Differential sputtering and magnetic sheath effects on the microscopic erosion pattern of the Tore Supra limiter

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1. Introduction

After the campaign dedicated to the study of the deuterium retention [1] in the Tore Supra tokamak, tiles of the Toroidal Pump Limiter (TPL) that are composed of Carbon Fiber Composite (CFC) have been analysed ex-situ [2]. The particle flux, under which the TPL is submitted, depends on the magnetic field orientation and leads to regions where the erosion dominates over the redeposition. Observations with Atomic Force Microscopy (AFM) and Scanning Electron Microscopy (SEM) have pointed out the presence of a ripple structure in those regions and where the fibers of the CFC are oriented perpendicularly to the surface. Additionally the erosion rate of the TPL has been evaluated to 5.5 nm/s considering a redeposition of 60%. This lies much above normal beam experiments [4] as in order to reach this rate a sputtering yield of 9% would be required. In order to understand the formation of the ripple pattern and the large value of the erosion rate, simulations of the tile surface under deuterium flux have been undertaken. The flux calculation takes the cyclotron motion and sheath deviation into account.

2. Experimental observations

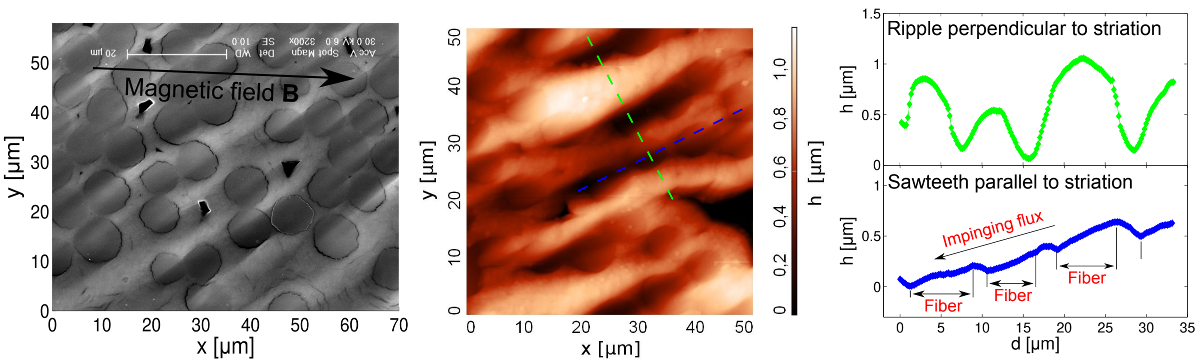


Figure 1: SEM (left) and AFM (middle) imaging of a surface of a tile from the TPL. Profiles (right) from AFM in the directions perpendicular and parallel to the ripple.

The images of the tile surface obtained by SEM and AFM are presented in Figure 1. The CFC fibers appear darker than the surrounding matrix on the SEM picture. A striation oriented at approximately 40° with respect to the magnetic field is visible. The black triangle at the bottom right of the AFM picture corresponds to a hole on the tile. The profile parallel to the striation exhibits sawteeth, while the profile perpendicular to that direction exhibits ripple. The origin of such a pattern can be linked to the grazing incidence of the ions as well as to the sputtering coefficient that differs between the fibers and the matrix. In the framework of this analysis, measurements have shown that this coefficient is 25% larger for the fibers than for the surrounding matrix.

3. Sheath simulations

In order to evaluate the direction of the impinging ion flux on the surface, numerical simulations of the Debye sheath and magnetic pre-sheath have been undertaken with a 1D PIC code [5]. The following parameters have been used: $\tau = T_i/T_e = 100$ eV/20 eV $= 5$, $\xi = r_L/\lambda_D = 11$ (representative of a weakly magnetised plasma and thus of a strong deviation of the particles from the magnetic field lines) and $\alpha_{\mathbf{B}} = 1.33°$, the angle between the surface and the magnetic field. We also have used $P_0 = 3T_e$ that is a reasonable approximation for the sheath potential in the case of light ion plasma.

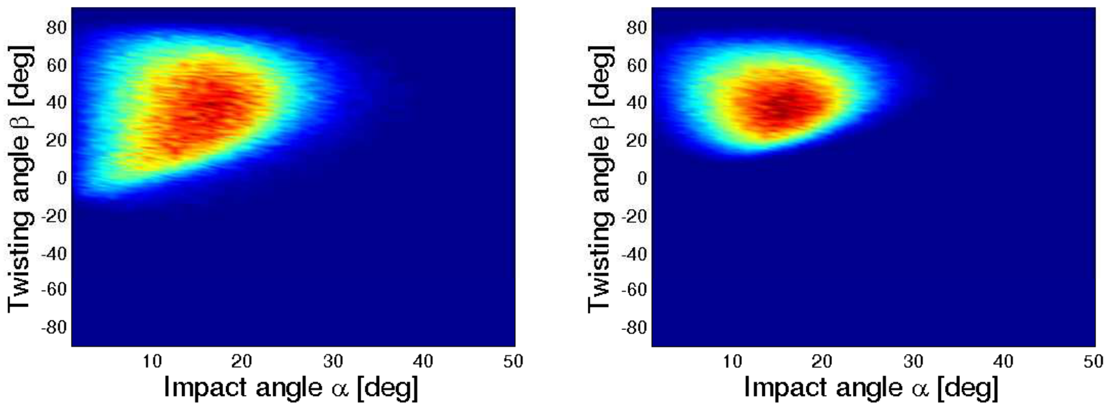


Figure 2: Impact angle α and twisting angle β flux distribution without (left) and with (right) electric sheath potential.

The impact angle α (between the flat surface and the particle trajectory) and twisting angle β (between the projection of the magnetic field on the flat surface and the particle trajectory) obtained by simulations are displayed in Figure 2. The cases without (left) and with (right) the sheath are depicted. The average twisting angle is 41.1° (43.0°) and the average impact angle is 14.2° (16.0°) for the case without (with) the sheath. This small difference due to the sheath electric field shows that the average impinging flow orientation is mainly due to the ion cyclotron motion.

4. Erosion simulations

The erosion modeling is realized through the solving of a 2D surface $h(x,y)$ recession equation that takes the impact angle dependence into account:

$$\frac{\partial h}{\partial t} = \sum_{\alpha,\beta} -\frac{Y(x,y,\varphi)\Phi(\alpha,\beta)}{n}\left[\sin\alpha - \frac{\partial h}{\partial x}\cos\alpha\cos\beta - \frac{\partial h}{\partial y}\cos\alpha\sin\beta\right] \tag{1}$$

where φ is the angle between the particle trajectory and the rough surface and Φ is the particle flux distribution obtained with the PIC code. The ion species is deuterium. The angle dependent sputtering is evaluated with the SRIM 2008 code [6] for an impact energy of 200 eV that is relevant for our conditions. The surface is modeled with disks corresponding to fibers that have a 25% larger sputtering yield than the surrounding matrix. The initial surface is flat.

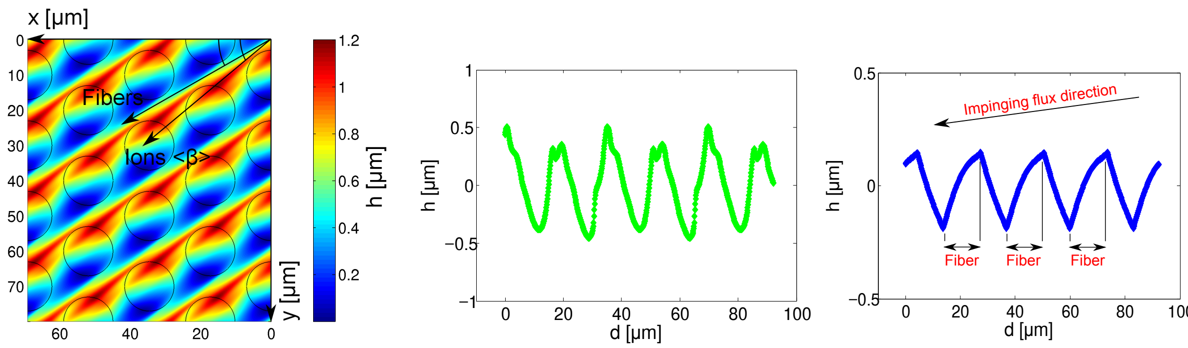
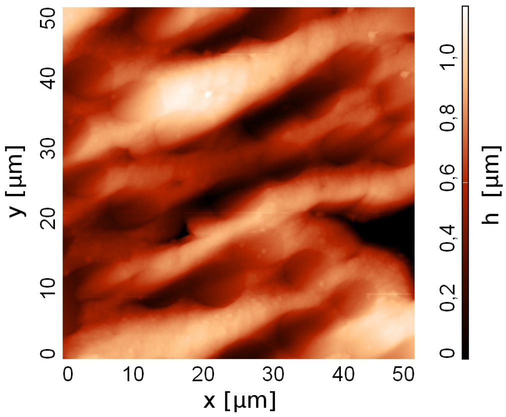


Figure 3: Left: Eroded periodic surface (black lines represent limits between fiber and matrix). Middle: Profile perpendicular to the valleys. Right: Profile parallel to the valleys.

The first simulations have been performed for a periodic system, the orientation of the fibers being 30° and the average impinging flux $\langle\beta\rangle$ being chosen to be 40° with respect to the Ox axis. Figure 3 shows that in this case valleys are created in the direction of the fibers: this points out the importance of the CFC organization. In addition, a sawteeth profile and a ripple profile are reproduced by those simulations. Without any angle dependence of the sputtering yield this system would have evolved indefinitely. However taking it into account makes the surface roughness reach the equilibrium. In this state the erosion rate is everywhere the same. These first simulations show that the driving mechanism for the ripple is the differential erosion between fibers and matrix.

Moving on to a realistic surface taking into account fiber disorder we can compare the erosion pattern obtained with simulations and the analyses of the tile performed with AFM. This is shown in Figure 4. By taking an average β angle of 38° we have found the best agreement between modeling and experiment. With a slightly different angle (30°-45°), striation occurs in the same direction and at the same locations. However, the erosion pattern is different in regions



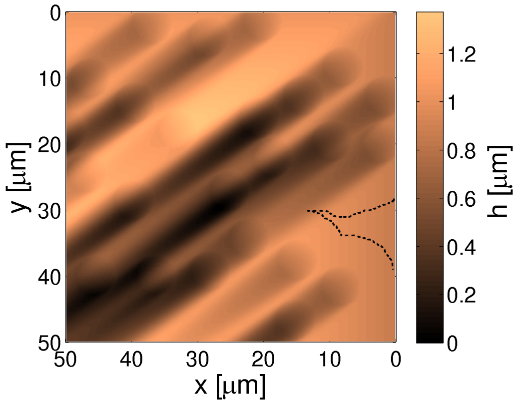


Figure 4: Surface roughness observed with AFM (left) and simulated (right). The dashed line represents the hole extension.

where the fibers are situated far from each other. The average twisting angle β is close to the value obtained with the PIC code and the origin of the discrepancy could be the tilting of the tile while performing the AFM scan. The erosion rate is found to be 6.1 nm/s which is in a quite good agreement with the experimental observation. To reach this value, a net redeposition of 60% has been used. If the simulations had been performed with a sputtering yield independent of the angle between the impinging flux and the surface, a simulated erosion rate of only 2.7 nm/s would have been obtained. This points out the importance of taking this effect into account.

5. Conclusions

Simulations of the erosion of CFC under a deuterium flux have been performed. They showed that the formation of a striation on the tiles of the Tore Supra limiter is due to a different sputtering yield between fibers and matrix. The sawteeth and ripple profiles have been recovered. The ripple orientation is influenced by the ion flux but is also determined by the fiber organization in the CFC. Accounting for angle dependent sputtering is mandatory to obtain an equilibrium state in a periodic system but also to approach the experimental erosion rate. Simulations of the sheath with a PIC code emphasizes that the deuterium flux direction is mostly due to the ion cyclotron motion.

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