 K, samples were heated by the ion beam itself and no active heating by the IR-heater was done.

Erosion rate estimated by weight loss during ion beam irradiation. Weight loss was measured by a microbalance (Metler, MX5) with readability of 1  $\mu$ g. Surface profile was measured by a surface profilometer (SNF, DekTak3) with a stylus radius of 12.5  $\mu$ m. Depth profiles of atomic composition in irradiated RAF was measured by XPS (X-ray induced photoelectron spectroscopy). After the irradiation of samples, they were exposed to air when delivering them to the XPS device. Therefore, impurity atoms such as oxygen and carbon were adsorbed on the top surface before XPS measurements.

### 3. Results of RAF erosion

Fig. 1 shows a surface profile of an ion irradiated RAF sample measured by the surface profilometer. In this case, a hydrogen ion beam with 0.8% carbon was used. The irradiated surface became rough with roughness of about 100 nm. A surface profile of the eroded area, shown in Fig. 1, was downward convex. This profile was caused by the ion flux distribution and the surface deformation of the irradiated samples. Ion flux distribution was the main cause, but in some cases surface deformation was too large to remove its effect on depth estimation. To calculate averaged depth of irradiated area, 11 line profiles separated by 0.5 mm each were measured by the surface profilometer across the eroded area of the samples (5 mm in diameter). This measurement gave a detailed 3D pictures of eroded areas, which was useful to estimate averaged depth. Under similar irradiation conditions, tungsten showed blistering [9]. RAF samples, however, did not show blistering probably due to the small grains and/or low hydrogen trapping energy at grain boundaries.

Erosion evaluated from two measurements, weight loss and erosion depth, is shown in Fig. 2. In Fig. 2(a), an effective sputtering yield was deduced from weight loss and incident fluence, under the assumption that samples consisted of only Fe. This assumption is acceptable because the major alloying element in RAF, Cr, has similar atomic number and surface binding energy to Fe, leading to a similar sputtering yield. It is noted that three hydrogen species (333 eV H, 500 eV H and 1 keV H) have similar sputtering yields for Fe. It is found that effective sputtering yields were increased with sample temperature for both 1.3% C and 0.8% C. The increment in the effective sputtering yield when the temperature was increased from about 470 to 770 K for 1.3% C was about  $6.6 \times 10^{-3}$ , which corresponded to about 34% of the yield at 770 K. On the other hand, the increment was about 18% for 0.8% C, smaller than that

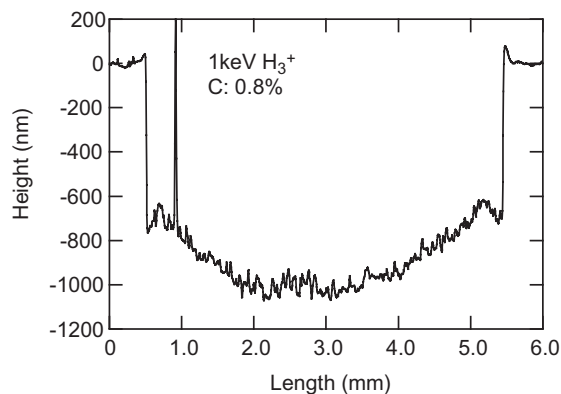


Fig. 1. Surface profile of irradiated RAF sample.

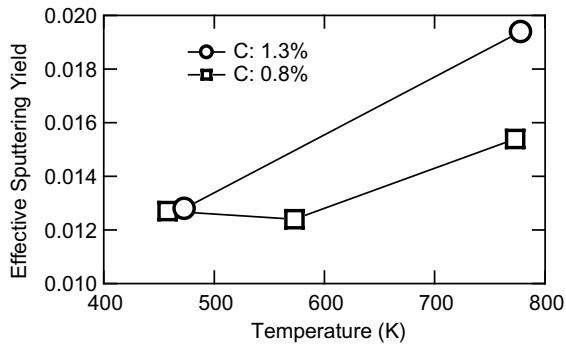


Fig. 2. Effective erosion yield as a function of temperature for the carbon concentrations in the ion beams of 0.8% and 1.3%.

for 1.3% C, though the yield was similar at about 470 K. This difference is attributed to the difference in carbon concentration on the sample surface during mixed ion irradiation. This will be discussed in Section 4.

**4. Discussions of carbon behavior and erosion yield**

The temperature dependence of erosion yield by mixed ion beam irradiation has a close relation to the behavior of implanted carbon atoms in RAF. Fig. 3 shows depth profile of atomic composition measured by XPS. Etching was done by a 2.9 keV Ar beam. Etching time of 300 s corresponds to about 20 nm. In both Fig. 3(a) and (b), at the top surface (etching time of 0 and 10 s) high concentrations of oxygen and carbon were observed. Since they were adsorbed due to exposure to the air, these data points are neglected in the following discussion. For 773 K, carbon concentration in the material is uniformly very low (about 3%), see Fig. 3(a). On the other hand, for 453 K, carbon concentration of about 20% was observed near the top surface and decreased with depth to about 15 nm, see Fig. 3(b).

The difference in depth profiles at different temperatures could be attributed to carbon diffusion in RAF. Since there are no data yet on carbon diffusion in RAF, the carbon diffusion coefficient in Fe,  $3.94 \times 10^{-7} \times \exp(-0.831[eV]/kT)$  ( $m^{-2} s^{-1}$ ) [10], is used in this discussion. In this diffusion coefficient, activation energy of C diffusion in Fe (0.831 eV) is low enough for C atoms to diffuse swiftly at the temperature of 773 K. Detailed carbon diffusion behavior in Fe was calculated by the EDDY code [2], which includes collision cascade processes, material compositional changes, and carbon impurity diffusion in RAF.

Calculated depth profiles of carbon atoms are shown in Fig. 4 for carbon concentration of 0.84% in the beam. In the case of no-diffusion (zero temperature limit), implanted carbon atoms stay near the surface. The

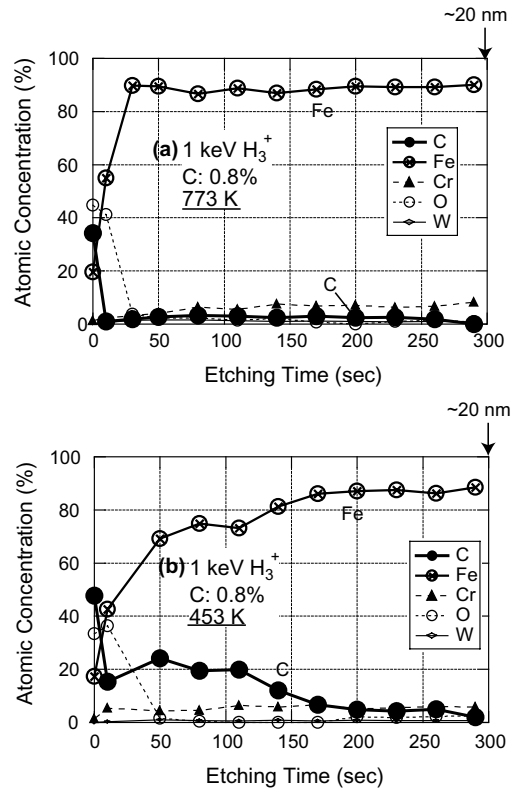


Fig. 3. Depth profiles of atomic composition measured by XPS for 773 K (a) and 453 K (b). Carbon concentration in the beam is 0.8%.

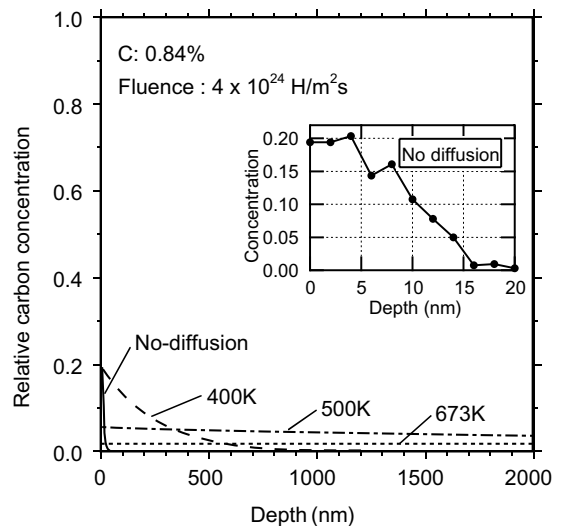


Fig. 4. Depth profile of implanted carbon atoms in Fe with temperature as a parameter calculated by the EDDY code. An insert shows detailed carbon depth profile for the case of no-diffusion (zero temperature limit).

surface concentration of C is about 0.2 and the carbon distribution extends to the depth of about 20 nm, see Fig. 4. This simulation result is in good agreement with the experimental results at the sample temperature of 453 K. This means that implanted carbon atoms did not diffuse into the bulk at the temperature of 453 K in the experiment. In the simulation, however, carbon atoms diffuse deep into the bulk even at the temperature of 400 K, see Fig. 4. This discrepancy may be attributed to the inappropriate diffusion coefficient used here (the diffusion coefficient of C in Fe or RAF may be different). In addition, chemical sputtering of carbon becomes a dominant erosion process for graphite at 773 K [11]. This same chemical erosion process could also reduce carbon concentration near the surface of RAF.

At low temperatures, carbon atoms did not diffuse deep into the bulk but stayed at the top surface to protect RAF from sputtering erosion. The experimental surface carbon composition was about 20% for 453 K and 0.8% C in the beam, see Fig. 3. The erosion yield was reduced by about 20%, compared to the case with no carbon atoms on the surface, which corresponded to the results for 773 K and 0.8% C in the beam. As was mentioned in Section 3, the experimental effective erosion yield for 453 K and 0.8% C was lower than that for 773 K and 0.8% C by 18%. This experimental result agrees well with the reduction rate of the erosion yield estimated above.

The reduction rate of the effective erosion yield for 1.3% C also agrees well with carbon atom composition at the surface. Fig. 5 shows calculated carbon concentration at RAF surfaces by the EDDY code in the no-diffusion case as a function of carbon concentration in the ion beams. Surface carbon concentration increased with carbon concentration in ion beams and reached a maximum value of 1 at 2.0% C, over which carbon

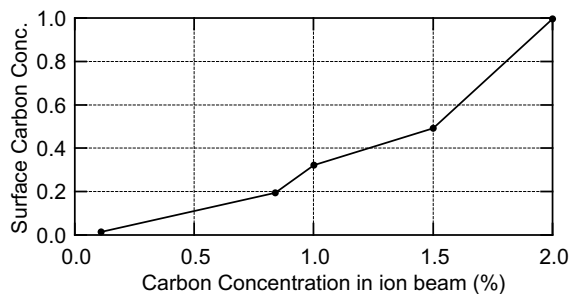


Fig. 5. Surface carbon concentration on Fe as a function of carbon concentration in ion beams calculated by the EDDY code.

atoms accumulated on RAF surfaces. From Fig. 5, the surface carbon concentration for 1.3% C is about 40%, which also roughly agrees with the reduction rate of the effective erosion yield for 1.3% C case (34%, see Section 3).

## 5. Conclusion

The erosion depth of RAF irradiated by hydrogen and carbon mixed ion beams (mainly 1 keV  $H_3^+$ ) is found to be temperature dependent. In the case that carbon concentration in the hydrogen beam is 0.84% (1.3%), the effective erosion yield at 453 K is lower than that at 773 K by 18% (34%). Temperature dependent erosion is caused by carbon diffusion into the bulk. Namely, implanted carbon atoms stay near the top surface and protect the RAF from sputtering erosion in the low temperature case (453 K), while implanted carbon atoms diffuse into the bulk and is not available for reduction of sputtering erosion in the high temperature case (773 K). The change in the effective erosion yield with temperature is consistent with the change in surface carbon concentration.

## Acknowledgements

The authors are grateful to Dr M. Sato in JAERI for providing RAF samples.

## References

- [1] Y. Ueda, K. Tobita, Y. Katoh, *J. Nucl. Mater.* 313–316 (2003) 32.
- [2] R. Kawakami, K. Ohya, *Jpn. J. Appl. Phys.* 40 (2001) 5399.
- [3] T. Kawakami, T. Shimada, T. Yonezawa, Y. Ueda, M. Nishikawa, *Rev. Sci. Instrum.* 71 (2000) 1144.
- [4] T. Shimada, T. Kawakami, Y. Ueda, A. Sagara, M. Nishikawa, *J. Plasma Fusion Res.* 3 (2000) 312.
- [5] Y. Ueda, H. Kikuchi, T. Shimada, A. Sagara, B. Kyoh, M. Nishikawa, *Fusion Eng. Des.* 61–62 (2002) 255.
- [6] M. Tamura, H. Hayakawa, A. Yoshitake, A. Hishinuma, T. Kondo, *J. Nucl. Mater.* 155 (1988) 620.
- [7] M. Sato, Y. Miura, S. Takeji, H. Kimura, K. Shiba, *J. Nucl. Mater.* 258–263 (1998) 1253.
- [8] K. Tsuzuki et al., *J. Nucl. Mater.* 283–287 (2000) 681.
- [9] T. Shimada, H. Kikuchi, Y. Ueda, A. Sagara, M. Nishikawa, *J. Nucl. Mater.* 313–316 (2003) 204.
- [10] H. Mehrer (Ed.), *Diffusion in Solid Metals and Alloys*, Springer-Verlag, Berlin, 1990.
- [11] J. Roth, C. Garcia-Rosales, *Nucl. Fusion* 36 (1996) 1647.