Effect of surface roughness on erosion behaviour of tungsten divertor components on ASDEX Upgrade

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1. Introduction

Tungsten (W) has been actively studied and it has proven to be a good candidate material for the plasma-facing components (PFCs) of future fusion devices: it has a high melting point, small erosion yield by physical sputtering, and retention of plasma fuel in W PFCs will remain at low levels [1]. However, under reactor conditions, intense power and particle loads can damage the PFCs, leading to their original surface becoming strongly modified and its roughness being altered. Consequently, the erosion, deposition, and retention characteristics may change drastically [2]. With this in mind, we have investigated the effect of surface roughness on net erosion and deposition of W close to the low-field-side (outer) strike line (OSP) of the ASDEX Upgrade (AUG) tokamak; this is the region where PFCs are subjected to the largest power and particle loads. The results have been obtained from the ion beam analysis of W-coated samples with varying surface roughness after the samples had been exposed to identical L-mode plasma discharges using the DIM-II divertor manipulator of AUG [3].

2. Experimental

For the experiment, a number of graphite samples were produced with 20-30 nm thick W coatings. Before coating, the surfaces of the samples were either polished (smooth samples, average surface roughness R_a~0.3 µm), milled (nominal samples, R_a~1 µm), or sandblasted (rough samples, R_a~4 µm). The samples were mounted on two adjacent target tiles, made of bulk W, to form three distinct poloidal rows around the strike-line region (see Figure 1). The fourth row, denoted by “marker samples”, consisted of special probes with poloidal W, Mo, and uncoated stripes on a milled graphite surface to investigate prompt re-deposition of W [4].

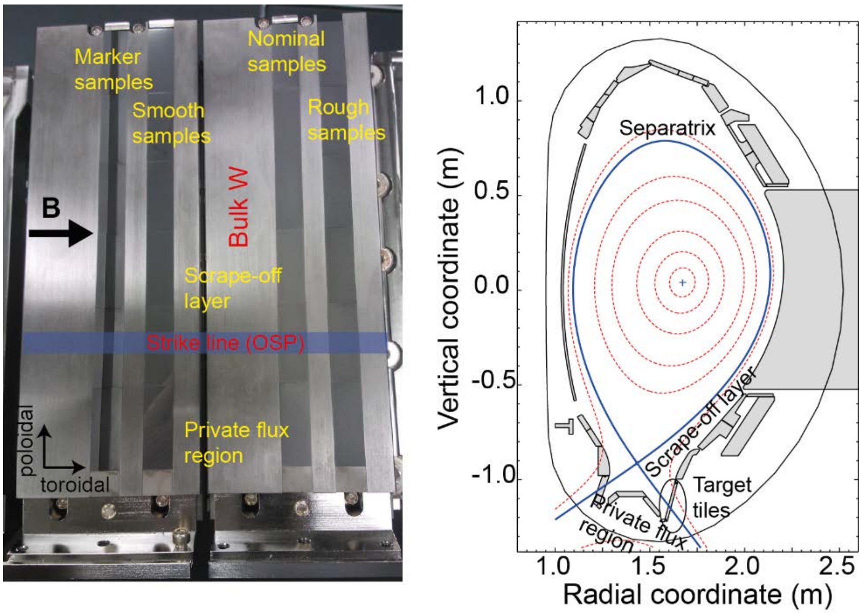

Figure 1. (left) Photograph of the different samples, mounted on bulk-W target tiles before exposure to AUG plasmas. (right) Cross-section of the AUG torus and the magnetic configuration during the experiment.

The samples were exposed to low-density, high-temperature L-mode plasma discharges in deuterium with the overall exposure time of ~80 s. The plasma current was set to 0.8 MA, the toroidal magnetic field to -2.5 T, the core electron density was $\sim 2.0 \cdot 10^{19}$ m^{-3}, and electron cyclotron resonance heating (ECRH) at 1.3 MW was applied. The Langmuir-probe measurements around the OSP gave the following estimates for the maximum electron density and temperature at the samples: $n_{e,OSP} \sim 0.5 \times 10^{19}$ m^{-3} and $T_{e,OSP} \sim 30$ eV.

Before and after the experiment, the thicknesses of the surface layers were determined using Rutherford Backscattering Spectrometry (RBS) [4]. A 2.0-MeV $^{4}He^{+}$ ion beam was used and the backscattered particles were detected at an angle of 165°. The measurement error is ~5%, mainly caused by inaccuracies in fitting of the measured RBS spectra. In addition, Nuclear Reaction Analysis (NRA) was carried out to determine the amount of boron (B), carbon (C), and nitrogen (N) – main impurities during the experiment [4] – on the samples. Here we report the data of B whose profile was identified by measuring the yield of protons originating from the reaction $^{11}B(^{4}He,p)^{14}C$ at 135° with 4.75-MeV $^{4}He^{2+}$ ions.

3. Results

The poloidal net deposition/erosion rates for W on the different samples are shown in Figure 2a. Net erosion of W is clearly visible in the immediate vicinity of the OSP while on both sides of it net deposition takes over. Towards the peripheral regions from the strike line, no significant erosion or deposition can be observed.

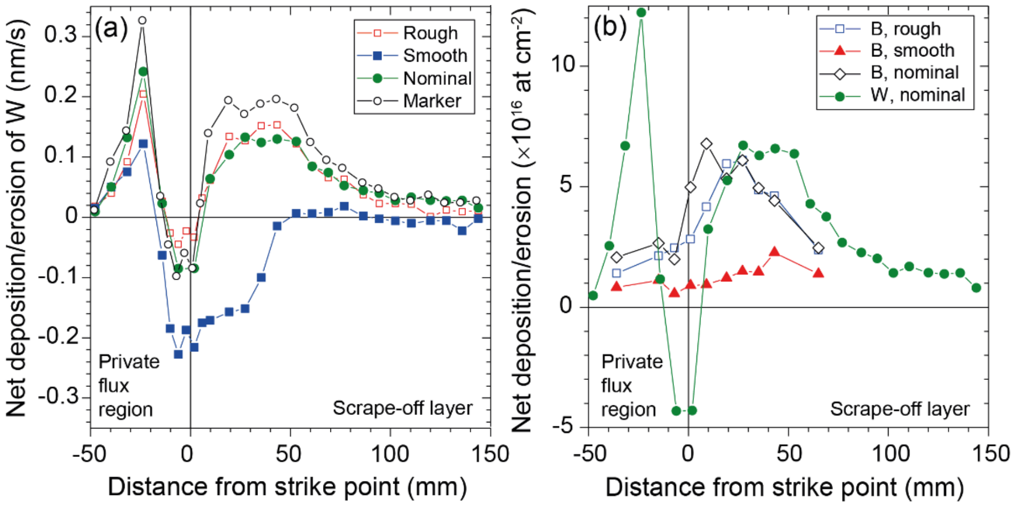

Figure 2. Poloidal net deposition/erosion profiles of (a) W (in nm s^{-1}) and (b) B (in at cm^{-2}) on different samples. In (b) the W profile from the nominal samples in (a) has been reproduced and converted into at cm^{-2}.

The net erosion peak at the OSP is 10-20 mm wide and the maximum erosion consistently increases from 0.03 nm s^{-1} (rough samples) to 0.08 nm s^{-1} (nominal and marker samples) and finally to 0.2 nm s^{-1} (smooth samples). We can conclude that on rough surfaces net erosion is reduced due to re-deposition of the ejected material into areas shadowed by protruding surface features or due to re-implantation of sputtered atoms into neighbouring hills [5].

Net deposition, for its part, shows a different dependence on surface roughness. For the samples with the smoothest surface, deposition is unambiguously observed only in the private flux region (PFR) while for the other samples, the deposition peaks on both sides of the OSP are prominent and especially the one on the scrape-off layer (SOL) side is relatively broad (width >50 mm). In addition, beyond a certain roughness level the surface quality seems not to play any noticeable role – as one can notice from the deposition profiles on rough and nominal samples being practically identical. Interestingly, on the marker samples, the net deposition is some 50-60% larger than on the W stripes of the marker samples with similar roughness. This may be connected with the fact that the marker samples were located magnetically upstream of the other samples thus receiving a larger share of material influx from areas outside the OSP region, including the AUG main chamber.

The net deposition profiles of W are in line with those determined for B (see Figure 2b); the profiles for C and N (not shown) are qualitatively similar. In the SOL, the main peak agrees with the location of the largest deposition of W and smooth samples show 2-4 times less deposition than the rough or nominal ones. In the PFR, no deposition is visible, potentially because all the B originates from the main chamber. However, also missing data points due to a sparse measurement grid may have contributed to the shape of the profiles. Worth noticing is also that the surface densities of B and W are comparable, suggesting that co-deposition of W and impurities play a large role.

Assuming deposition and erosion being toroidally symmetric, the following estimates are obtained for integrated erosion/deposition (negative/positive) in the OSP region: 7.4×10^{18} atoms s^{-1} (or 2 mg s^{-1}) for rough samples, 6.7×10^{18} atoms s^{-1} for nominal samples, 11.0×10^{18} atoms s^{-1} for marker samples, and -4.4×10^{18} atoms s^{-1} for smooth samples. The divertor would thus be considerably eroded if the surfaces were atomically smooth while in the case of rough surfaces the overall balance is shifted towards net deposition.

4. Conclusions

A number of W-coated samples with various surface roughnesses were exposed to low-density and high-temperature deuterium plasma discharges at the OSP region of AUG. The net erosion rate was observed to be the highest close to the actual strike line and to increase by more than a factor of five as the roughness was decreased by an order of magnitude. In addition, prominent net-deposition regions emerged on both sides of the main erosion peak as the R_a value of the surface roughness increased beyond an approximate limit of 1 μm. The accumulation of material was largely independent of the surface roughness and we speculate that its origin is connected with the influx of W and impurities from surrounding regions or even from the main chamber, resulting in co-deposition around the OSP.

Our results are consistent with the existing long-term data [5], although there the deposition and erosion peaks were less prominent: during some 5600 s of plasma operations with different scenarios and strike-point positions, an order-of-magnitude increase in surface roughness only altered the net erosion by a factor of 2-4. The existence of two net-deposition peaks surrounding the strike line, however, is clearly specific for the particular experiment with a high electron temperature and apparently significant $\mathbf{E}\times\mathbf{B}$ drift along the sample surfaces [6].

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