Carbon erosion and deposition
of tokamak plasma facing components

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Introduction

Tokamaks, where a hot plasma (electron temperature Te ~ a few keV) is confined by magnetic fields into a toroidal chamber (close magnetic lines), are the most promising magnetic fusion devices. Currently, only deuterium is routinely used (D + D reaction) but the future tokamak ITER will use tritium (D + T reaction). Radial transport carries ions to the plasma edge where they are guided to walls through open magnetic field lines. Up to now, carbon has been the favourite material for parts of the walls receiving the highest fluxes of heat and particles, in particular because of its good thermal conductivity. In the French tokamak Tore Supra, the main Plasma Facing Component (PFC) is the toroidal limiter, a castellated assembly of 2 x 2 cm^2 tiles made in a C/C composite provided by the SPS company (Sepcarb®N11).

Unfortunately, carbon is easily eroded by the plasma particles and the transport of either eroded carbon particles (atoms, small clusters, hydrocarbons etc.) or particles grown into the plasma (polyaromatic hydrocarbons, base structural units, nanoparticles ...) lead to the deposition of carbon layers, from a few to a few hundreds of µm thick, in various places in the chamber and containing various amount of deuterium [1-4]. Retention of hydrogen isotopes in these deposits becomes a serious safety issue when there is tritium is used, preventing from using carbon as PFC material. Deposits can also detach and form dust particles, a second serious safety issue because dust is potentially reactive in the event of accidental air or water leak. Understanding the formation of carbon deposits is the objective of this study.

Experimental

Recent progress was achieved in this field with the DITS project [5,6] (Deuterium Inventory in Tore Supra). The project includes (i) a dedicated campaign to load the vessel walls with deuterium, (ii) the dismantling of a sector of the toroidal limiter to extract selected samples, and (iii) an extensive sample analysis program. For the D wall-loading experiments (phase i), more than 160 long (> 1 min), identical discharges were performed for a total time of ~5 h of plasma. The dismantled part of the limiter is shown in Fig.1a: a periodic pattern of erosion- or deposition-dominated zones is shown. This complex pattern is due to the periodic structure of the magnetic field, which leads to various ion energies and ion fluxes onto the limiter surface. Fig. 1b shows an infrared thermography image of the same part of the limiter.

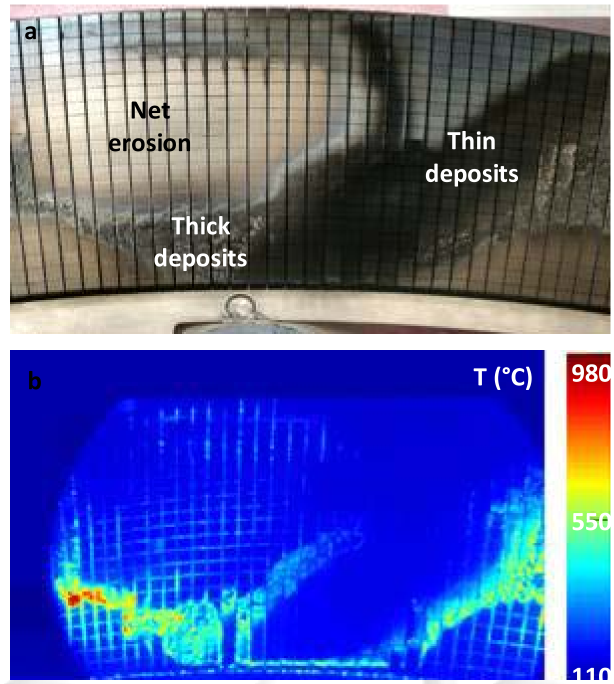

Fig. 1 Dismantled part of the toroidal limiter: (a) erosion- or deposition-dominated zones, and (b) temperature cartography obtained by infrared thermography.

The lowest temperature is that of the water loop cooling the PFCs. Temperature can be significantly higher, either due to high ion fluxes (erosion zone) or due to loosely attached deposits (thick deposit zone, gaps in between tiles).

Measurements were performed on a selected set of tiles extracted from the different zones of the toroidal limiter, using combined methods: local and integrated D-content measurements with Nuclear Reaction Analysis and Thermo-Desorption Spectrometry, respectively, as well as spectroscopic and structural analyses with Raman microscopy Scanning and Transmission Electron Microscopy (SEM, TEM) and Atomic Force Microscopy (AFM), respectively. We focused in this paper on these latter analyses.

Entire tiles were removed from the three zones of interest, i.e. from the net erosion zone, the thick deposit zone, and the thin deposit zone (Fig. 1a). The five sides of each tile (the plasma facing top of the tile and the four lateral sides, corresponding to gaps between tiles, were examined. SEM was performed at the Microscopy Center of the Université de Provence (Marseille, France) using an ESEM Philips XL 30 microscope with a 5 nm resolution and at the CP2M (Marseille, France) using a SFEG Philips XL30 microscope with a 1.2 nm resolution. TEM and HR-TEM images were performed for thin foils cut by the FIB (Focussed Ion Beam) method in the top surface of the eroded tile and in the deposits of both the top surface of the thick deposit tile and the gap side surfaces using a JEOL 2010 F field emission microscope, with a 0.19 nm structural resolution and a 1 nm spot size.

Results and Discussion

Fig. 2 shows two examples of SEM images recorded for the top surface of a (a) thick deposit tile and (b) an eroded tile.

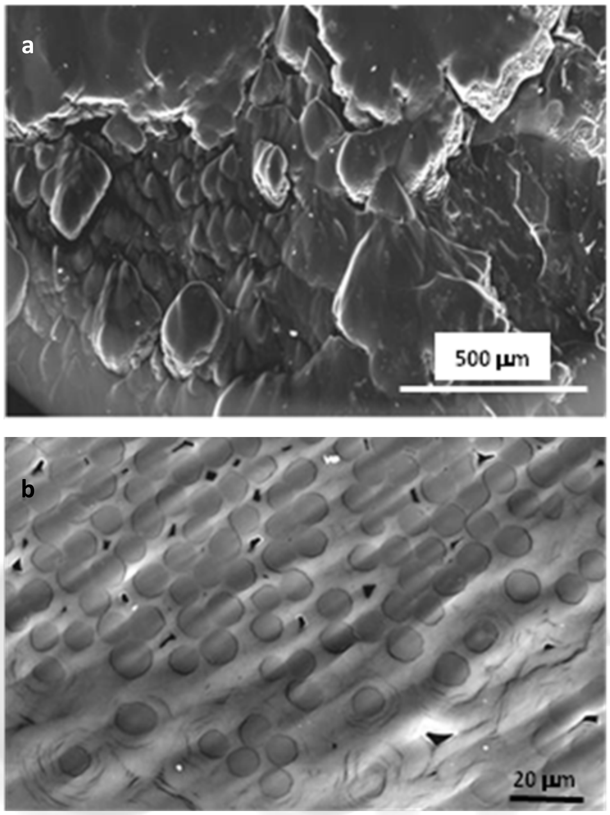

Fig. 2 SEM images of the top surface of (a) a thick deposit tile and (b) an eroded tile.

The top surface of the thick deposit tile shows loosely attached and flaking deposits, with a typical tip-shaped surface. The tips are lying on the surface and their orientation is perpendicular to the toroidal direction (that of the magnetic field). Deposits with tips are also visible on the four lateral surfaces of both the eroded and the deposited tiles, down to a about 1 mm inside the gap. They are loosely attached and flaking for gaps in the toroidal direction whereas they are strongly attached for gaps in the perpendicular direction. Tips are inclined with respect to the tile lateral surface, and with the same main orientation. Consistently, tip size is smaller for thin deposition than for thick deposition.

The top surface of the eroded tile is smooth, the fibre structure and the porosity of the C/C composite being still visible. Note that at a larger magnification deposits are observed inside these porosities. A striation is clearly visible, the distance between grooves being of the order of magnitude of the fibre size. AFM experiments have confirmed that this contrast is due to grooves, with a typical depth of about 0.5 µm. A difference of erosion (fibres being more eroded that the matrix) has also been clearly evidenced.

In the case of the eroded tile, TEM shows a thin layer of amorphous carbon (~ a few tens of nm) at the surface, covering the crystalline carbon structure. In the case of the top of the thick deposit tile, Raman spectra reveal that the atomic structure is mainly amorphous, whereas nano-crystalline carbons can be found in the gap deposits, (nano-onions, graphitic ribbons...). A layered deposition has also been evidenced, with graphitic and amorphous alternate layers, or with metal-containing and metal-free alternate layers.

These structural analyses give indications on the deposit formation processes and the transport of carbonaceous materials on the plasma edge of Tore Supra. Alternate layers are marks of the plasma discharge history, disruptions causing the end of a discharge most often ablating metal from the tokamak walls. Note the graphitic / amorphous series correspond to duration less than that of a discharge, probably to special events such as flaking occurring during a discharge. The tip direction and the groove orientation are most probably correlated to ion and carbon flow orientation but the correlation is far from being obvious and currently under study.

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