Carbon Erosion and Dust Formation 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 containing high atomic hydrogen flux ($\sim 10^{24}\mathrm{m}^{-2}\mathrm{s}^{-1}$). Chemical sputtering by atomic hydrogen irradiation with an incident energy below 1 eV eroded the graphite targets significantly, and the sputtering yield was roughly estimated to be 0.002-0.005, which is as high as that obtained by ion beam experiments. The transport of the released hydrocarbon along the gas flow results in carbon dust formation on the eroded graphite target and also on the silicon and graphite targets located at the remote position. The dust structure strongly depends on the target surface temperature, and the graphite dust turns into diamond crystals when the surface temperature rises to 1100 K.

Keywords: plasma-surface interaction, dust formation, atomic hydrogen plasma, carbon material

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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. Divertor graphite tiles, however, are eroded significantly by irradiation with high particle and heat flux divertor plasmas. Sputtering erosion and dust formation of carbon materials have significant effects on 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 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.

In this paper, high power inductively coupled plasmas (ICPs) [1] with a power level of ~20 kW are used to study plasma surface interactions and dust formation mechanism. High power ICPs have characteristic features, such as a high particle flux (ion flux: 10^{20}-$10^{21}\mathrm{m}^{-2}\mathrm{s}^{-1}$, atomic hydrogen flux: 10^{23}-$10^{24}\mathrm{m}^{-2}\mathrm{s}^{-1}$), high heat flux ($\sim 1\,\mathrm{MW/m}^2$), and low temperature (~ 1 eV) under experimental conditions, which include an input power of 15 kW, argon gas flow rate of 60 slpm and hydrogen gas flow rate of 2 slpm. High power ICPs are the irradiation source for both low energy and dominant atomic hydrogen. Although the working gas pressure is high (P ~ 5 kPa), these features are very helpful in studying the fundamental mechanism of carbon erosion and dust formation in detached plasmas.

Experimental results of argon-hydrogen mixture (Ar: 60 slpm, H_2: 0, 2, 8 slpm) plasma irradiation onto graphite targets are reported. Figure 1 shows a schematic diagram of a plasma irradiation system. One graphite target (IG-430U fabricated by TOYO Tanso Co.) is located under the plasma torch and five other graphite or silicon crystal targets, with diameters of 15 mm, are placed at different positions to determine how the irradiation condition affects graphite target erosion and dust formation. These targets were exposed to argon-hydrogen mixture plasmas for 180 minutes. The target surface temperature is not actively controlled in this experiment. The surface temperature is indirectly controlled by changing the experimental conditions, such as the input power, position of the induction coil and so on. First, we observed the mass change of the graphite target before and after plasma irradiation. The electron temperature and density, measured by an electrostatic double probe, are $T_\mathrm{e}\sim 1$ eV and $n_\mathrm{e} = 10^{17}$-$10^{18}\mathrm{m}^{-3}$ at target position 1. Electromagnetic fluid simulation [2] indicated that the degree of ionization is about 0.1 %, and the dominant particles bombarding the graphite target under the experimental conditions were atomic hydrogen, not ions.

It was found that erosion occurred both in the graphite targets facing the plasma (No.1-3) and those placed in the shadow region (No.4-6). The maximum erosion rate was observed in graphite target 1, which was irradiated directly by both hydrogen ions and atoms. The erosion rate de-

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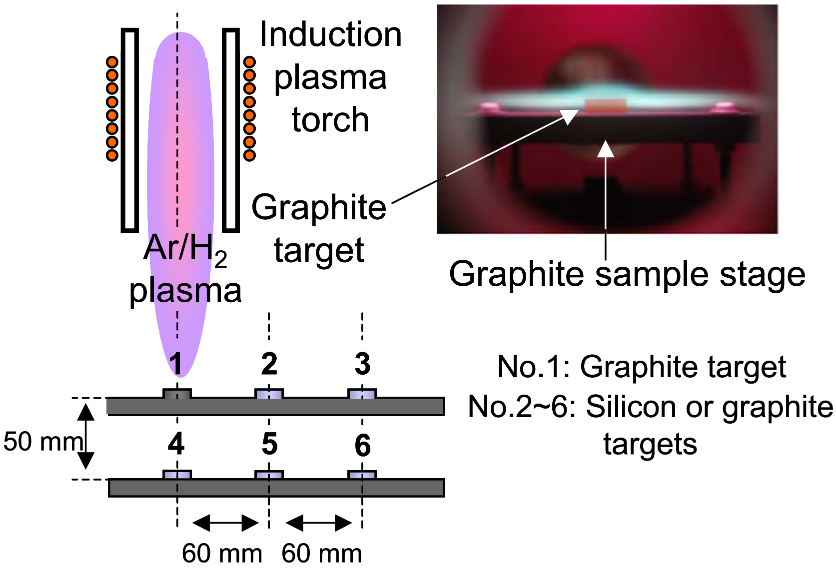

Fig. 1 Schematic diagram of a high power ICP irradiation system.

creases rapidly for targets further from the plasma. Figure 2 shows the radiation spectra observed 5 mm above the graphite target 1 during Ar and Ar/H_2 plasma irradiation. With the addition of hydrogen, the band spectra of CH and C_2 are observed strongly, which is a good indication of hydrogen chemical sputtering. A rough estimation of the chemical sputtering yield by low energy atomic hydrogen irradiation is 0.002-0.005, which is close to that obtained in the beam irradiation experiments [3]. 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 plasmas show that most of the hydrogen molecules introduced into the induction plasma are dissociated, to be atomic 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. Figures 3 (a)-(f) show SEM pictures of carbon dust particles observed on the graphite and silicon targets at different locations. Dust particles with characteristic shapes are found on graphite and silicon targets placed at both open and shadow areas, as shown in the figure. The observed particles range in size from a submicron to about 10 μm. The average size of the dust particles becomes small and their density decreases as the distance of the target position from the main irradiation point increases. The structure of the dust strongly depends on the target surface temperature T_s. When T_s is higher than 1100 K, the carbon dust exhibits a diamond structure, as shown in Fig. 3 (a), and it shows ball, agglomeration, granular, flake or fiber shapes when $T_s < 1100$ K.

From these experimental observations a rough description of the process of graphite target erosion to dust formation is summarized in Fig. 4. Graphite targets are significantly eroded by irradiation of an Ar/H_2 plasma with high atomic hydrogen flux to generate hydrocarbon particles C_yH_z by chemical sputtering. The released hydrocarbon particles are carried along the gas flow with the dissociation processes (thermal dissociation), and reach the target surfaces located in remote and shadow regions. In this experiment, high flux and low energy atomic hydrogen particles bring significant graphite erosion by chemical sputtering, and carbon dusts, which have various shapes and structure depending on the irradiation condition, are formed and scattered on the graphite target even in the erosion dominant condition. The experimental results indicate that the particle structure of diamond or graphite,

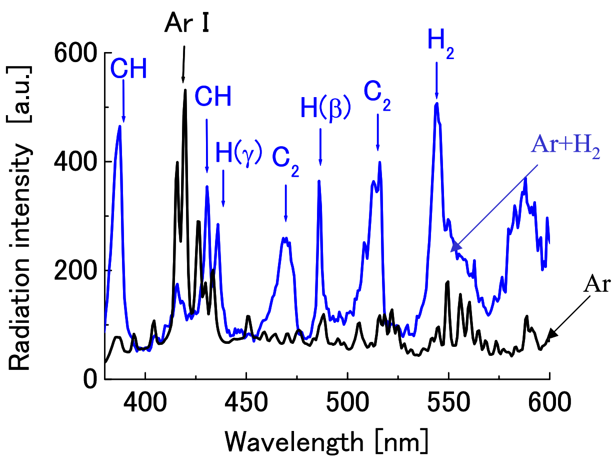

Fig. 2 Radiation spectra at 5 mm above graphite target 1 during Ar (black line) and Ar/H_2 (blue line) plasma irradiation.

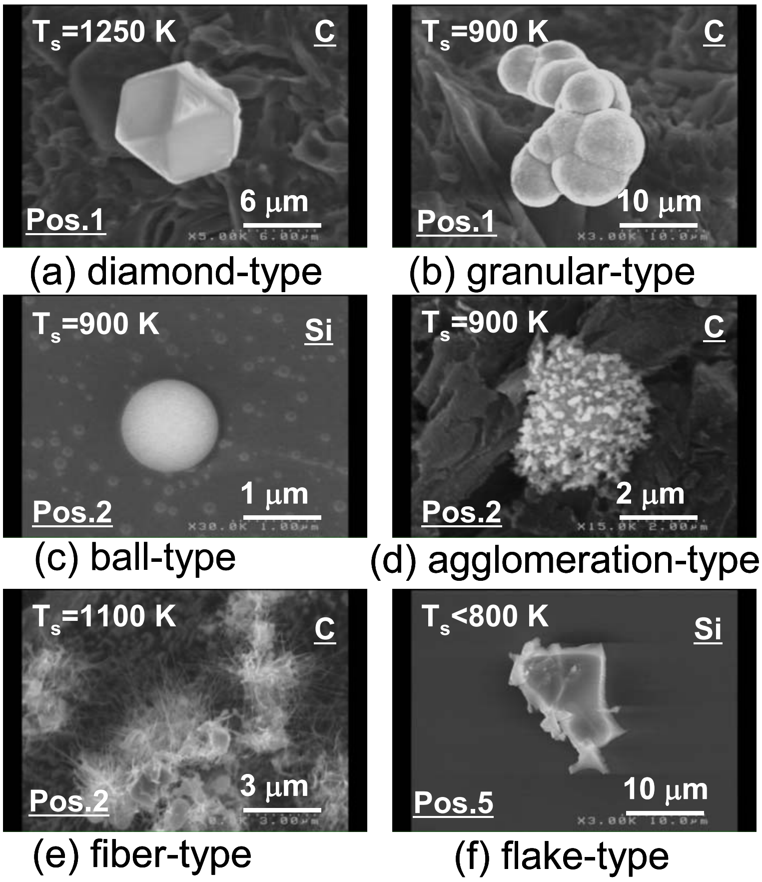

Fig. 3 SEM pictures of carbon dust on the graphite targets and silicon crystal targets.

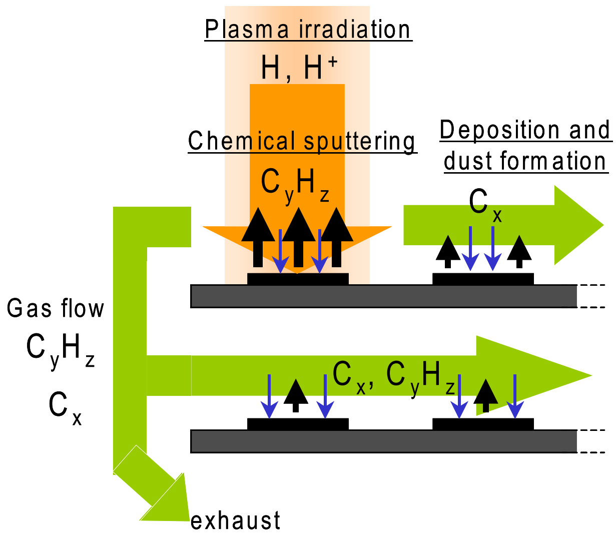

Fig. 4 Schematic illustration of erosion and dust formation.

depends strongly on the target surface temperature. Therefore, particle growth occurs on the target surface. Increasing the surface temperature of the graphite and silicon targets up to 1100 K turns the graphite granular particles into diamond crystals.

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