Chemical Erosion of Carbon Material
Irradiated with Low Energy Atomic Hydrogen Neutrals

Y. Takeguchi1, M. Kyo1, Y. Uesugi1, Y. Tanaka1, S. Masuzaki2

1Division of Electrical and Computer Science Kanazawa University, Kanazawa, 920-1192, Japan
2National Institute for Fusion Science, Toki, 509-5292, Japan

Abstract: Experiments on erosion and dust formation of the carbon materials have been performed using high power inductively coupled plasma of low plasma temperature (~1 eV) and high atomic hydrogen flux of ~1024 m-2s-1. Chemical sputtering yield with atomic hydrogen irradiation was roughly estimated to be 0.001-0.004, which is as high as that obtained by ion beam and fusion plasma experiments. When diamond coated graphite is irradiated by the irradiation of low energy hydrogen atoms, the chemical erosion of material has hardly occurred.

Keywords: chemical erosion, plasma-surface interaction, diamond coated graphite, ICP

1. Introduction

Carbon materials, such as isotropic graphite, and carbon fiber reinforced composites (CFC) are superior material as plasma facing components (PFCs), which are used in a fusion reactor because of their high thermal conductivity and tensile strength. Graphite divertor tiles, however, are eroded significantly by the irradiation of the high particle and heat flux divertor plasmas. Erosion and dust formation of carbon material bring many significant effects on the performance of the fusion reactor, such as tritium retention, impurity release, degradation of vacuum sealing, and electrical isolation, etc. So far several methods to reduce the divertor plasma heat load have been tested and it has been recognized that the detached divertor plasma operation[1] is the most probable one in the fusion reactor. Although the detached divertor works well for heat load reduction, the graphite erosion by the irradiation of low energy hydrogen ions and atoms in the detached divertor plasma is not yet understood well. It is very important to examine the plasma surface interactions in detached plasmas for the future reactor design. In the detached divertor plasma, it is thought that the hydrogen ion flux into plasma facing components decreases drastically because hydrogen ions are cooled below several electronvolt by strong gas injection and neutralized by volume recombination of hydrogen ions. Therefore, the existence of low energy hydrogen atoms will have significant effects on plasma surface interaction in the detach divertor plasmas. In this report, carbon erosion properties by low energy atomic hydrogen irradiation have been studied using high-pressure Inductively Coupled Plasmas (ICPs)[2-4].

2. Experimental setup

Figure 1 shows a schematic diagram of a plasma irradiation system using high power ICPs. Experiments have been performed by irradiating argon-hydrogen mixture plasmas to graphite target. Argon gas flow rate is 60 litters per minutes (slpm), and the injection rate of hydrogen gas into argon plasma is 0, 3, 5, 8 slpm. A MOSFET inverter power supply with maximum rf power of 30 kW at a frequency of ~400 kHz has been used for the power supply of ICP. The input power was set to 10–15 kW in this experiment. Graphite target (IG-430U, Toyo Tanso Co. Ltd.) or diamond coated graphite target (Diamond layer is coated on graphite target IG-430U)
using CVD, Tomei diamond Co. Ltd.), with diameter of 15 mm, is placed on the stage made from boron nitride under the plasma torch. Irradiation time is kept at 180 minutes. In order to examine the effect by ion particle into graphite target, a dc bias voltage can be applied between the graphite target and vacuum chamber. The surface temperature of the graphite target is measured with a radiation thermometer through a quartz window. The surface temperature is not actively controlled but controlled indirectly by changing the experimental conditions, such as the input power, axial position of the induction coil and so on. In order to investigate plasma properties, spectroscopic measurement and Langmuir probe measurement are carried out at the point 3 mm above the graphite target as shown in figure 2. After 180 minutes the application of plasma irradiation, graphite target was collected and the weight was measured to obtain the change in mass before and after argon-hydrogen mixture plasma irradiation.

3. Results and discussions
3.1. Plasma parameter of ICP
Probe measurements of argon-hydrogen mixture plasmas show that the electron temperature and electron densities near the graphite target, and ion fluxes into the target are in the range of 0.5-1.5 eV, \(10^{17}-10^{18} \text{ m}^{-3}\) and \(10^{19}-10^{20} \text{ m}^{-2}\text{s}^{-1}\) respectively. The incident energy of ion into graphite target are estimated to be about 4 eV, taking account of the electron sheath of the target. In this experiment, the erosion by physical sputtering has hardly occurred because both the argon and hydrogen incident energies are much less than the threshold energy of the graphite[5]. The atomic hydrogen density and hydrogen ion density are estimated from the results of electromagnetic fluid simulations under local thermodynamic equilibrium condition[6]. Figure 3 shows the densities of hydrogen atoms and ions near the graphite target as a function of H\(_2\) gas flow rate. These results from ICP simulations indicate that the degree of ionization is below 0.1% in the present experiment conditions, and dominant particles bombarding the graphite target are hydrogen atoms not ions. In addition, it is estimated that the atomic hydrogen flux is as high as \(10^{23}-10^{24} \text{ m}^{-2}\text{s}^{-1}\), which is four order of magnitude higher than that of hydrogen ions.

From these results, it is shown that high power ICPs has characteristic features, such as high neutral particle flux \(\Gamma \sim 10^{23}-10^{24} \text{ m}^{-2}\text{s}^{-1}\), high heat flux \(\Gamma_{\text{heat}} \sim 1\text{MW/m}^2\), and low temperature \(T_e \sim 1\text{eV}\). Although the working gas pressure is high (P \(\sim\) 5kPa), these features are very helpful in studying the fundamental mechanism of carbon erosion and dust formation in detached plasma conditions.

3.2. Erosion of graphite target
Table 1 shows the weight loss of the graphite target in different irradiation condition. The graphite target is slightly eroded by pure argon plasma irradiation. It seems that RES (Radiation Enhanced Sublimation) occurs slightly on the graphite target. With addition of hydrogen into argon plasmas, the erosion of graphite target is extremely enhanced. Figure 4 shows the emission spectra from the plasma at 3 mm above the graphite target during argon and argon-hydrogen mixture plasma irradiation. With inclusion of hydrogen, the molecular band spectra of CH and C\(_2\) are observed strongly, which is a good indication of chemical sputtering. Figure 5 shows emission image of the graphite and surrounding plasmas.

![Graph showing atomic hydrogen density and hydrogen ion density as a function of H\(_2\) gas flow rate](image1)

![Emission spectra from the plasma at 3 mm above the graphite target for pure Ar (solid line) and Ar/H\(_2\) (dotted line) plasma irradiation.](image2)

![Emission image of the graphite and surrounding plasmas](image3)
in Ar+H₂ plasma irradiation. Figure 6 shows intensity distribution of Ar I, Hα, CH, C₂ emission. From these figures, it is found that C₂ particles and hydrocarbon gas tend to localize above graphite target. These results indicate that the hydrocarbon particles release from the graphite target by chemical sputtering. Their released hydrocarbon particles are dissociated by electron impact into hydrocarbon radicals and carbon molecules, which redeposit on graphite target by strong gas down-flow.

Chemical sputtering yield by the irradiation of low energy hydrogen atoms is estimated from the weight loss of graphite target and atomic hydrogen flux given by the electromagnetic fluid simulation.

Figure 7 shows surface temperature, T_s dependence of the chemical sputtering yield estimated as mentioned above. From this figure, the chemical sputtering yield by low energy atomic hydrogen irradiation is 0.001-0.004, which is close to those obtained in the ion beam experiments[7] and the fusion plasma experiments[8, 9]. The erosion of graphite target depends on surface temperature of graphite target strongly. The peak of the chemical sputtering yield by atomic hydrogen irradiation is obtained when T_s ~ 900K. The peak temperature of chemical sputtering is higher than that of other experimental data. It is considered that the difference in the peak temperature is caused by the difference in the incident energy and the flux of particles into the target. The chemical sputtering yields of graphite target are measured, when dc bias voltage is applied to the target.

The chemical sputtering yield by hydrogen atoms with positive biasing of +50 V and negative biasing of -60V, are almost same as those without biasing. It is found that the change of hydrogen ion flux do not affects on the erosion of graphite target.

Figure 8 shows comparison of the chemical sputtering yield between hydrogen ion and atom irradiation as a function of the particle flux. Chemical sputtering yield obtained in the present experiments is plotted on the same figure given by J. Roth et al [9]. From this figure, it is recognized that the chemical sputtering yield by hydrogen atoms has the same magnitude and same flux dependence as those of hydrogen ion irradiation.
3.3. Erosion of diamond coated graphite target

In order to compare the erosion rate between isotropic graphite and other material coated graphite, polycrystal diamond coated graphite was tested. Figure 9 shows SEM image of diamond coated graphite target before and after irradiation of argon-hydrogen mixture plasma. The weight loss of diamond-coated target is as low as ~0.2 mg, while that of graphite in the same irradiation condition is about 100 mg. However, the damages are found on the target surface. These damages on target surface are caused by the chemically etching of crystal defects such as crystal grain boundary, etc. Figure 10 shows emission spectra from the plasma at 5 mm above graphite target and diamond coated graphite target for Ar/H₂ plasma irradiation. From these observations, it is found that chemical sputtering has hardly occurred on the diamond-coated target in the present experiment condition.

4. Conclusion

The present work is the study of the erosion properties on graphite materials and diamond coated graphite materials using high power ICP, which have low plasma temperature (~1 eV) and high atomic hydrogen flux (~10²⁴ m⁻²s⁻¹). Graphite target is eroded low energy atomic hydrogen irradiation. Chemical sputtering yield by hydrogen atoms was roughly estimated to be 0.001-0.004 in high flux region of ~10²⁴ m⁻²s⁻¹. The value of chemical sputtering yield by low energy hydrogen atoms is in the same range as that by energetic hydrogen ion irradiation. Flux dependence of the chemical sputtering yield in the atomic hydrogen irradiation shows the same trend as that in hydrogen ion. In detached divertor plasmas, it is thought that the chemical sputtering by hydrogen atoms generated by volume recombination will have significant effect on the graphite material erosion. In the case of plasma irradiation onto diamond coated target, chemical erosion is suppressed drastically. This preliminary result shows a possibility to use diamond coated on the graphite fast wall in place of the pure graphite materials. In near future detailed experiments on chemical erosion of tungsten coated graphite target in addition to the diamond coated one.

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References