Characteristics of the modification of the near-surface layer and sputtering of graphite under high intensity ion irradiation

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Abstract. In this paper, features of the modification of near-surface layer of R6510P100D01 grade graphite under irradiation by deuterium and helium ions at a temperature of 2050 °C is investigated. It is shown that irradiation by such ions at a flux density of \(1.4 \times 10^{18}\) ion/cm\(^2\)s initiates vacancy transport from the irradiated surface to the bulk of the sample, leading to the formation of a porous layer inside the sample with a thickness of over 2 mm. High sputtering yields, exceeding those for irradiation by the same ions at room temperature with a moderate intensity ion fluxes, lead to the conclusion that in these conditions, sublimation is the main mechanism of the removal of carbon atoms from the surface of graphite.

1. Introduction

Graphite is used as a material for plasma-facing components in a number of fusion and plasma technology facilities [1] undergoing high intensity and high temperature plasma irradiation. At the same time, the features of modification and sputtering of graphite under these conditions are not sufficiently studied.

In our previous works, dependence of the erosion of graphite under high intensity and high temperature irradiation by hydrogen and deuterium ions on the irradiation dose [2], irradiation temperature [3] and flux density of irradiating ions [4] were studied. It was deduced that irradiation within the temperature range of 750–2050 °C by hydrogen and deuterium ion fluxes with power densities of up to 40 MW/m\(^2\) and ion flux density of about \(1.4 \times 10^{18}\) ion/cm\(^2\)s initiates vacancy diffusion from the irradiated surface into the bulk of the sample, which leads to the formation of a porous layer with the thickness that exceeds the penetration depth of ions in the material by few orders of magnitude.

In this work, the results of further research on the formation of near-surface porous layers in graphite under high intensity high temperature ion irradiation by helium and deuterium ions. The experiments were conducted on the “CODMATT” (COating Deposition and MATerial Testing) stand [5]. The experimental parameters were as follows: residual gas pressure \(<2 \times 10^{-6}\) torr; energy of irradiating ions 14 keV/ion; ion flux \(1.4 \times 10^{18}\) ion/cm\(^2\)s. Surface temperature of the irradiated samples was 2050 °C. R6510P100D01 grade graphite was used to make samples with the area of the irradiated surface \(10 \times 10\) mm\(^2\) and thickness in the range of 0.5 to 4 mm. A method of sample preparation is described in work [2].
2. Sputtering of the sample by helium and deuterium ions

Figure 1 shows that the thickness of the sputtered layer relative to the unirradiated surface \( L_{\text{surf}} \) in the range of all irradiation doses both for deuterium and helium ions is less than the thickness of the irradiated layer calculated by measuring the mass loss of the sample \( L_{\text{mass}} \).

![Figure 1. Dependence of \( L_{\text{mass}} \) and \( L_{\text{surf}} \) on the dose of irradiation by \( \text{D}_2^+ \) and \( \text{He}^+ \) ions.](image)

As was noted in work [2], this fact is explained by thermally activated vacancy diffusion from the ion stopping range into the bulk of the sample resulting in the formation of a porous structure in the near-surface layer of graphite. Thickness of a porous layer is, undoubtedly, larger than a difference between \( L_{\text{mass}} \) and \( L_{\text{surf}} \). Nevertheless, this variable is going to be used when analysing the features of porous layer formation, assuming some correlation between it and a thickness of a porous layer.

The value of \( L_{\text{surf}} \) increases slower than the value of \( L_{\text{mass}} \) at first stages of irradiation (figure 1), pointing at the fact that the porous layer atoms that are transported towards the surface of the sample when vacancies diffuse to the bulk of the sample reduce the rate of surface erosion. At a certain irradiation dose (thickness of a porous layer), the difference between \( L_{\text{surf}} \) and \( L_{\text{mass}} \) is stabilized, showing that the rate of growth of the porous layer and rate of surface sputtering are equalized, as in the removal of carbon atoms from the surface occurs at the same rate as the diffusion of carbon atoms from the bulk to the surface.

The rate of removal of carbon atoms from the surface of fine-grade graphite during its irradiation by hydrogen and deuterium ion fluxes with the power density of approximately 20 MW/m\(^2\) and at a temperature of 2050 °C exceed the rate of removal of carbon atoms during irradiation of graphite by the same types of atoms at the same energy, at a lower intensity of the ion flux and room temperature by two orders of magnitude. The reason behind this is possibly the decrease in the bond energy of carbon atoms with the surface due to the development of porous layer by ion irradiation. Almost identical sputtering coefficients of carbon under irradiation by \( \text{He}^- \) and \( \text{D}_2^+ \) ions (1.13 and 0.96 at./ion, respectively) allow for considering sublimation activated by ion irradiation to be the primary mechanism of their removal from the surface of graphite at 2050 °C.

3. Sputtering of samples with varying thickness

Experiments with the samples of the varying thickness allowed for gaining a degree of information on the processes in the porous layer, as well as its penetration depth in the bulk of graphite. Alterations in the structure and profile of the opposite side of the irradiated samples of 1.5 mm thick at the irradiation dose of \( 2.66 \times 10^{20} \) ion/cm\(^2\) was visible with the naked eye, leading to the conclusion that the thickness of a porous layers is at least as much as the thickness of a sample. On the opposite side of
the 0.8 mm sample after irradiation, multiple pores of up to 100 μm in diameter were observed, as well as a 300 μm wide hole in the center.

![Graph showing sputtering coefficients of graphite samples with varying thicknesses.]

**Figure 2.** Sputtering coefficients of graphite samples with varying thicknesses.

At the irradiation dose of $1.33 \times 10^{20}$ ion/cm$^2$, new formations could be observed with a naked eye on the opposite side of a 1 mm thick sample, and a 100 μm wide hole was formed through the 0.7 mm sample. Despite the decrease in the irradiated surface area caused by the growth of the hole through the samples with thicknesses varying from 0.7 to 0.5 mm, sputtering coefficient for them increased with the decrease in thickness. This was due to the decrease of carbon atom diffusion to the surface that hindered the destruction of the surface structure. As such, the rate of amorphisation of the sputtered surface layers increased, and the bond energy between the surface carbon atoms decreased.

4. **Conclusion**

It is shown that the thickness of a near-surface porous layer formed under high intensity high temperature sputtering of graphite increases in the first period of irradiation and then stabilizes, indicating an equilibrium between the rate of removal of surface carbon atoms and the rate of diffusion of carbon atoms from the surface towards the bulk. Thickness of a porous layer reaches 1.5 mm during irradiation at a temperature of 2050 °C by ions with an irradiation dose of $2.66 \times 10^{20}$ ion/cm$^2$.

It is shown that sublimation of carbon atoms activated by ion irradiation is the main mechanism of their removal from the surface of graphite under irradiation by He$^+$ and D$_2^+$ ions at a temperature of 2050 °C, with their respective sputtering coefficients being 1.13 and 0.96 at./ion.

As the thickness of the samples decreases, the rate of diffusion of carbon atoms to the surface from the bulk that inhibits the destruction of the surface structure decreases as well, the amorphisation of the sputtered surface layers increases, the bond energy of carbon atoms on the surface decreases, and the sputtering coefficient increases.

**References**

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