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Peculiarity of deuterium ions interaction with tungsten surface in the condition imitating combination of normal operation with plasma disruption in ITER

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Abstract

Tungsten is a candidate material for the ITER divertor. For the simulation of ITER normal operation conditions in combination with plasma disruptions samples of various types of tungsten were exposed to both steady-state and high power pulsed deuterium plasmas. Tungsten samples were first exposed in a steady-state plasma with an ion current density $\sim 10^{21}$ m^{-2} s^{-1} up to a dose of 10^{25} m^{-2} at a temperature of 770 K. The energy of deuterium ions was 150 eV. The additional exposure of the samples to 10 pulses of deuterium plasma was performed in the electrodynamical plasma accelerator with an energy flux 0.45 MJ/m^2 per pulse. Samples of four types of tungsten (W–1%La_2O_3, W–13I, monocrystalline W(1 1 1) and W–10%Re) were investigated. The least destruction of the surface was observed for W(1 1 1). The concentration of retained deuterium in tungsten decreased from 2.5×10^{19} m^{-2} to 1.07×10^{19} m^{-2} (for W(1 1 1)) as a result of the additional pulsed plasma irradiation. Investigation of the tungsten erosion products after the high power pulsed plasma shots was also carried out. © 2001 Published by Elsevier Science B.V.

Keywords: Co-deposition; Deuterium; Disruption; Sputtering yield; Tungsten

1. Introduction

Tungsten is considered as a candidate armor material for the ITER-FEAT divertor components because of its high energy threshold for physical sputtering, low sputtering yield as well as its high melting temperature, low vapour pressure, good thermal conductivity and high temperature strength. Recent studies on hydrogen isotope retention in the different tungsten grades under plasma exposure [1–4] or under irradiation by monoenergetic D^+-ion beams [5–9] has been done. Since the CFC-composite will exist on the other highest power load components in the divertor, the production of codeposited carbon layers on tungsten is unavoidable. It has been shown [3,6] that the presence of carbon film on the W surface leads to an increase of the integral hydrogen concentration within the surface tungsten layer.

The studies of the effect of a combined steady-state deuterium plasma with parameters close to those expected in ITER-FEAT [2,9] and a high power pulsed plasma, simulating plasma disruptions, on the deuterium retention and erosion of various tungsten grades are presented in this given paper. In addition, a study of the effect of carbon codeposition during the plasma disruption process on the deuterium retention in tungsten, has also been done.

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2. Experimental technique

Several types of tungsten were used in the experiments: dispersion strengthened alloy W–1%La_2O_3, weakly alloyed tungsten (W–Mo–Y–Ti) designated as W–13I, produced in Russian Federation, W–10%Re and monocrystalline W((1 1 1) face). All these materials, except of W–10%Re alloy, are recommended for study as candidate materials for ITER-FEAT [10]. After electrolytic polishing eight samples were exposed simultaneously to a steady-state deuterium plasma in a facility [11] with a beam plasma discharge up to a fluence of 10^{25} m^{-2} at two temperatures 770 and 1370 K. The ion current density was 7.7×10^{21} m^{-2} s^2, deuterium ion energy was 150 eV, plasma density $n_e = 1.7 \times 10^{18}$ m^{-3}; electron temperature $T_e = 17$ eV. The samples were weighted with a microbalance before and after irradiaton. The additional irradiation of the samples in the electrodynamic plasma accelerator was performed at the deuterium plasma concentration 10^{21} m^{-3} and at the maximal ion energy of 1 keV. The energy flux density was 0.45 MJ/m^2 per pulse, the number of pulses did not exceed 10. The pulse duration was 60 μs.

For studying the plasma disruption effect on the deuterium accumulation all the samples after treatment by the pulsed plasma irradiation, were again exposed to the steady-state plasma under the above mentioned irradiation conditions.

To study the C + D codeposition effect on deuterium retention under plasma disruptions the W targets irradiation by the high power pulsed deuterium plasma fluxes were done. Carbon atoms were redeposited from receiver device chamber walls in the process of irradiation.

After each plasma treatment a study of target surface microstructure with the JEOL scanning microscope was done. Deuterium depth distribution profiles in the tungsten were determined by the method of elastic recoil detection analysis (ERDA). In these experiments, the analyzed He^+-ion beam with the energy 2.2 MeV was incident on the sample at an angle of 15° to its surface. The recoil atoms were analyzed with a semiconductor detector at an angle of 30° relative to He^+-ion incidence direction.

Monocrystalline silicon samples were used as the erosion product collectors. The collectors were located in a plasma flux shadow in parallel and in front of the target at small angle to the normal.

3. Experimental results

3.1. Sputtering and erosion of tungsten

In spite of the fact that the deuterium ion energy was equal 150 eV and the sputtering energy threshold was 165 eV [12], the weight of all the targets was reduced after the exposure in the stationary plasma. This fact can confirm the presence of an oxide film on the tungsten surface [12]. The measured sputtering yields are within the range $(5.7–8.9) \times 10^{-4}$ at./ion and agree with that for the tungsten oxide [12]. The sputtering by O^+ and C^+ ions is negligible because of small impurity concentration in plasma.

The surface microstructures of four various target types after exposure in a steady-state deuterium plasma at 770 K are slightly changed. As a result of the W–13I plasma exposure some differently oriented grain faces are manifested. On the surface of W–%La_2O_3 along the grain boundaries and within the grains after exposure in the stationary plasma the La_2O_3-precipitates and holes of etching are observed as a result of surface etching. On the surface of W–10%Re alloy a cell-like surface structure was manifested after stationary plasma irradiation. After the steady-state plasma treatment, any damage such as cracks and holes are absent on monocrystalline W(1 1 1) surface.

The subsequent treatment of W–13I, W–1%La_2O_3, W–10%Re alloys by the pulsed plasma flux results in the cracking of the target surfaces along the grain boundaries and in the emergence of holes (Fig. 1(a)). However, one should note that there is no visible damage on the monocrystalline W(1 1 1) surface (Fig. 1(b)).

As shown in Fig. 1, the tungsten droplets were detected on the sample surface, independent of the tungsten type. The presence of droplets on the tungsten surface, and in the cracks, confirm the melting of the tungsten surface in the process of the plasma disruption simulation.

3.2. Deuterium retention

The deuterium depth distributions in the W samples after exposure to the steady-state plasma are presented in Fig. 2. Deuterium concentration in the first 50 nm does not exceed 1 at.%. In the samples of W–1%La_2O_3, W–10%Re and W(1 1 1) a smooth deuterium concentration maximum at the depth 15–25 nm is observed. For the W–13I alloy a maximum was not detected. At a depth exceeding 50 nm the deuterium concentration in all the W types is uniform in depth, equal ~0.2 at.%.

A high deuterium diffusion coefficient (2×10^{-5} cm^2 s^{-1} [13]) for the time of the experiment results in an uniform deuterium distribution in depth down to $(D \cdot t_{exp})^{1/2} \approx 0.4$ cm and results in a low concentration for the whole depth. The observed concentration maxima are probably related to the presence of an oxide film on the W surface. Deuterium is mainly accumulated at the boundary between the film and tungsten. On slightly-damaged surfaces of monocrystalline W and W–10%Re the oxide film is more stable and the maximal deuterium concentration is greater than that on W–13I

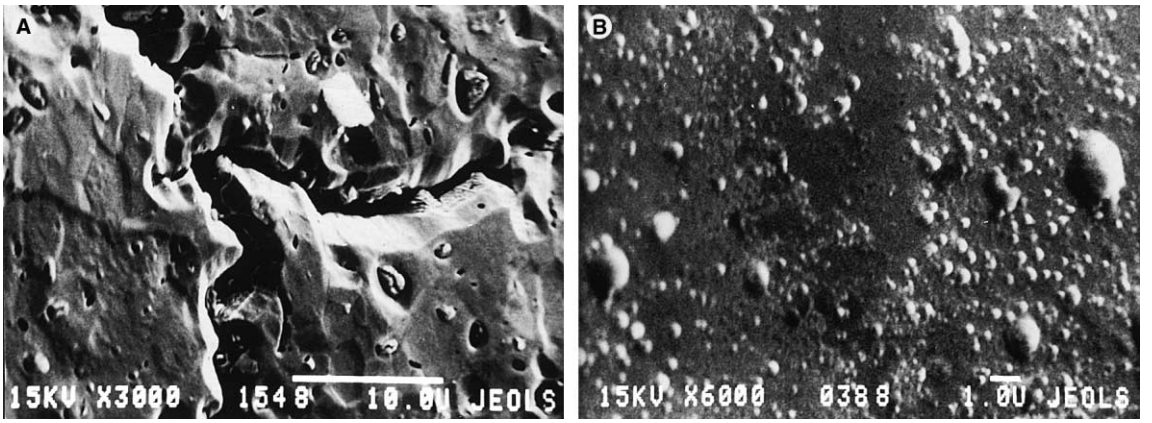

Fig. 1. SEM photographs of the surfaces for the several tungsten types after exposure in stationary deuterium plasma ($E = 150$ eV, $j = 7.3 \times 10^{20}$ m^{-2} s^{-1}, D = 10^{25} m^{-2} , 770 K) and additional irradiation by pulsed (10 pulses, 60 μs, 0.45 MJ/m^2 per pulse) deuterium plasma: (a) W–1%La_2O_3, (b) W(1 1 1).

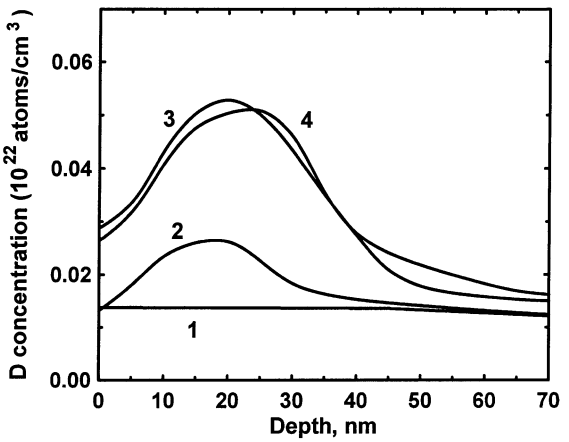

Fig. 2. Deuterium depth distributions in the samples of W–13I (curve 1), W–1%La_2O_3 (curve 2), W–10%Re (curve 3), W(1 1 1) (curve 4) after exposure in stationary deuterium plasma at the temperature 770 K up to fluence D = 10^{25} m^{-2}.

and W–1%La_2O_3 surfaces. As seen in Fig. 2, in the tungsten (W–13I) alloyed with yttrium there is no maximum in the depth deuterium distribution that can confirm the oxide film absence on the tungsten surface after an exposure to the steady-state plasma. It has been sputtered in the irradiation process by deuterium ions. A reduction of the deuterium content in the surface layer of W–1%La_2O_3 is evidently provided by the presence of the lanthanum oxide precipitates as well as by the deuterium re-emission process through the etching holes.

The integral deuterium concentrations in the surface layers, 70 nm, of the tungsten samples at the temperature of 770 K are given in Table 1.

After exposure of the samples in the stationary plasma at the temperature 1370 K deuterium has not been detected in any of the tungsten samples, this agrees with the published data [1–7].

The surface layer removal after pulsed plasma irradiation does not significantly change the integral deuterium concentration within the samples of W–13I and W–1%La_2O_3 in which the depth deuterium distribution is uniform (see Table 1). In the samples W(1 1 1) and W–10%Re at a reduction in the integral deuterium concentration is provided by evaporation of surface layers, containing the deuterium distribution maxima.

The deuterium depth distributions in the C + D co-deposited films formed after an effect of 10 plasma pulses

Table 1
Integral deuterium concentrations in W surface layers after steady-state and pulsed plasma irradiation

No.	Material	Integral concentration of deuterium (m^{-2})				
		Steady-state plasma	Steady-state + pulsed plasmas	Steady-state + pulsed + steady-state plasmas	Pulsed plasma at (C + W) codeposition	
					D	H
1.	W–13I	1.20×10^{19}	1.44×10^{19}	0.90×10^{19}	1.84×10^{20}	2.80×10^{21}
2.	W–1%La_2O_3	1.30×10^{19}	1.39×10^{19}	1.10×10^{19}	2.06×10^{20}	2.91×10^{21}
3.	W–10%Re	2.20×10^{19}	0.84×10^{19}	1.80×10^{19}	1.90×10^{20}	1.51×10^{21}
4.	W(1 1 1)	2.50×10^{19}	1.07×10^{19}	2.60×10^{19}	2.57×10^{20}	3.62×10^{21}

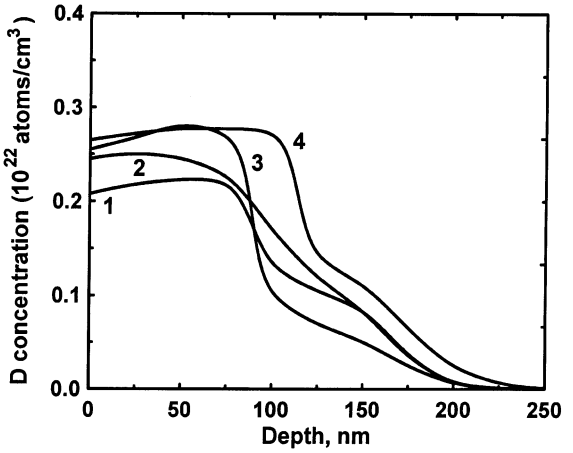

Fig. 3. Deuterium depth distributions in (C + D) codeposited layers on W–13I (curve 1), W–1%La_2O_3 (curve 2), W–Re (curve 3), W(1 1 1) (curve 4) after irradiation by pulsed (10 pulses, 60 μs, 0.45 MJ/m^2 per pulse) deuterium plasma.

are given in Fig. 3. The integral deuterium concentrations under such irradiation conditions of codeposited layers on tungsten are also given in Table 1. The deuterium concentration in the codeposited layer, 50 nm thick, exceeds the corresponding values for tungsten without carbon film by more than an order of magnitude after exposure to both steady-state and pulsed plasma irradiation. Such an effect is provided by accumulation of deuterium in the carbon surface layer and does not depend on the type of the tungsten substrate. The fact that the carbon film accumulates a great amount of hydrogen is of interest. The integral hydrogen concentration in carbon films exceeds the concentration of deuterium in them by about an order of magnitude (see, Table 1). Such an effect is probably provided by a great concentration of hydrogen in the vacuum chamber walls.

3.3. Erosion products

The size of the droplets captured with the collectors depends on the collector position respective to the irradiated target. The Fig. 4 illustrates the size distribution of droplets for the collectors located in parallel and in front of the target at a small angle to the normal. Small droplets either return to the target of fly-off in parallel to the surface (Fig. 4(a)) and their maximum of the size distribution is within the range 0.1–0.2 μm. Large droplets fly-off closer to a normal to the surface (Fig. 4(b)) and have maximum of size distribution is in the range 2.5–5 μm.

4. Conclusion

1. At a steady-state deuterium plasma (with ion energy 150 eV) exposure the sputtering yields of W–13I, W–1%La_2O_3, W–10%Re and W(1 1 1) are within the range $(5.7–8.9) \times 10^{-4}$ atom/ion and agree with the corresponding values of the tungsten oxide.
2. A monocrystalline W(1 1 1) is the most stable to a complex effect of steady and pulsed plasmas.
3. At the irradiation temperature 1370 K deuterium has not been detected in the tungsten surface layer.
4. After an exposure in the stationary plasma at the temperature of 770 K the integral deuterium concentration in the tungsten first 70 nm layer does not exceed 2.5×10^{19} m^2. At a depth exceeding 50 nm deuterium is distributed uniformly in depth and its concentration is about 0.2 at.%.
5. As a result of the subsequent W irradiation by the pulsed plasma, the integral deuterium concentration decreases for monocrystalline W(1 1 1) and W–10%Re samples.
6. The integral deuterium concentration in the (C + D) codeposition film formed during pulsed plasma irradiation increases by more than an order of magnitude in comparison with the deuterium accumulation in tungsten samples without codeposited layer.
7. Small droplets either return back to the surface or fly to a collector parallel to the target, whereas large droplets fly to the collector in front of the target.

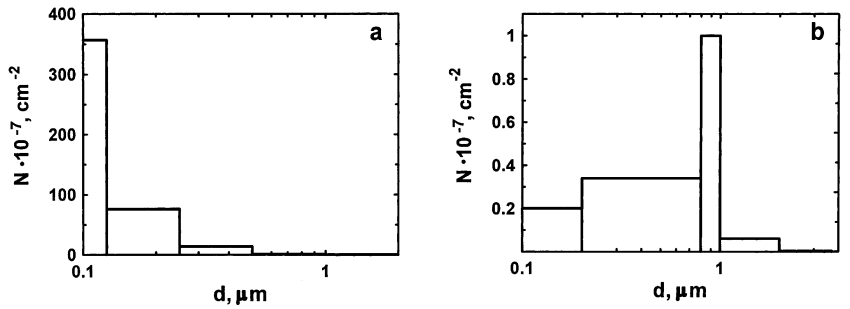

Fig. 4. Diameter distributions of tungsten droplets for the collectors located in parallel (a) and in front of the target at a small angle to the normal of surface (b).

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