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Carbon Erosion under Heavy Atomic Hydrogen Irradiation

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Experiments on erosion and dust formation on graphite materials have been performed using high power induction plasmas of low plasma temperature (∼1 eV) and high atomic hydrogen flux (∼10^{24} $m^{-2}s^{-1}$). Chemical sputtering by atomic hydrogen irradiation with incident energy below 1 eV erodes the graphite targets significantly, and generates hydrocarbon particles C_xH_y. The chemical sputtering yield was roughly estimated to be 0.002-0.005, which is as high as that obtained by ion beam and fusion plasma experiments. Chemical sputtering by hydrogen atoms are generated by recombination in the detached divertor plasmas will have a significant effect on the graphite tile erosion.

Keywords: Carbon, Erosion, Plasma-Material Interaction, Sputtering

1. Introduction

Carbon materials, such as isotropic graphite, and carbon fiber reinforced composites (CFC) are superior plasma facing components, which are used in a fusion reactor because of their high thermal conductivity and tensile strength. Graphite tiles, however, are eroded significantly by irradiation of high particle and heat flux divertor plasmas. Sputtering erosion and dust formation of carbon materials have significant effects on fusion reactor performance, 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 is 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 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 and dust formation mechanisms in detach divertor plasma for future reactor design. In the detached divertor works, it is thought that hydrogen ion flux into plasma facing components decreases because hydrogen ions are cooled by strong gas injection and neutralized by recombination of hydrogen. Therefore, the existence of hydrogen atoms will have significant effect on plasma surface interaction in the detach divertor plasmas more than the energetic ions. In this paper, Carbon erosion by atomic hydrogen has been studied using high pressure Inductively Coupled Plasmas (ICPs)[2]. The authors report how large atomic hydrogen irradiation affect the erosion of graphite.

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2. Experimental setup

Figure 1 shows a schematic diagram of a plasma irradiation system using ICP. In this paper, experiments have been performed by irradiating argon-hydrogen mixture (gas flow rate, Ar: 60 slpm H_2: 0, 2, 4, 6, 8 slpm) plasmas to graphite targets. A MOSFET inverter power supply with maximum rf power of 30 kW at a frequency of ∼450 kHz has been used for the power supply of ICP. The input power is 15 kW in this experiment. Six graphite targets (IG-430U fabricated by TOYO Tanso Co.) with diameters of 15 mm, are placed at different positions to determine how the irradiation condition affects graphite target erosion. Three graphite targets are located on the table facing Ar/H_2 plasmas (Pos.1-3) and another three graphite targets are located below the top table (Pos.4-6) where the targets are not irradiated directly by the plasma. The target surface temperature is measured by a radiation thermometer. In this experiment, the surface temperature is not actively controlled but indirectly controlled by changing the experimental conditions, such as the input power, position of the induction coil and so on. In addition, to investigate plasma properties, spectroscopic measurement and Langmuir probe measurement are carried out at the point 5 mm above the graphite target of position 1 as shown in Figure 2.

3. Results and discussion

3.1 Plasma parameter of ICP

At first, the electron temperature, electron density and ion flux have been measured by Langmuir probe. From probe measurements of Ar/H_2 mixture plasmas, it is shown that the electron temperature and electron density near the target position 1, and ion flux

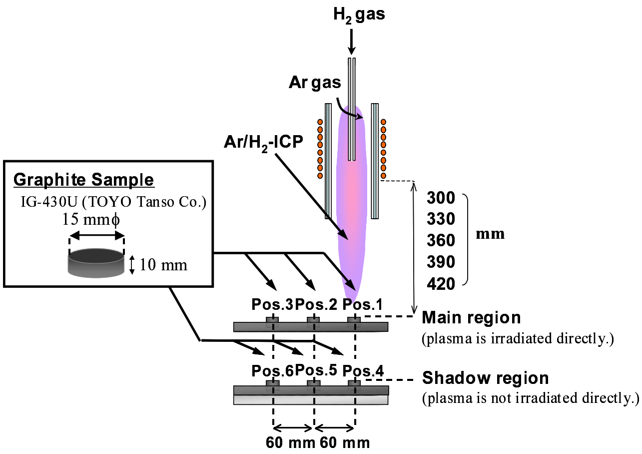

Fig. 1 Schematic diagram of a plasma irradiation system using ICP.

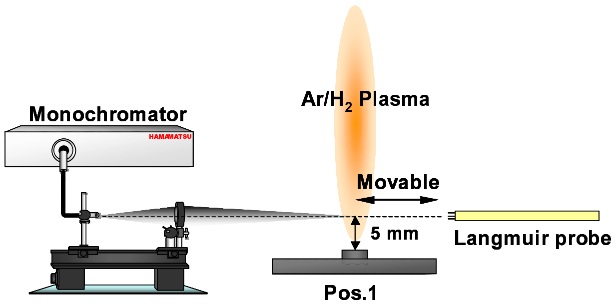

Fig. 2 Schematic diagram of measurement system.

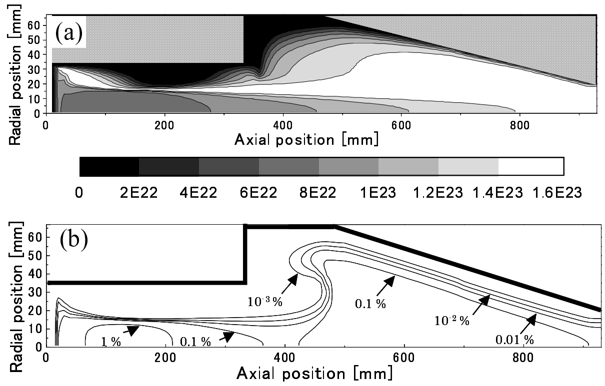

Fig. 3 Two-dimensional distribution of (a) atomic hydrogen density and (b) the degree of ionization obtained by fluid simulation.

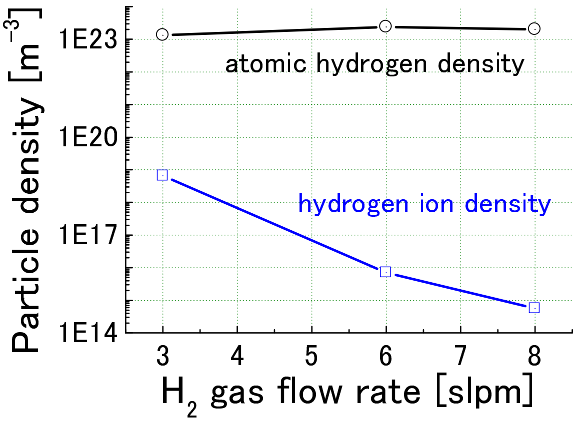

Fig. 4 Atomic hydrogen and hydrogen ion density near the graphite target of position 1 as a function of the H_2 gas flow rate obtained by fluid simulation. (Input power: 15 kW, Ar gas flow rate: 60 slpm)

onto the target 1 are 0.5-1.5 eV , 10^{16}-10^{17} m^{-3} and 10^{19}-10^{20} $m^{-2}s^{-1}$ respectively. The incident energy of ion and atom of hydrogen into graphite target are about 5 eV and 1eV respectively, taking account of the electron sheath on the graphite surface. The atomic hydrogen density and hydrogen ion density are estimated from the results of electromagnetic fluid simulations under local thermodynamic equilibrium condition[3]. Figure 3 shows a two-dimensional distribution of atomic hydrogen density and the degree of ionization. And, figure 4 shows atomic hydrogen and hydrogen ion densities as a function of the H_2 gas flow rate. These result from ICP simulations indicate that the degree of ionization is below 0.1% in the present experiment conditions, and the dominant particles bombarding the graphite target are atomic hydrogen, not ions. In addition, it is estimated that the atomic hydrogen flux is as high as 10^{23}-10^{24} $m^{-2}s^{-1}$, which is four order in magnitude higher than that of hydrogen ions. From these results, it is shown that high power ICPs have characteristic features, such as a high particle flux (ion flux: 10^{19}-10^{20} $m^{-2}s^{-1}$, atomic hydrogen flux: 10^{23}-10^{24} $m^{-2}s^{-1}$), high heat flux ($\sim$1 MW/m_2), and low temperature ($\sim$1 eV). Although the working gas pressure is high (P $\sim$5 kPa), these features are very helpful in studying the fundamental mechanism of carbon erosion and dust formation in detached plasmas, where atomic and molecular hydrogen particles play an import role in the plasma-material interactions.

3.2 Graphite erosion by chemical sputtering and RES

After 180 minutes of plasma irradiation, graphite targets have been collected and their weights have been measured to have the mass change of the graphite target before and after Ar/H_2 plasma irradiation. Table 1 shows the weight loss of the graphite target located at different position (Pos.1-6). With addition of hydrogen into Ar plasmas, graphite target erosion is extremely enhanced. It is thought that this erosion is mainly attributed to chemical sputtering of graphite

Tab. 1 Weight loss of graphite target by Ar/H_2 plasma irradiation.

	Pos.1	Pos.2	Pos.3	Pos.4	Pos.5	Pos.6
Ar:60 slpm, H_2:0 slpm	4.4 mg	2.7 mg	2 mg	0.2 mg	0.1 mg	-0.5 mg
Ar:60 slpm, H_2:2 slpm	35.4 mg	36.6 mg	5.3 mg	-0.2 mg	0.2 mg	0.4 mg
Ar:60 slpm, H_2:8 slpm	88.2 mg	95.6 mg	19.4 mg	-0.2 mg	0.3 mg	0.3 mg

targets. Figure 5 shows the radiation spectra from the plasma at 5 mm above the graphite target 1 during Ar and Ar/H_2 plasma irradiation. With inclusion of hydrogen, the band spectra of CH and C_2 are observed strongly, which is a good indication of chemical sputtering by atomic hydrogen. This result indicates that hydrocarbon gas occurs from the surface of graphite target by chemical sputtering. It seems that this production of hydrocarbon gas bring carbon dusts, and carbon dusts will redeposit on the graphite targets. Therefore, mass change of graphite which is shown in table 1 is a composition between erosion by chemical sputtering and redeposition of the hydrocarbon and carbon particles. Figure 6 shows Emission image of the graphite target and surrounding plasmas in Ar/H_2 plasma irradiation. From this figure, It is recognized that C_2 particles localize above graphite target. Because of this, gas flow from upstream prevent occurring hydrocarbon gas from spreading in the chamber. On the other hands, it is found from table 1 that the graphite carbon is slightly eroded by pure argon plasma irradiation. RES (Radiation Enhanced Sublimation) seems to be the cause of this erosion. Here, occurring physical sputtering of carbon by irradiation of argon ion needs incident energy of over 25 eV[4]. In this experiment, incident energy of argon ion is below 5eV. Therefore, physical sputtering have hardly occurred in this experiment. The graphite erosion by pure argon plasma irradiation must be due to RES. From these results, It seems that the erosion of graphite targets is due to a chemical sputtering and RES in this experiment.

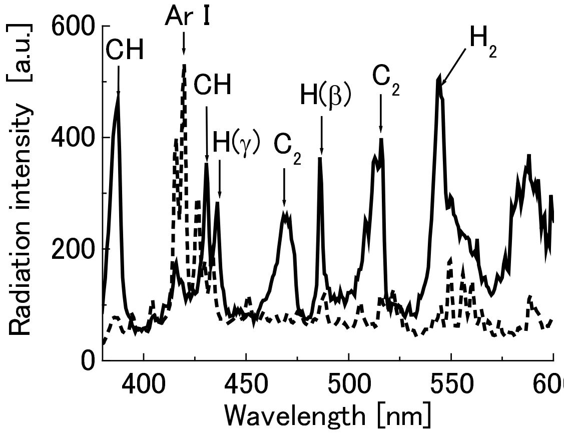

Fig. 5 Radiation spectra from the plasma at 5 mm above graphite target of position 1 for pure Ar (dotted line) and Ar/H_2 (solid line) plasma irradiation.

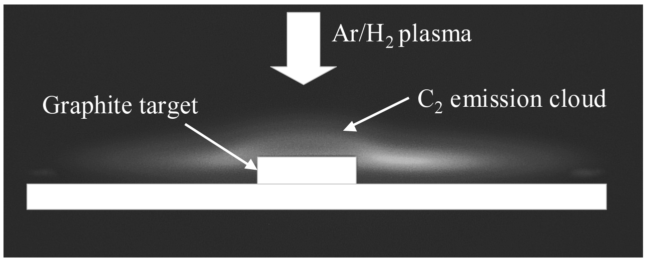

Fig. 6 Emission image of the graphite target and surrounding plasmas in Ar/H_2 plasma irradiation.

3.3 Flux and temperature dependence of the graphite erosion

From table 1, it can be easily shown that the graphite erosion is the dominant phenomenon in this experiment. It is found that significant erosion occurred in the graphite targets facing the plasma (Pos.1-3). But, targets placed in the shadow region (Pos.4-6) have hardly eroded. The maximum erosion rate was observed in graphite target of position 1, which has been irradiated directly by both hydrogen ions and atoms. It is found that the weight loss of the graphite target of position 3 is much smaller than that of both position 1 and position 2. Figure 7 shows the weight loss of the graphite target of position 1 after plasma irradiation as a function of the surface temperature. This figure indicates that the graphite erosion depends strongly on surface temperature in each H_2 gas flow rate in this experiment. The peak of weight loss is obtained when surface temperature is about 900 K.

3.4 Chemical sputtering yield by atomic hydrogen irradiation

In order to investigate the importance of graphite erosion by atomic hydrogen irradiation, the authors

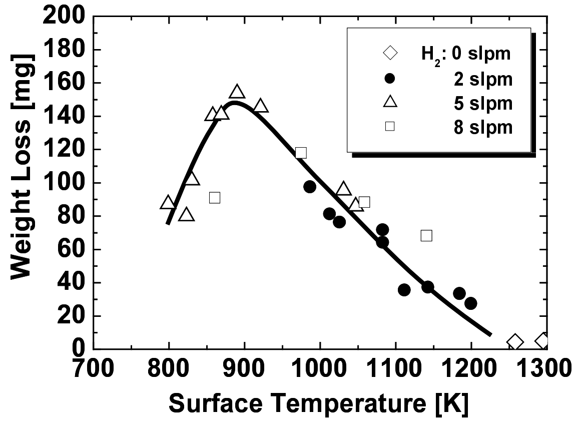

Fig. 7 Weight loss of the graphite target as a function of the surface temperature with Ar/H_2 plasma irradiation. H_2 gas flow rate is changed which keeping Ar flow rate constant at 60 slpm

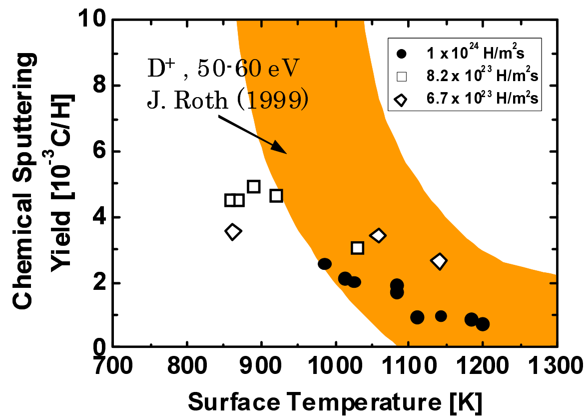

Fig. 8 Surface temperature dependence of chemical sputtering yield in different irradiation conditions.

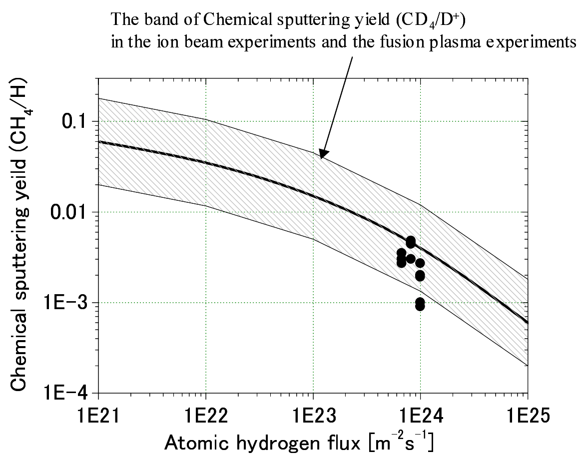

Fig. 9 Atomic hydrogen flux dependence of chemical sputtering yield estimated by the weight loss of graphite targets.

estimate chemical sputtering yield. A rough estimation of the chemical sputtering yield by low energy atomic hydrogen irradiation is 0.002-0.005. Here, the chemical sputtering yield is estimated by the weight loss of the graphite target and the hydrogen gas feed rate. Since the electromagnetic fluid simulation of the induction plasma shows that most of the hydrogen molecules introduced into the induction plasmas are dissociated, to atoms in the core region, the influx of atomic hydrogen is estimated on the basis that the introduced hydrogen particles are fully dissociated in the core plasma and the generated atomic hydrogen particles are carried equally downward along the cross sectional area of the plasma column. Figure 8 shows the surface temperature dependence of chemical sputtering yield estimated as mentioned above. The peak of the chemical sputtering by atomic hydrogen is obtained when the surface temperature is about 900 K, which is close to those obtained in the ion beam experiments[5] and the fusion plasma experiments[6,7]. Figure 9 shows atomic hydrogen flux dependence of chemical sputtering yield. Although the values of chemical sputtering yield by atomic hydrogen are plotted in this figure, these results are also close to those obtained in the ion beam experiments and the fusion plasma experiments.

3.5 Comparison between the graphite erosion by continuous irradiation and repeated irradiation

Above experiment, the graphite targets have been collected after 180 minutes of plasma irradiation continuously. In the case of the fusion experimental devices, the divertor tiles are removed from the devices and investigated after several times of experiment. In order to experiment under the more practical condition, the repeated irradiation has been introduced. This repeated irradiation is carried out as follows; a experimental time set was repeated six times, and each set was composed of Ar/H_2 plasma irradiation for 30 minutes and 10 minutes interval. In the repeated irradiation, the surface temperature is changed in accordance with the existence of plasmas as shown in figure 10. In the paper, The weight loss of the graphite targets in continuous irradiation is compared to that in repeated irradiation. Table 2 shows the result of comparison between the weight loss of graphite targets by continuous irradiation and repeated irradiation. The weight loss of graphite targets of position

Tab. 2 Comparison between the weight loss of graphite target by continuous irradiation and repeated irradiation.

	Surface temperature			Weight loss		
	Pos.1	Pos.2	Pos.3	Pos.1	Pos.2	Pos.3
Ar:60 slpm, H_2:2 slpm (repeated irradiation)	930 K	–	–	104.9 mg	8.1 mg	1.8 mg
Ar:60 slpm, H_2:2 slpm (continuous irradiation)	987 K	906 K	–	97.4 mg	35.9 mg	2.1 mg

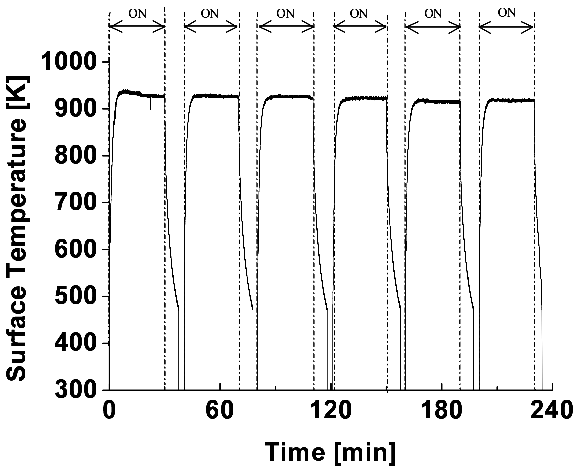

Fig. 10 Time evolution in surface temperature of the graphite target of position 1 in the repeated irradiation.

1 have been indicated similar value in both irradiate condition. However, the shape of carbon dusts created on the target of position 1 have been different in each irradiate condition. The detail of this discussion will be given in another opportunity.

4. Conclusion

The erosion on graphite materials have been investigated using high power ICP which have low plasma temperature (~1 eV) and high atomic hydrogen flux ($\sim 10^{24}$ $m^{-2}s^{-1}$). Graphite targets are significantly eroded by irradiation of Ar/H_2 plasmas with high atomic hydrogen flux to generate hydrocarbon particles C_xH_y by the chemical sputtering. On the other hand, physical sputtering have hardly occurred in this experiment. It is found that significant erosion has occurred in the graphite targets which were irradiated directly by the plasma. But, the targets placed in the remote region have hardly eroded. The sputtering yield by atomic hydrogen have been roughly estimated to be 0.002-0.005, which is as high as that obtained by ion beam and fusion plasma experiments. It is obtained that the value of chemical sputtering yield by atomic hydrogen are mostly similar to that by hydrogen ion. In detached divertor plasma, it is thought that the chemical sputtering by hydrogen atoms generated by recombination will have significant effect on the graphite erosion. In addition, the weight loss of graphite target in continuous irradiation is compared to that in repeated irradiation. The weight loss of graphite target of position 1 have been indicated similar value in both condition of irradiation. However, the shape of carbon dusts created on the target of position 1 have been different in each irradiate condition.

5. Acknowledgements

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