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Carbon dust formation from re-deposited layers in high-density hydrogen/helium plasmas in the NAGDIS-II device

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Abstract

Formation of carbon dust particles on a graphite surface irradiated by a high-density hydrogen plasma and a mixed hydrogen/helium plasma has been investigated in the NAGDIS-II linear divertor plasma simulator. Carbon dust particles are generated at the center region of the graphite surface facing the high-density plasma. No dust particles are formed in the peripheral region. These observations indicate that the re-deposition process of the hydrocarbon ions due to a strong plasma flow at the center of the plasma column is one of the key factors determining the dust growth as well as chemical sputtering.

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Keywords: Carbon deposition; Re-deposition; Divertor material; Dust particles; NAGDIS-II

1. Introduction

Various kinds of dust particles have been observed in many fusion devices [1–6]. Carbon dust formation in the plasma edge of fusion devices is a critical issue, mainly related to safety hazards, such as tritium inventory and steam-induced hydrogen explosions [3,4]. However, the mechanism of carbon dust formation and its transport in fusion devices are not fully understood. Basic experiments on the formation of carbon dust in plasmas relevant to plasma edge conditions of fusion devices can improve the understanding of the underlying physics.

Carbon dust particles are considered to be generated mainly from re-deposited carbon layers formed on cold remote material surfaces or plasma-facing surfaces. Hydrocarbon species, C_xH_y, which could be generated as a result of erosion of carbon materials, are thought to be transported to the remote region, causing carbon deposition on the cold surface. In the JET tokamak, thick re-deposited carbon layers were observed at the cold remote region near the pumping area [2]. Similar re-deposited carbon layers were also observed at the target plate located below the toroidal pump limiter in the Tore Supra tokamak [6]. Carbon dust particles or flakes could be generated by erosion of these re-deposited carbon layers.

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On the other hand, the formation of carbon dust particles on plasma-facing surfaces is not clear yet, and in this paper we will attempt to focus on this question. We describe experiments conducted in the NAGDIS-II divertor plasma simulator, where carbon dust particles were generated by exposing a graphite surface to a high-density hydrogen/helium plasma.

2. Experimental set-up

Experiments have been carried out in NAGDIS-II [7], which can generate high density mixed hydrogen/helium plasmas as well as pure hydrogen and/or helium plasmas in steady state. The plasma density of the discharge can be controlled by changing the dc discharge current. The magnetic field strength is 0.25 T. Fig. 1 shows the experimental set-up. Plasma parameters are measured with a single Langmuir probe. Typical electron density and temperature at the target in a pure hydrogen plasma are $2 \times 10^{18}\,\mathrm{m}^{-3}$ and 10 eV, respectively. The diameter of the plasma column is about 20 mm. High-grade isotropic graphite samples (IG430U, Toyo Tanso Co. Ltd.) of hexagonal shape with a side length of 28 mm are mounted on the water-cooled copper target located at the end of the vacuum chamber. The target is electrically floating. Surface temperature on the graphite target is measured with an optical pyrometer through a quartz window. Characterization of carbon dust, as re-deposited layers on the graphite surface, was performed by means of a Scanning Electron Microscope (SEM) and an Energy-Dispersive X-ray Fluorescence Spectrometer (EDX).

3. Experimental results and discussion

Fig. 2 shows SEM photographs taken at the central region of the graphite surface irradiated by a pure hydrogen plasma with an electron density of $2.4 \times 10^{18}\,\mathrm{m}^{-3}$ and an electron temperature of 11 eV. The hydrogen ion flux density and fluence are $4.5 \times 10^{22}\,\mathrm{m}^{-2}\mathrm{s}^{-1}$ and $5.9 \times 10^{26}\,\mathrm{m}^{-2}$, respectively. The surface temperature of the sample during plasma irradiation is about 1000 K. It is found that many carbon dust particles are formed on the graphite surface with widely varying shapes and sizes, as shown in Fig. 2(a). The largest size observed was 20 μm. Fig. 2(b), which is a magnification of Fig. 2(a), shows that the large carbon clusters consist of an agglomeration of sub-micron sized small spherical dust particles. The EDX analysis shows that these particles are purely carbon. We do not know the hydrogen composition because the EDX cannot analyze elements lighter than Be. The large carbon particles are easily peeled off from the graphite surface due to some vibration and/or thermal stress.

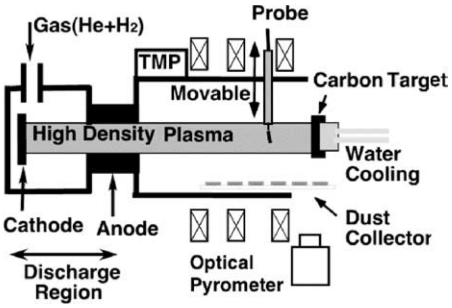

Fig. 1. Schematic arrangement of the experimental set-up.

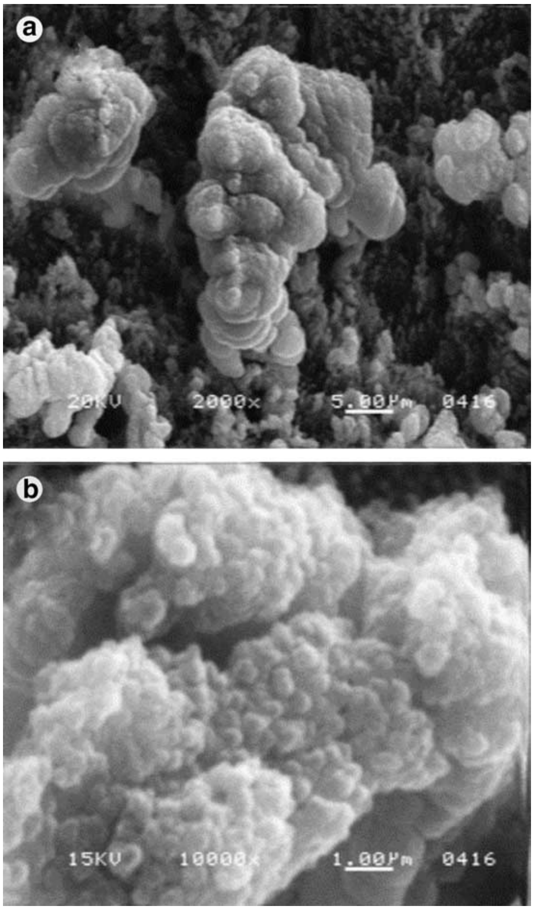

Fig. 2. SEM photograph showing the carbon dust formation on the graphite target irradiated by a pure hydrogen plasma with an electron density of $2.4 \times 10^{18}\,\mathrm{m}^{-3}$ and an electron temperature of 11 eV. The ion flux density and fluence to the graphite target are $4.5 \times 10^{22}\,\mathrm{m}^{-2}\mathrm{s}^{-1}$ and $5.9 \times 10^{26}\,\mathrm{m}^{-2}$, respectively. (b) is a magnification of (a).

The same graphite targets have been exposed to pure helium and/or mixed helium/hydrogen plasmas. In a pure helium plasma, no carbon dust is generated even if the ion flux and fluence to the target are one order magnitude larger than those in Fig. 2. On the other hand, in a helium plasma with a small amount of hydrogen gas injection, where the primary gas (helium) flow rate to the dc discharge region is 0.51 Pa m^3/s and the injection rate of hydrogen gas is 0.051 Pa m^3/s, carbon dust particles can be formed. These experimental results indicate that chemical sputtering and reactions associated with hydrogen are the key to generating the carbon dust particles on the plasma-facing graphite surface.

Fig. 3 shows SEM photographs of the graphite surface exposed to a pure hydrogen plasma, taken at different radial position r away from the center of the plasma column as indicated in the inset in Fig. 3(c). The radius of the plasma column is about 10 mm as noted above. At the central position ($r = 0$ mm) large carbon dust particles of sub-micron size are observed. The size of these particles is found to decrease with increasing radial distance r from the center as shown in Fig. 3(b) and (c). Outside of $r = 12$ mm, the surface morphology is dramatically changed. There are no carbon dust particles in this outer region and a typical surface erosion pattern is observed especially at $r = 15$ mm. These observations indicate that the deposition of carbon occurs mainly in the central region that is facing the high-density plasma. Erosion of the graphite, on the other hand, occurs at the peripheral region of low-plasma density, as shown in Fig. 3(f).

Fig. 4 shows the exposure time dependence of the surface modification on the graphite target irradiated by a low-density hydrogen plasma (3×10^{17} m^{-3}). The surface morphology in the central region ($r = 0$ mm) of the graphite surface is changed gradually with exposure time. However, no indication of carbon dust deposition on the graphite surface is observed. Hence, the growth of the carbon dust layers can be attributed to re-deposition of the hydrocarbon as a result of pronounced plasma flow to the graphite central surface in high-density plasmas.

Here, we briefly discuss the influence of plasma flow on the hydrocarbon transport by estimating the slowing-down time τ_s. We assume that CH_4^+ with a thermal velocity of 7.7×10^2 m/s, corresponding to the irradiated carbon surface temperature of 1000 K, is interacting with a hydrogen plasma of density 2.0×10^{18} m^{-3}, ion temperature 1 eV, and electron temperature 10 eV; the slowing-down time τ_s is calculated to be 5.6 µs. On the other hand, at the low density of 3.0×10^{17} m^{-3}, τ_s is calculated to be 37 µs. The time of flight of CH_4^+ passing across the high-density plasma region (~10 mm) is estimated to be 13 µs. This simple analysis shows that in a high-density plasma (2.0×10^{18} m^{-3}), the transport of CH_4^+ is strongly influenced by the flowing plasma because τ_s is smaller than the time of flight. Of course, we also need to consider the effect of cyclotron motion of the CH_4^+ because its gyro-radius is ~5 mm at a magnetic field strength of 0.1 T.

In order to analyze the ionization and dissociation processes of CH_4 emitted from the graphite surface, we solved simple rate equations for CH_n^+ and CH_n where $n = 1$–4. For example, the rate equation for CH_4 is described by

$$\frac{dn_{CH_4}}{dt} = -n_e n_{CH_4}\left(\langle\sigma v\rangle^{(1)} + \langle\sigma v\rangle^{(2)} + \langle\sigma v\rangle^{(3)} + \langle\sigma v\rangle^{(4)} + \langle\sigma v\rangle^{(5)}\right) - n_{H^+} n_{CH_4}\langle\sigma v\rangle^{(6)},$$

where n_{CH_4}, n_{H^+} and n_e are densities of CH_4, proton and electron, respectively. Rate coefficients $\langle\sigma v\rangle$ of ionization

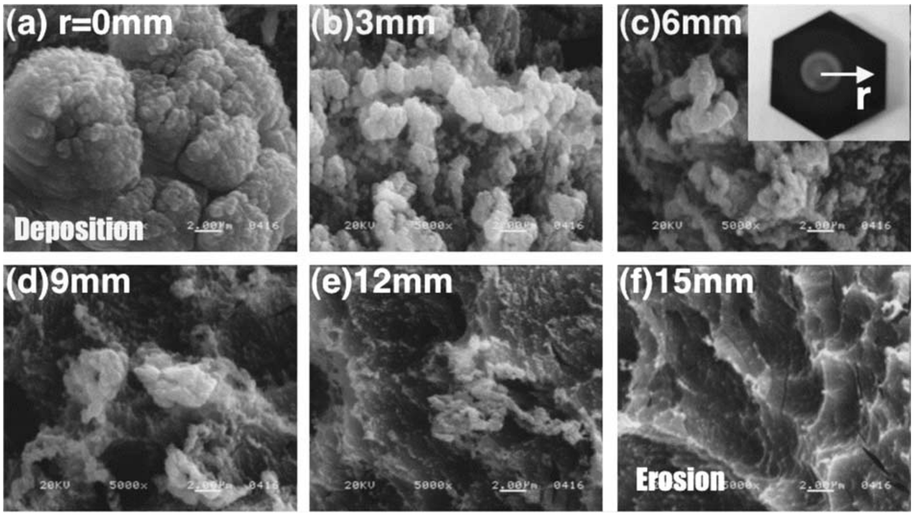

Fig. 3. Change of surface morphology of a graphite target irradiated by a pure hydrogen plasma as a function of the radial position r. Experimental conditions are the same as those in Fig. 2.

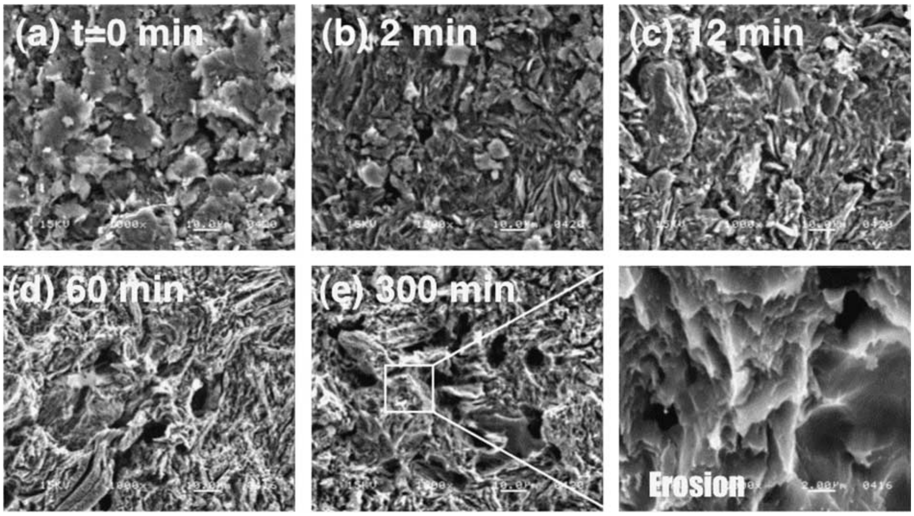

Fig. 4. Surface modification of a graphite surface in a low-density hydrogen plasma (3×10^{17} m^{-3}), with exposure time as parameter. No carbon dust particles are observed.

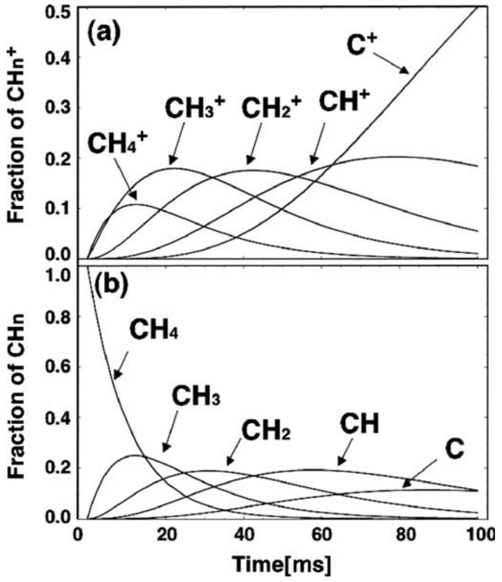

Fig. 5. Temporal formation of hydrocarbon species as calculated by the rate equations given in the text.

and dissociation processes in this equation are corresponding to the following reactions [8]:

$$CH_4 + e \rightarrow CH_4^+ + 2e \tag{1}$$

$$CH_4 + e \rightarrow CH_3^+ + H + 2e \tag{2}$$

$$CH_4 + e \rightarrow CH_2^+ + 2H + 2e \tag{3}$$

$$CH_4 + e \rightarrow CH^+ + 3H + 2e \tag{4}$$

$$CH_4 + e \rightarrow CH_3 + H + e \tag{5}$$

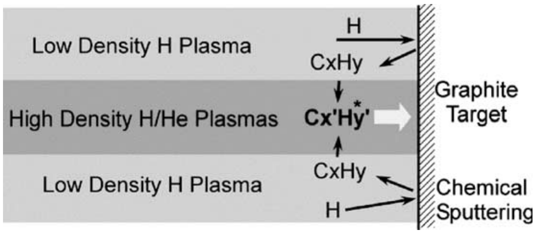

Fig. 6. Schematics illustrating the hydrocarbon transport in high-density, pure hydrogen or mixed hydrogen/helium plasmas. The ∗ signifies electronically excited hydrocarbon species, including hydrocarbon ions.

$$CH_4 + H^+ \rightarrow CH_4^+ + H \tag{6}$$

Data for the rate coefficients given in Ref. [8] are used in our analysis. Fig. 5 shows the time dependences of the fractions CH_n and CH_n^+ in a hydrogen plasma with an electron density of 2.0×10^{18} m^{-3} and an electron temperature of 10 eV. It is found that about 20% of the total number of CH_4 molecules can become hydrocarbon ions (CH_4^+, CH_3^+ and CH_2^+) within 10 μs, which means that CH_4 can be ionized during the passage through the plasma column. The above discussion is schematically summarized in Fig. 6. Hydrocarbon species emitted from the peripheral region or central region are easily ionized in the high-density plasma region, and transported to the graphite target by the streaming plasma.

4. Conclusion

Carbon dust formation on plasma-facing components has been investigated in the NAGDIS-II linear divertor plasma simulator. Carbon dust layers are formed at the center region of the graphite target surface, which is a high-density region with substantial plasma flow. Larger carbon dust particle are formed by aggregation of smaller ones. No indication of dust formation is observed in low-density hydrogen plasmas, or in pure helium plasmas. Moreover, carbon dust particles can be easily peeled off from the surface. In brief, we conclude that the redeposition process of hydrocarbon ions due to pronounced plasma flow at the center of the plasma column in high-density plasmas is one of the key factors determining the dust growth as well as chemical sputtering.

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