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ScienceDirect

Journal of Nuclear Materials 363–365 (2007) 66–71

journal of nuclear materials

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Surface studies of tungsten erosion and deposition in JT-60U

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Abstract

In order to study tungsten erosion and migration in JT-60U, 13 W tiles have been installed in the outer divertor region and tungsten deposition on graphite tiles was measured. Dense local tungsten deposition was observed on a CFC tile toroidally adjacent to the W tiles, which resulted from prompt ionization and short range migration of tungsten along field lines. Tungsten deposition with relatively high surface density was found on an inner divertor tile around standard inner strike positions and on an outer wing tile of a dome. On the outer wing tile, tungsten deposition was relatively high compared with carbon deposition. In addition, roughly uniform tungsten depth distribution near the upper edge of the inner divertor tile was observed. This could be due to lift-up of strike point positions in selected 25 shots and tungsten flow in the SOL plasma.

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PACS: 52.55; 52.40.H; 52.25.V

Keywords: Divertor material; Impurity transport; Ion–surface interactions; JT-60U; Tungsten

1. Introduction

Tungsten is a leading candidate for plasma facing materials of divertors and armor materials of blanket first walls due to a low physical sputtering yield, a high melting temperature, and a high thermal conductivity. On the other hand, accumulation of tungsten ions in core plasmas leading to enhancement of radiation loss is a major concern. Therefore, control of tungsten erosion and transport is one of the important issues to prove compatibility of tungsten walls with high performance plasma operation.

In order to study these subjects, erosion and transport of high Z materials have been studied in several tokamak devices such as ASDEX-U [1], Alcator CMod [2], and TEXTOR [3]. Although quite a few important results have been found in these experiments, plasma confinement and stored energy of these devices are quite different from those of ITER. Therefore, it is not reliable to use these results for the evaluation of tungsten divertor

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0022-3115/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.jnucmat.2006.12.060

performance in ITER and more research works in larger confinement devices are necessary.

In JT-60U, DT equivalent fusion gain Q of 1.25 and stored energy of 10.9 MJ were already achieved [4,5]. There have been no high Z wall experiments under these high performance plasma conditions. Therefore, it is very valuable to make high Z divertor experiments in JT-60U to understand high Z materials behavior in tokamak plasmas which can be extrapolated to ITER and DEMO conditions.

For this purpose, in JT-60U tungsten coated CFC graphite tiles were installed in outer divertor region to study tungsten erosion and transport during the experimental campaign 2003–2004. During this campaign, maximum stored energy is about 7 MJ. After the campaign, many graphite tiles (mostly in the same toroidal section as the tungsten tiles) were removed to measure tungsten redeposition profile in the divertor region.

In this paper, we present a poloidal distribution of tungsten surface density in the divertor region (an inner divertor and an dome) in JT-60U for the first time. These results are compared with those of carbon atom deposition from graphite tiles and $^{13}CH_4$ puffed from the outer divertor position.

2. Experimental

In this experiments, tungsten coated tiles (50 μm vacuum plasma spray (VPS) coating with W/Re multilayer on CFC tiles) were installed in the outer divertor region. Twelve tungsten tiles were installed in the P-8 section (one other tiles in P-17 section, total number of sections are 18). This tile array covered about 1/18 toroidal length. A photograph of the tungsten tile array in P-8 section and typical magnetic surface diagram for standard discharges

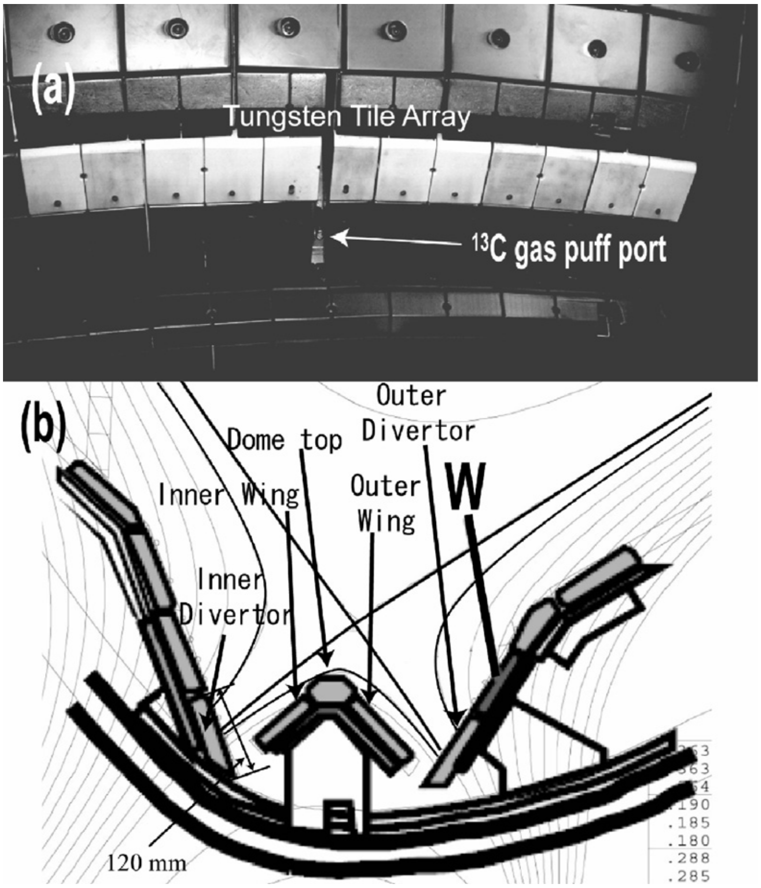

Fig. 1. Photo of tungsten tile array in an outer divertor region (a) and cross sectional view of tile arrangement in the divertor region (b). Broken line in (b) shows separatrix lines for the outer strike point on the W tiles.

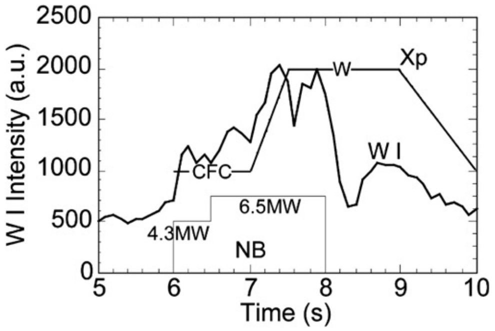

Fig. 2. Evolution of WI line intensity (4008.75 Å) and outer strike point position X_p. 'CFC' and 'W' mean the strike points on the CFC graphite tile and W-tile, respectively.

are shown in Fig. 1. There were no additional W sources in the chamber.

Surface density of deposited tungsten was measured by EDX (Energy dispersive X-ray spectrometry) and XPS (X-ray photoelectron spectroscopy). XPS was mainly used for absolute calibration and evaluation of the accuracy of the EDX results. Both methods, EDX and XPS, have some ambiguity in obtaining absolute atomic concentration. Errors in XPS measurements originated mainly in an Ar etching process (energy 4 keV). The Ar etching changed top surface atomic concentration due to selective sputtering. In addition, shape of etched surface was not flat, which also affects depth profile. In general, depth profile broadens due to this effect. Errors caused by the Ar etching effect, however, can be estimated by sputtering simulation (SRIM2003). For EDX, characteristic X-ray signals from carbon atoms are strongly influenced by surface roughness and it is not easy to estimate errors caused by this effect. These are the reasons why we relied on XPS measurements for absolute estimation of tungsten surface density.

On the outer wing of the dome, EDX measurements from the surface can measure all deposited tungsten, since tungsten deposition was only near the top surface (see Fig. 3(b)) and electron beam of EDX (energy 20 keV) could cover this tungsten deposition layer by considering mass density of carbon deposited layer (0.91 g/cm^3) [6,7]. Therefore, on this tile surface, relative tungsten density profile was obtained by EDX measurements and absolute

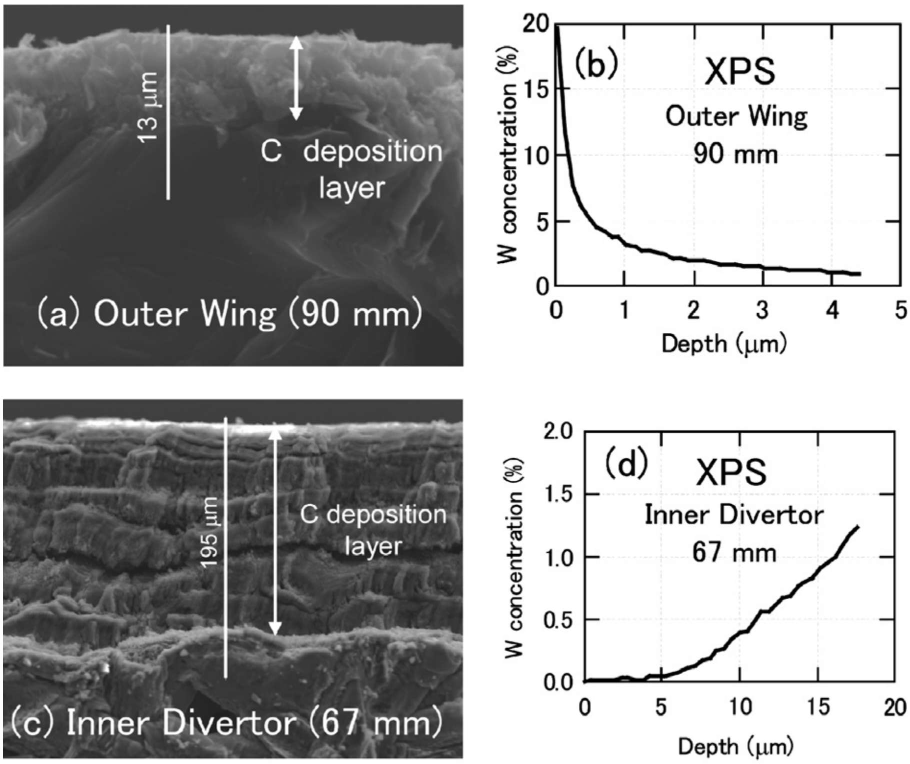

Fig. 3. Fracture surface (a) and depth profile of W concentration measured by XPS; (b) on the outer wing tile at 90 mm from the upper edge. Fracture surface (c) and depth profile of W concentration by XPS (d) on the inner divertor tile at 67 mm from the upper edge.

number of tungsten surface density was determined by XPS measurements at two positions.

On the inner divertor tiles, EDX is used to measure depth distribution in the inner divertor tile. Tungsten codeposited with carbon in this position and depth distribution of tungsten extended up to about 50 μm in depth. XPS depth profile measurements by Ar etching could not reach this depth position. Therefore, we used EDX line analysis along cross section of the samples in these cases. Effects of surface roughness would also obscure the estimation of the absolute tungsten concentration if we used both tungsten X-ray signals and carbon X-ray signals for the calculation of it. But in this study, we used only tungsten X-ray signals for tungsten depth profile, which was not absolutely calibrated. Because the effect of surface roughness is much lower for tungsten X-ray signals due to low attenuation in carbon materials. Absolute calibration of tungsten concentration in this case was done to compare with the XPS signal at the position of 28.7 mm from the top edge, where ^{13}C deposition layer on tungsten layer was negligibly thin and tungsten depth profile near the surface can be measured by XPS.

In the last 10 shots in the experimental campaign, ^{13}C marked methane was puffed between the outer divertor CFC tiles (see Fig. 1(a)) to study carbon migration in JT-60U. Total amount of injected $^{13}CH_4$ was 2×10^{23} molecules. The ^{13}C methane puffing resulted in very thick deposition layers (>200 μm) on the adjacent outer divertor tiles and thick deposition layers (∼10 μm, mixed with normal carbon ^{13}C) on the inner divertor tiles around the inner strike points [8]. This deposition layers hindered the surface W layers deposited before ^{13}C puffing. In these cases, depth profiling was done by the EDX line analysis along fracture surfaces of the graphite tiles.

3. Results on tungsten erosion and deposition

In most discharges (about 1000 shots in the campaign), the strike points were located on the CFC graphite tiles just below the tungsten tiles (see Fig. 1(b)). In selected 25 discharges, the strike point positions were moved up to the tungsten tiles for about 2–6 s. Tungsten release from the W-tiles were observed by visible spectroscopic measurements (W I line, wavelength : 4008.75 Å) along the W-tile surface. An example is shown in Fig. 2 for the ELMy H-mode plasmas with the plasma current of 1 MA and line averaged electron density of about $2 \times 10^{19}\ m^{-3}$. The W I intensity increased after moving the outer strike point to the W-tiles as well as after an increase in NBI power (see Fig. 2). In addition, W I line was also observed with the outer strike point on the CFC tiles. Therefore, most of tungsten erosion and deposition on graphite tiles during this experimental campaign probably took place during discharges without the outer strike point on the W-tiles. Effective sputtering yield of the W tiles was evaluated to be roughly 10^{-4}, similar to the results of ASDEX-U [9].

Fig. 3 shows SEM photos of the fracture surfaces and tungsten depth profiles measured by XPS for the outer wing and the inner divertor tiles. On the outer wing tiles, carbon deposition was observed at the lower side (near an pumping slot) (see Fig. 3(a)), but no clear deposition at the upper side. Tungsten exists only in the near surface layers within the analysing depth of EDX. Similar profile was also found at the position of 20 mm in the outer wing tile. Therefore, EDX point analysis data for

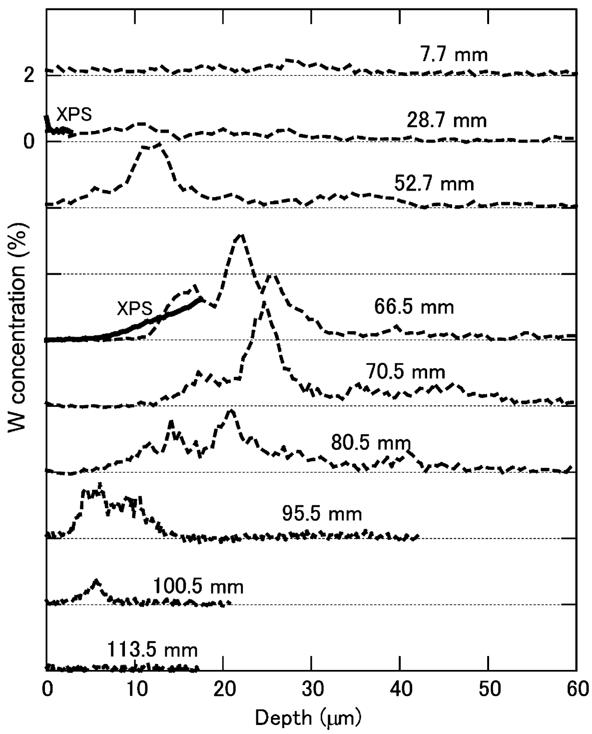

Fig. 4. W depth distribution measured by EDX line analysis along fracture surface of the inner divertor tile. The positions in mm were measured from the upper edge of the tile. The depth profiles by XPS are also shown at 28.7 mm and 66.5 mm.

the surface of the tiles were used to evaluate surface density of tungsten. It was confirmed that the tungsten surface density determined by the EDX point analysis roughly agreed with the calculated value using the XPS depth profiles within the factor of 1.5.

On the other hand, on the inner divertor tiles, very thick carbon deposition was observed (see Fig. 3(c)). The details of these carbon deposition was reported by Gotoh et al. [10]. Tungsten was deposited with carbon to form thick mixed material layers but were embedded beneath the ^{13}C deposition layers which was the thickest around the inner strike positions in standard discharges. From the XPS depth profile (Fig. 3(d)), it is clearly shown that tungsten exists in sub-surface layer, deeper than 5 μm. This depth profile agrees well with ^{13}C depth profile by SIMS, which started to decrease around ∼4 μm [8].

Fig. 4 shows the depth profile of tungsten concentration in the inner divertor tile measured by EDX. Absolute calibration of tungsten signals by EDX was done to compare with the XPS signal at 28.7 mm. Depth profiles by EDX and XPS were also compared at 66.5 mm (see Fig. 4). Although the XPS depth profile changes more gradually than that of EDX due to uneven etching surfaces, their absolute values almost agree with each other. From about 50 mm to 95 mm, where ^{13}C deposition layer covered W and C mixed layers, tungsten depth profiles had clear peaks. On the other hand, the upper side of the tile (7.7 mm and 28.7 mm, Fig. 4) showed roughly uniform depth profiles with low tungsten concentration up to about 30 μm were formed.

Dense localized tungsten deposition was observed on the toroidally adjacent CFC graphite tiles to the W tiles, which was attributed to prompt ionization

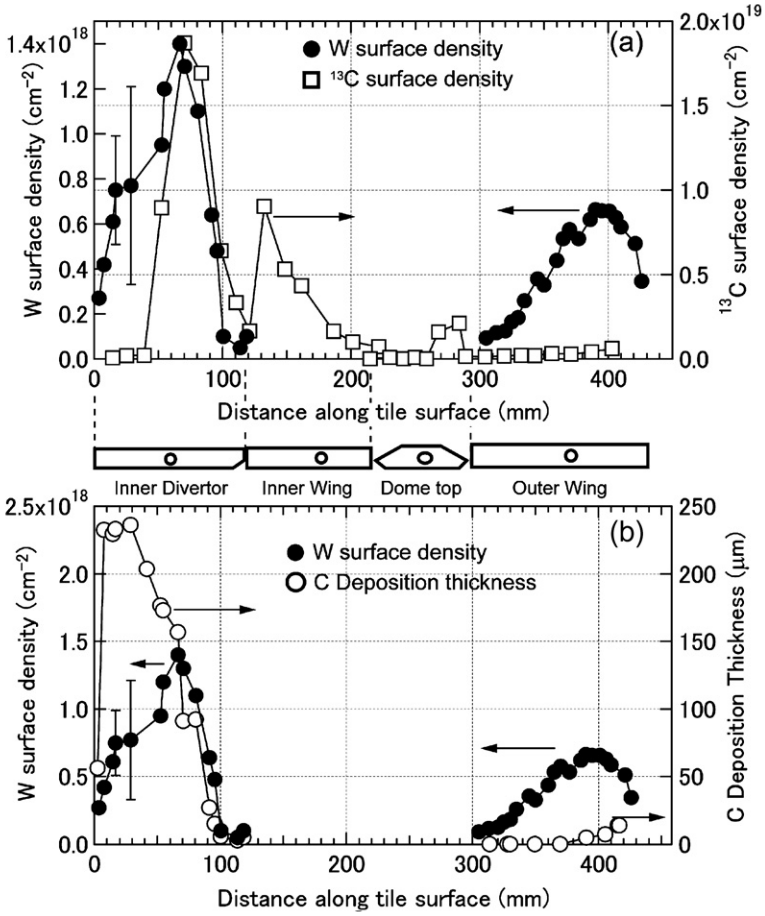

Fig. 5. Poloidal distribution of tungsten surface density in cm^{-2} in the divertor region with ^{13}C surface density (a), and C deposition thickness (b).

of sputtered tungsten atoms and short range migration along the toroidal magnetic field to be deposited. The e-folding width of the layers was about 10 mm in the middle of the tile. By considering the angle between the field line and the tile surface (5°), ionization length of sputtered W was roughly 1 mm. On the other hand, no dense tungsten deposition was found on a poloidally adjacent CFC graphite tile on which outer strike points were usually located in standard discharges.

Poloidal distribution of tungsten surface density was plotted in Fig. 5 together with the ^{13}C surface density profile (a) and the normal carbon deposition profile. On the inner divertor tile, the deposition peaks of tungsten and ^{13}C are the same, indicating that both elements migrated along separatrix field lines and deposited. This is similar to the results in ASDEX-U [11]. The tungsten deposition profile also has some tails on the upper end of the tile. This deposition could be formed under the plasma operation in which the inner and outer strike points were moved up in selected 25 discharges. In addition, since the tungsten depth profiles are roughly uniform (no clear structure, suggesting this deposition took place in all discharges), tungsten migration in the SOL could contribute. For normal carbon deposition (sputtered from graphite tiles), a lot of carbon ions sputtered and migrated through SOL plasmas formed thick deposition layer in the upper side of the inner divertor (see Fig. 5(b)). In standard discharges with the strike points on the CFC tiles, the W-tiles were located in the SOL region and some of sputtered tungsten atoms could reach the inner divertor region through the SOL plasma.

On the outer wing tiles, deposition of ^{13}C (puffed from the hole between the outer divertor tiles) and long term carbon deposition increased toward the lower end of the tile, similar to the case of tungsten deposition. The ratio of the tungsten to the carbon, however, is quite different from that in the inner divertor case. The ratio of tungsten deposition to carbon deposition is much higher on the outer wing tile than that on the inner divertor tile. On the outer wing tile, the tungsten deposition could take place following sputtering of tungsten atoms from the W-tiles and inward drift motion or by some abnormal events (disruption, etc.). Similar process should also occur for the carbon deposition. The reason for the higher deposition of tungsten could be attributed to low resputtering of the W deposition layer.

4. Conclusion

Tungsten deposition in the divertor region eroded from the W-tiles installed in the outer divertor was measured to study tungsten migration in JT-60U. On the inner divertor tile, tungsten was mainly deposited around the inner strike position, similar to the ASDEX-U result [11]. This suggests that tungsten transport from the outer divertor to inner divertor (especially around the strike position) is common phenomenon for divertor tokamaks. In addition, significant amount of tungsten deposited on the outer wing tiles of the dome, which is reported for the first time. Tungsten deposition increased toward the lower side of the tile. This tungsten transport could be attributed to inward drift of tungsten ions in a private region or some abnormal events such as ELMs or disruptions. More studies are needed to comprehensively understand this phenomenon.

By comparing deposition profiles of tungsten with ^{13}C, puffed as $^{13}CH_4$ from the outer divertor position, deposition profiles showed similar tendency such that ^{13}C and tungsten depositions had a peak around inner strike position and their surface densities on the outer wing increased toward the lower end of tiles (there is an evacuation slot). The ratio of tungsten deposition to ^{13}C deposition, however, is much higher on the outer wing tile than the inner divertor tile. The possible reasons are lower resputtering of deposited tungsten than deposited carbon on the outer wing tile or higher tungsten deposition rate on the outer wing tile. This is very important finding to understand migration mechanism of impurities generated at the outer divertor. More study on this issue is necessary.

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