EXPOSURE OF TUNGSTEN SURFACE TO HIGH-FLUX OF HELIUM AND ARGON IONS

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Present work investigates the erosion yields of tungsten exposed to intense beams of He and Ar ions using weight-loss measurements. The ion beams were generated by FALCON ion source, typical particle fluxes were in the range of $(0.4…1.0)\times10^{22}$ $m^{-2}\cdot s^{-1}$ and the heat fluxes were 0.3…0.8 $MW\cdot m^{-2}$. Investigations show that the erosion yield for He ions is in line with simulations and experimental literature data on physical sputtering, while for Ar bombardment one has observed lower erosion yields. The morphology of the surface has also been studied with SEM.

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INTRODUCTION

The long-term solution of the energy problem is tightly connected to International Thermonuclear Experimental Reactor (ITER) which is currently under construction at its site in Cadarache, France. ITER operation and discharge regimes are under investigation still. Stability of the plasma-facing materials exposed to high particle fluxes and fluence is one of the problems which need to be addressed by ITER. It has been agreed that tungsten surface will be used at least in the divertor region [1] where particle and heat loads are rather intense. Preliminary estimations show that these components will be exposed to particle fluxes in the range of $10^{20}…10^{23}$ $m^{-2}\cdot s^{-1}$, while heat fluxes will be up to 3 $MW\cdot m^{-2}$ [2]. The total number of discharges should be about 10^4 with the average duration of the each pulse up to 400 s according to currently existing specifications of ITER. This results in total particle fluence of $10^{27}…10^{30}$ $m^{-2}\cdot s^{-1}$.

The given fluence range for the divertor component could be used to evaluate its lifetime based on physical sputtering. Unfortunately, this range has not been investigated with laboratory devices, which may provide suitable accuracy for measurement of the erosion yields. The ion beam setups like HiFIT could provide particle fluxes up to 3.6×10^{21} $m^{-2}\cdot s^{-1}$ at the energy of kilo electron volt range [3]. Various plasma devices can provide much lower energies for the particle fluxes of $\approx10^{22}$ $m^{-2}\cdot s^{-11}$ and above [4-6]. As an intermediate solution, FALCON ion source has been developed to provide the fluxes typical for plasma devices, however, at kilo electron volt range [7, 8]. It is based on design of closed drift thrusters (also known as Hall thrusters), which are typically used as space propulsions [9]. In contrast to plasma devices, its simplicity and compactness allow it to be installed virtually on any vacuum system and provide the setup for the fusion oriented plasma-material research.

Present work continues our previous studies with the bombardment of tungsten surface with hydrogen ions in the high-flux range [10]. It is supposed that this range can contain new effects, which influence the material erosion and, therefore, the long-term lifetime of the plasma facing components. In this work the investigation is further extended to helium and argon ion fluxes, and the erosion of the surface is studied by both weight-loss method and ex-situ post bombardment scanning electron microscopy. The obtained results are further compared to experimental data from literature as well as to the results of the computer simulations based on binary-collision approximations. This allows identifying the deviations from pure physical sputtering, which can be the indication of new mechanisms influencing the surface erosion.

1. METHODS

The tungsten samples were exposed to the ion beam generated by FALCON ion source. The discharge gap was filled with He or Ar working gas. The acceleration voltage was 5.4 keV and the average energy of the ion beam was 2.2 keV. The ion flux for He was in the range of $(0.4…0.5)\times10^{22}$ $m^{-2}\cdot s^{-1}$ and the heat flux was 0.3…0.4 $MW\cdot m^{-2}$. This led to the increase of the sample temperature up to 770°K. The particle flux for Ar ion beam was 10^{22} $m^{-2}s^{-1}$ and the heat flux was about 0.8 $MW\cdot m^{-2}$. Therefore, the sample exposed to Ar ion beam heats up to a temperature of 970 K. Both ion beams had irradiated the samples up to the fluence above 10^{26} $m^{-2}\cdot s^{-1}$.

The samples were made of polycrystalline tungsten manufactured by Plansee with a purity of 99.999 % wt. This material was proposed for ITER. The dimensions of the samples were 12×15×0.8 mm. The grain sizes were estimated to be in the range of 5…20 μm. All specimens were mechanically polished to the mirror-like surface. The temperature of the sample was evaluated basing on Stephan-Boltzmann law and preliminary measurements with thermocouple, see details in [10].

The erosion yield has been measured by using ex-situ weight-loss measurements before and after the exposure. The absolute accuracy of the weight measurements was ±5 μg, while typical weigh-change of the sample before and after the exposure was well above 1 mg. The charge collection measurements are assumed being a good representative of total number of incident particles. Details of ion beam characterization could be found in [8]. Therefore, weight-loss measurements of erosion introduce negligible errors under given conditions.

After the exposure, the surface of the samples has been examined with scanning electron microscopy (SEM).

2. RESULTS AND DISCUSSION

Results of erosion yield measurement are shown in Fig. 1. Bombardment of W samples with He ion beam has been performed in a few steps to evaluate the fluence dependent erosion yield. The data are compared to TRIDYN simulations [11] and experimental data taken from [12].

Fig. 1,a shows the fluence dependent erosion yield of W sample exposed to He ion beam. Experimentally measured erosion yield is stable in the fluence range up to 10^{26} m^{-2}, and it is in a good agreement with the results of simulation. Fig. 1,b shows the experimentally measured data against the energy dependent sputtering yield as obtained by simulations and experimental data [12]. One can see that the measured erosion yields are in a good agreement with data for physical sputtering and could be well explained by this phenomenon.

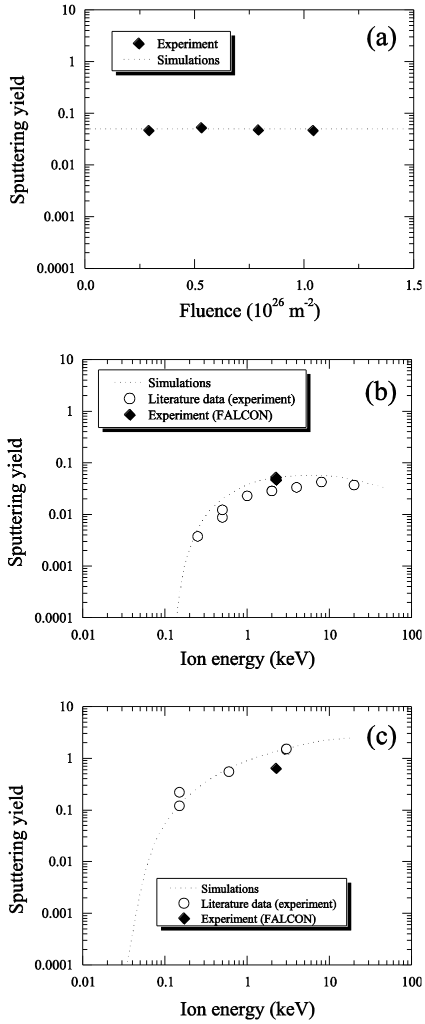

Fig. 1. Sputtering yields: (a) as a function of fluence for W sample exposed to He ions; (b) comparison of data for He ions bombarding W; (c) comparison of data for Ar ions bombarding W

At the same time erosion of W sample with Ar ion beam shows the yield which is somewhat lower than results of simulations and literature data [12]. Generally, erosion of W with heavy noble gases is well reproduced by the simulations with programs based on binary-collision approximation. Therefore, the observed difference could not be explained by the experimental errors and the possible low amount of light impurities, which potentially decrease the measured erosion yield. Most probable explanation of the observed lower sputter yield is the high particle and heat fluxes. At the same time, the temperature of the surface has possibly not contributed to observed decrease, because similar surface temperature has been reached during exposure with He and with H ion beams [10].

Fig. 2 shows the morphology of the surface after the exposure as obtained by SEM. The morphology of the sample exposed to He ions is shown in Fig. 2,a. This surface is typical for sputter erosion mechanism. Similar morphology has been observed in [10], where W surface has been exposed to high-flux H ion beam. Surface shows no blisters or other features which can be found on the surface exposed to He ion flux.

On the other hand, recently carried out experiments on bombardment of the W surface with high heat and particle fluxes of H-He mixture [13] have shown that the measured erosion yield exceeds the yield for physical sputtering only by factor of two. This might be explained by origination of the features on the surface and consequent increase of the local angle of incidence.

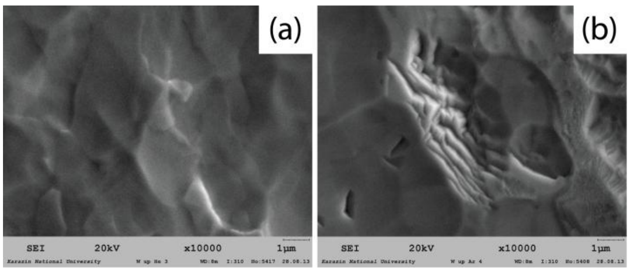

Fig. 2. The SEM images of W surface exposed to: (a) He ion beam; (b) Ar ion beam

The morphology of W surface exposed to Ar ion beam is shown see in Fig. 2,b. One can observe small pores and cracks with typical dimension of ≈1 µm. Similar defects had not been observed in case of irradiation of W surface either with H ions [10] or with He ions. Therefore, factors like surface temperature or high flux have not resulted in production of such features. Origination of the features might be explained by factors like mass of the incident ions and/or amount of the sputtered atoms from the surface.

CONCLUSIONS

The tungsten samples were irradiated with keV ion beams featuring He or Ar species. The beam has been generated by FALCON ion source with typical particle fluxes of (0.4…1.0)×10^{22} m^{-2}s^{-1} and the heat fluxes of 0.3…0.8 MW·m^{-2}. The heat fluxes elevate the temperature of the samples up to 770…970 K. The long exposure with intense particle flux allowed reaching fluence above 10^{26} m^{-2}.

The weight-loss measurements have shown nearly constant erosion yield for He ion beam as fluence increases. The measured erosion yields have been compared to experimental data taken from literature and to the results of the simulation. Erosion yield of tungsten with He ion beam is in a good agreement with data for physical sputtering. At the same time erosion yields produced by Ar ion beam are below yields for physical sputtering by factor of two. The morphology of the surface exposed to He ion beam has been found to be typical for erosion produced by physical sputtering. In contrast, bombardment of the W surface with Ar ion beam produces pores and cracks with typical dimension of 1 μm.

Therefore, high-flux and high-fluence exposure of the tungsten with Ar ions can involve the effects, which decrease the erosion while He ion flux does not demonstrate this kind of effects limiting its influence within the physical sputtering.

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ОБЛУЧЕНИЕ ПОВЕРХНОСТИ ВОЛЬФРАМА БОЛЬШИМ ПОТОКОМ ИОНОВ АРГОНА И ГЕЛИЯ

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Исследуются коэффициенты эрозии вольфрама, измеренные с помощью метода потери веса. Образцы облучались интенсивными пучками ионов He и Ar. Ионные пучки генерировались ионным источником FALCON, при этом плотность потока ионов составляла $(0,4…1,0)×10^{22}$ м$^{-2}$·с$^{-1}$, а тепловой поток на поверхность составлял 0,3…0,8 МВт·м$^{-2}$. Исследования показали, что эрозия вольфрама под воздействием ионов He соответствует результатам экспериментов и литературным данным по физическому распылению, в то время как при бомбардировке ионами Ar коэффициенты эрозии ниже ожидаемых приблизительно в два раза. Морфология поверхности была исследована с помощью РЭМ.

ОПРОМІНЕННЯ ПОВЕРХНІ ВОЛЬФРАМУ ВЕЛИКИМ ПОТОКОМ ІОНІВ АРГОНУ ТА ГЕЛІЮ

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Досліджено коефіцієнти ерозії вольфраму, виміряні за допомогою методу втрати маси. Зразки опромінювались інтенсивними пучками іонів He та Ar. Іонні пучки з густиною потоку іонів $(0,4…1,0)×10^{22}$ м$^{-2}$·с$^{-1}$ та тепловими потоками 0,3…0,8 МВт·м$^{-2}$ генерувались джерелом іонів FALCON. Дослідження показали, що ерозія вольфраму під дією іонів He узгоджується з результатами інших експериментів та літературними даними з фізичного розпилення. За умови бомбардування іонами Ar здобуті коефіцієнти ерозії виявились меншими за очікувані майже вдвічі. Морфологію опромінених поверхонь було досліджено за допомогою РЕМ.