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Exposure of metal mirrors in the scrape-off layer of TEXTOR

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Abstract

Large molybdenum mirrors have been exposed in the SOL of TEXTOR in order to simulate conditions relevant for ITER optical components. Distortions of the reflectivity – increase as well as decrease – are found in the erosion and deposition dominated areas, respectively. The changes are most pronounced in the near UV and level off in the IR and can partly be attributed to observed surface changes. A novel periscope system was installed and mirrors exposed in a pilot experiment to simulate the transmission of light to distant sensors in ITER.

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1. Introduction

Metallic mirrors are foreseen in ITER diagnostic systems as optical elements viewing plasma radiation [1]. There is concern that the reflectivity of the mirrors will be affected by particle impact. Mirrors situated close to plasma in the main vessel will likely be subject to erosion by fast CX neutrals. Mirrors located in periscope-like tube systems in the divertor region are expected to experience deposition of impurities [2]. Molybdenum is candidate material, but little experience exists about the performance under non-uniform erosion or deposition conditions or the development of in situ cleaning techniques. Experiments are in preparation at JET [3], performed at T-10 [4] and Tore-Supra [5]. In TEXTOR, polycrystalline molybdenum mirror plates were exposed in the erosion and deposition dominated zone in the SOL. Optical properties of the mirrors were measured before and after exposure. A novel periscope-like tube system was built to investigate the particle transport in the tubes and to test techniques for mitigation of material deposition. The paper reports first results and identifies processes which might be responsible for the change of the reflectivity.

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2. Experimental

Polycrystalline mirrors from molybdenum were placed in the SOL plasma of TEXTOR. The photograph in Fig. 1 shows the experimental set-up and the appearance after exposure. One large mirror (115 mm × 74 mm) was fixed inclined at 20° to the toroidal fluxes. The mirror was partly protected by an aluminum bar which created a shadow. Outside the shadow some deposition becomes visible. One small mirror was placed for comparison at the rear side of the holder perpendicular to the toroidal direction. All mirrors were polished mechanically, had been rinsed and optically been precharacterized.

In the first experiment the edge of the mirror closest to the plasma was kept at a distance of 8 mm from the LCFS (plasma radius 46 cm) which is an erosion dominated zone in TEXTOR. It was exposed to 30 neutral beam heated (increasing from zero up to 1.3 MW) plasma pulses (line averaged density $n_{eo} = 1.5 \times 10^{19}\ m^{-3}$) with a total exposure time of 197 s. These conditions caused strong temperature rises (>1000 °C for ≈3 s) of the edge of the small mirror. The temperature of the large mirror measured by a pyrometer rose to 400–750 °C during the discharges. For the second experiment the closest edge of the mirrors to the plasma were placed at LCFS + 25 mm to cover primarily the deposition dominated zone. They were exposed to 58 (partially neutral beam heated) discharges with varying plasma density ($n_{eo} = 1.5\text{–}4.5 \times 10^{19}\ m^{-3}$) and a total exposure time of 312 s. The bulk temperature achieved 150 °C, local temperature rises have not been observed. Carbon deposition up to thicknesses of more than 200 nm took place except in shadowed regions and at the edges. After dismounting the surface and the deposits were investigated by ion-beam analyses.

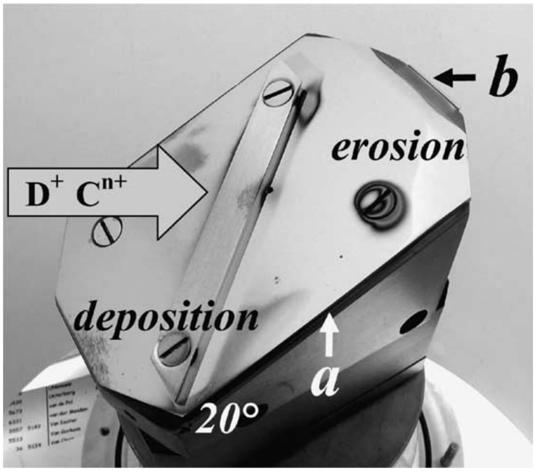

Fig. 1. Photograph of the mirror holder after exposure in the erosion dominated zone. The large mirror (a) is mounted 20° inclined on the graphite carrier, the small mirror (b) on the rear side perpendicular to the toroidal direction.

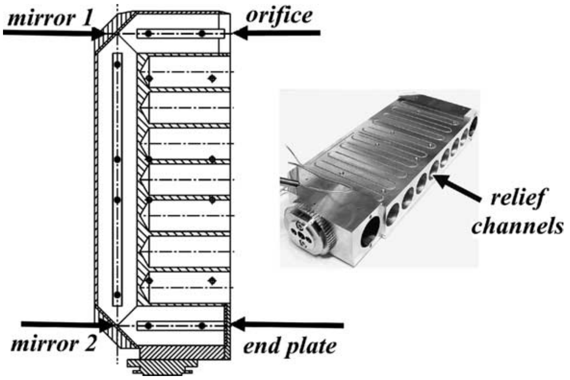

Fig. 2. Periscope system with mirror 1 (closest to the plasma), mirror 2 and end plate. The tubes (35 mm) are wrapped inside with exchangeable steel foils fixed at the wall by bars. The photograph shows the stainless steel body without end plate. Relief channels reduce weight.

The set-up of a periscope-like system on TEXTOR simulates the ITER diagnostic ports transmitting the plasma radiation to further distant sensors. Two plane mirrors were installed in tubes facing each other at a distance of 275 mm. The mirrors are oriented 45° with respect to the line of sight. The system is closed with a polished end plate and shown in Fig. 2. The orifice (35 mm diameter) is oriented perpendicular to the toroidal direction. The SOL fluxes hit the first mirror under 45°. Carbon transport inside and deposition can be investigated after dismounting of the system. The deposition patterns on exchangeable steel foils wrapped inside the tubes complete this information. The stainless steel body can be heated up to about 500 °C. Mirrors made from TZM (99% Mo, 0.1% Zr, 0.5% Ti) were used for the pilot experiment. The edge closest to the plasma was kept at 25 mm from the LCFS and the system exposed to 89 (partly neutral beam heated) plasma pulses ($n_{eo} = 1.5\text{–}4.5 \times 10^{19}\ m^{-3}$) with a total plasma exposure time of 1047 s. The temperature was 150 °C.

3. Results

Total and diffuse reflectivities were measured under almost normal incidence (3°20′) before and after exposure by means of a spectrophotometer (wavelength range $\lambda = 250\text{–}2500$ nm) with a space resolution of ≈10 mm. Fig. 3 shows examples for the wavelength dependence of the total reflectivity R_{tot} found on the two large mirrors. The central curves 1 represent the total reflectivity measured before and after plasma exposure at a location protected by the aluminum bar. The

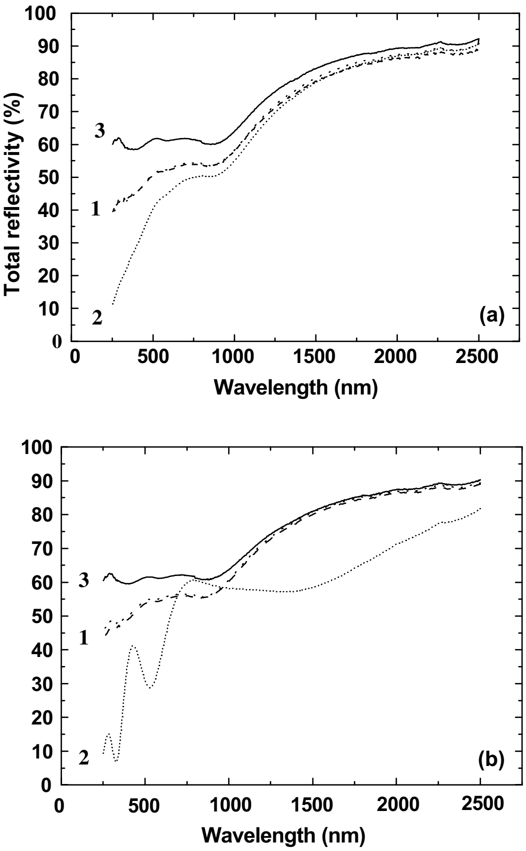

Fig. 3. Total reflectivity R_{tot} depending on wavelength measured on the molybdenum mirrors before and after exposure in a protected area (1) and after exposure in the deposition (2) and erosion (3) dominated area of the surface. Mirror (a) was exposed for 197 s and close to the plasma edge (LCFS + 8 mm), while (b) was exposed for 312 s and deeper into the SOL (LCFS + 25 mm).

lines coincide well, but stay below the values given for polycrystalline molybdenum in the literature [6]. As soon as deposition begins (curve 2 in Fig. 3(a)) the reflectivity decreases by absorption in the film (thickness ≈30 nm). The drop is most pronounced in the UV region and levels off in the IR. In addition to absorption, the reflectivity can be distorted significantly due to destructive and constructive interference in thicker deposits. The example (curve 2, Fig. 3(b)) was measured on the mirror plate exposed deeper into the SOL (LCFS + 25 mm) where carbon deposition dominates and a film up to about 220 nm thickness was formed.

Surprisingly, an increase of R_{tot} well beyond the literature values [6] was measured on surface areas which suffered from net erosion (curves 3). The increases are similar, independent whether the target mirror was exposed near the plasma edge (Fig. 3(a)) or deeper into the SOL (Fig. 3(b)). This increase is most pronounced ($\Delta R_{tot} \approx$ 10–20%) for short wavelengths and almost vanishes (1–3%) beyond about 1500 nm.

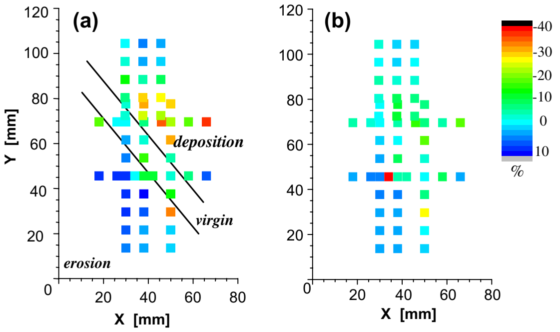

Fig. 4. Differences $\Delta R_{tot} = R_{after} - R_{before}$ given in colors at different surface locations for $\lambda = 250$ nm (a) and 500 nm (b). The co-ordinates x and y cover the mirror dimension (74 mm × 115 mm).

The local dependence of the reflectivity was measured at about $N = 50$ different spots by shifting the mirrors plates in the two directions (x and y) parallel to the sides. Before exposure the reflectivity scattered a little, i.e. the differences $\Delta R = R_i(\lambda) - R(\lambda)_{av}$ between one local measurement (index i) and the average out of the N measurements was less than about ±3% in the visible and the IR. For shorter wavelengths the scatter was about twice as much. After exposure the local changes were much larger. Fig. 4 shows the N differences $\Delta R_{tot} = R_{after} - R_{before}$ measured on the mirror exposed at LCFS + 8 mm. The differences are highest for $\lambda = 250$ nm (a) and achieve more than +12% (dark blue) [1] in the eroded part of the mirror, while reductions of −30% (deep red) occur in areas covered with deposits. In protected or shadowed areas ΔR_{tot} is in the scatter range ΔR observed before exposure (blue green). For increasing wave lengths (b) the changes are less pronounced. The intensity of the diffuse reflected light has also been measured at the identical locations, but contributes little since the differences do not exceed about ±2% on this mirror plate.

According to the theory [7] the reflectivity of light polarized perpendicular ($R_\perp$) to the plane of incidence increases with angle of incidence (θ_i), while the intensity of the parallel polarized component ($R_\parallel$) drops to zero until the *Brewster angle* ($\theta_B = 56°20'$ for $n = 1.52$) is reached and increases then. Compared to R_{tot} measured for non polarized light and normal incidence we therefore expect $R_\perp > R_{tot}$ (45–55% in the visible), while $R_\parallel < R_{tot}$ for $\theta_i < \theta_B$. The components $R_\perp$ and $R_\parallel$ were determined by means of a spectro-ellipsometer which measured the ellipticity of the linearly polarized light (azimuth angle 45°) after reflection in the wavelength

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[1] For interpretation of color in Fig. 4, the reader is referred to the web version of this article.

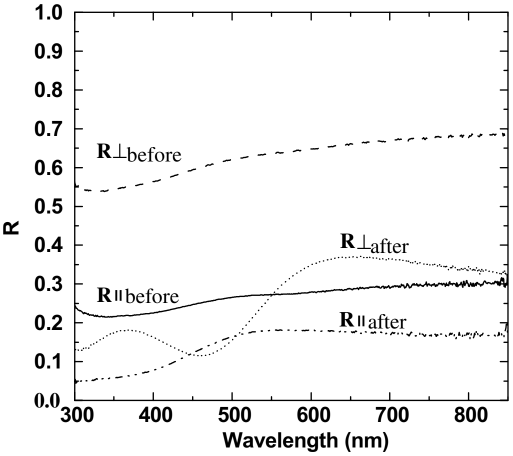

Fig. 5. Total reflectivity of polarized light $R_\perp$ and $R_\parallel$ for $\theta_i = 60°$ measured in the range $\lambda = 300$–850 nm before and after exposure in the deposition dominated area of the surface.

range 300–850 nm for two incident angles $\theta_i = 45°$ and 60°. Fig. 5 shows an example.

Mirror 1 exposed in the periscope for 1047 s showed a radial decaying deposit with a maximum thickness of about 400 nm as estimated by interference fringe analysis. The optical constants ($n = 1.65$, $k = 0.02$ for $\lambda = 632$ nm) taken into account were measured for the film deposited on the molybdenum mirror. The thickness corresponds to a deposition rate of about 0.4 nm/s (inclination angle 45°). Electron probe micro-analysis (EPMA) confirmed the thickness estimate and shows that the deposit consists mainly from carbon. Although the deposition rate on mirror 1 is high, no detectable deposition was found on the following mirrors and walls.

4. Discussion

An increase of R_{tot} in the erosion dominated areas is expected, because the mirrors used in the experiments were not especially cleaned before the exposure. The bombardment with plasma ions leads to a reduction of the surface impurity content [8,9] and shifts the reflectivity up to the standard values given in the literature for the well conditioned surfaces. The increase, however, beyond the standards as observed in the visible and near infrared region is not expected. The surface erosion which is estimated to be less than 1 μm [10] is mainly due to energetic deuterium and carbon ions. Part of the carbon remains intermixed in the near surface layer [11]. This is confirmed by SIMS depth profiling in the affected areas. But it has to be shown whether the presence of carbon in the interaction depth of ≈5 nm can further increase of the reflectivity.

The decrease of the total reflectivity in deposition dominated areas is due to absorption and by destructive interference if the deposit is thick enough. The example given (curve 3 in Fig. 3(b)) roughly fits the condition $i * \lambda/4 = n * x$ ($i = 1,2,3,\ldots$) for destructive or constructive interference using a film thickness of $x = 220$ nm and a refractive constant $n = 1.65$. The term $n * x$ deviates by about +10% in the IR and by −10% in the UV region. This is likely due to the varying thickness within spot size of the measurement. But diffraction of light cannot be excluded. Combining the results from SIMS depth determination and the deuterium analysis with NRA yields a ratio D/C ≈ 0.3. For ITER, a deposition of carbon on optical components is difficult to predict, but it is possible because of the chemical erosion and transport of the hydrocarbon radicals over long distances.

The deposition rate of ≈0.4 nm/s on mirror 1 (inclination angle 45°) in the periscope is less than found on the 20° inclined mirror (0.7 nm/s) at the comparable radial position. This might partly be due to the fact that roughly one half of the carbon entering the orifice becomes deposited on the inner tube wall, visible there as a transparent deposit. Part of the carbon will likely be re-eroded from mirror 1. It is surprising therefore that no further deposition could be detected on the following walls and mirrors. One reason could be that the exposure time of 1047 s is too short to grow a detectable layer. Another reason might be the pressure built up in the closed system which prevents the hydrocarbon radicals to penetrate deeper. Enhanced re-erosion of freshly formed deposits [12] may also play a role.

5. Conclusions

The experiments show that the reflectivity of metal mirrors drastically changes after the exposure to the SOL plasma in TEXTOR. Increases to values higher than standard values are observed in erosion dominated areas, as well as decreases of the reflectivity due to carbon deposition. Both effects are a concern for the mirrors in the ITER diagnostic ports and periscopes and can occur side by side on a mirror. It is obvious that the decrease of the reflectivity is due to absorption and destructive interference in the deposit, but the same time we did not find the full explanation for the observed increase. It seems that the conditioning of the surface plays an important role. All changes of the reflectivity are the most pronounced in the near UV region, the IR region is almost not affected. No detectable amounts of carbon were found on surfaces inside the periscope system beyond mirror 1. This behavior could be favorable for ITER, but the reasons for it remained unclear. These experiments are therefore a first step only to the understanding and developing of a model which can predict the ITER mirror performance.

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