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An overview of fuel retention and morphology in a castellated tungsten limiter

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ABSTRACT

A castellated tungsten test limiter composed of detachable segments was exposed to plasma discharges in the TEXTOR tokamak operated with graphite main limiters. Dismantling of the limiter enabled the analysis of surfaces located inside the castellation. The emphasis was on the determination of: (i) deposition and fuel retention; (ii) material mixing and new compound formation on plasma-facing surfaces and in the grooves of castellation. The investigation performed by means of accelerator-based ion beam analysis methods, microscopy and X-ray diffraction has brought several essential results: (i) deuterium retention on plasma-facing surfaces and in the castellation of metal PFC is strongly related to the co-deposition with carbon; (ii) both carbon and deuterium are detected only in narrow belts, a few millimetre broad, down the gap with the decay length of around 1.2–1.8 mm; (iii) the presence of copper droplets and tungsten oxide (WO_2) has been identified in the gaps. Different pathways leading to the oxide formation are considered.

1. Introduction

All plasma-facing components (PFC) in ITER will be castellated, i.e. composed of small blocks separated by narrow grooves (∼0.5 mm) in order to reduce thermally induced stress [1]. The contact of plasma with several different elements (including carbon) in PFC, as foreseen in ITER, will also lead to the co-deposition of eroded material together with fuel species in the grooves of castellation. This has been shown for castellated structures exposed to the plasma for long- [2–4] or short-term [5–7] in present-day tokamaks. For the carbon Mk-I divertor at JET, the inventory in gaps (6–10 mm wide) between tiles was at least twice greater than measured on plasma-facing surfaces [2]. In case of narrow gaps in beryllium divertor [3] and limiter tiles from JET [4] the presence of fuel was associated with the co-deposition of carbon. There will be over one million of such narrow grooves in ITER. As a consequence, fuel retention in the castellation may significantly contribute to the overall tritium inventory. Present comprehensive models of tritium retention do not include these effects and no quantitative assessment of the fuel retention in tile gaps at the ITER divertor exists [8,9].

This contribution provides an account on the detailed examination of surfaces inside the castellation of a tungsten (W) test limiter exposed to plasma discharges in the TEXTOR tokamak. The major aim of ex situ analyses was to determine the morphology on the plasma-facing surfaces and in the castellated gaps: (i) fuel retention; (ii) material mixing and new compound formation.

2. Experimental

The mushroom-shaped W limiter was composed of 12 individual segments brazed to a copper (Cu) base. The detachable segments were separated by 0.5 mm wide gaps. Two experiments were performed in TEXTOR operated with carbon main limiters which define plasma radius of a = 46 cm. In the first experiment, the limiter was kept for 157 s of the plasma operation (including 135 s of heating by neutral beams) at r = 48 cm, i.e. 2 cm deep in the scrape-off layer (SOL). In the second experiment performed a few months after the first one, the limiter was moved forward step-by-step in the SOL and, eventually, it was gradually immersed 15 mm inside the plasma (r = 44.5 cm). The limiter was preheated to 450–520 °C, i.e. above the brittle-to-ductile transition temperature in order to avoid tungsten damage under heat shock. After each experiment, the limiter was dismounted thus enabling morphology studies in the poloidally oriented gaps (i.e. grooves of castellation). The amount of co-deposited elements (carbon, boron and deuterium) was quantified using accelerator-based ion beam analysis (IBA)

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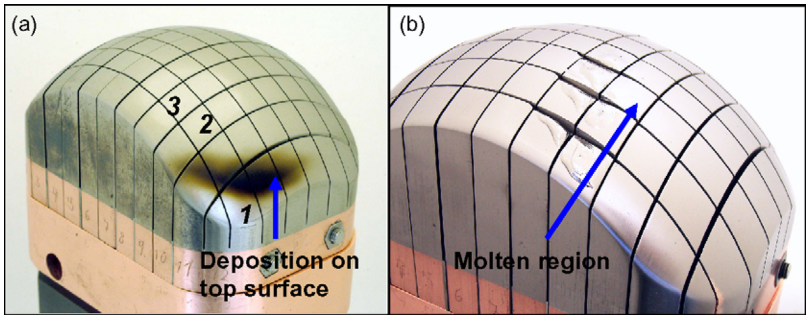

Fig. 1. W macro-brush limiter after the first (a) and second (b) exposure at TEXTOR. Slices analysed with IBA are numbered 1–3.

methods such as nuclear reaction analysis (NRA) and enhanced proton scattering (EPS). Surface topography was observed with scanning electron microscopy (SEM). The distribution of carbon and other elements in the gaps was analysed with energy and wavelengths dispersive X-ray spectroscopy (EDS and WDS). X-ray diffraction (XRD) was used to study compounds formed as a result of material mixing inside the castellation.

3. Results and discussion

3.1. Visual inspection

Images in Fig. 1a and b show the appearance of the limiter after the first and second experiments, respectively. The most characteristic features detected on surfaces are indicated by arrows. Only in the first case the deposition was found on outer surfaces at the far end of the limiter on the side facing the ion drift direction. This is qualitatively similar to results of earlier experiments with solid W limiters at TEXTOR [10,11]. In the second exposure the limiter surface temperature exceeded the melting point of W ($T_{m(W)} = 3410\,^{\circ}C$). The surface remained shiny but material melting and melt layer motion occurred on some segments, as reported in [12,13].

3.2. Co-deposition in castellated gaps

Images in Fig. 2a show the appearance of both sides of Slice 2 after the first experiment. The deposition inside the castellation is limited to narrow belts (3–5 mm wide) just below the entrance to the gap. Detailed deposition profiles of deuterium (D), boron (B) and carbon (C) measured with IBA on both sides of the slice are in Fig. 2b and c. One may notice some differences between the two sides of the slice. On Side B the deposition belt was formed only on a part of the slice. This is most probably related to the local temperature variations on the limiter surface and consequential removal of the whole or part of the deposit formed during previous shots.

There are several important features. The decay length (λ) of species in the castellation is in the range from 1.2 to 1.8 mm thus indicating that only a minute amount of species penetrates deep in the gap. The same result has been obtained also for Slice 3 and it has been observed that the shallow deposition inside the castellation on all other segments. This agrees with modelling performed be means of kinetic codes [4,14]. The concentration of all co-deposited species is small: below $4.2 \times 10^{17}\,cm^{-2}$ for carbon and $1 \times 10^{16}\,cm^{-2}$ for deuterium, thus showing – as expected – very low fuel inventory on hot tungsten surfaces. The presence of deuterium is always associated with the co-deposition of carbon.

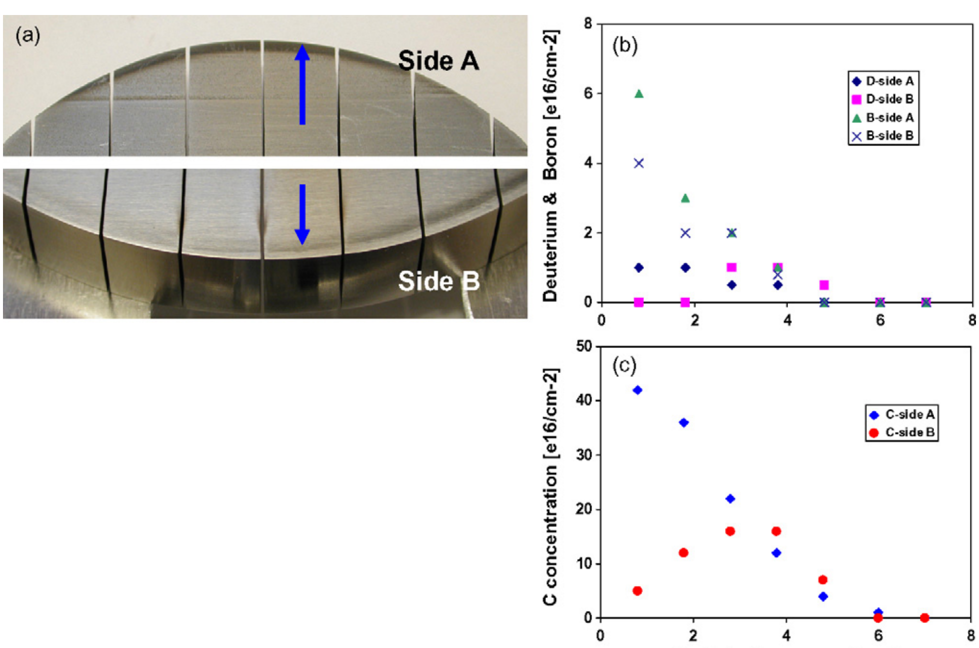

Fig. 2. Deposition belts in gaps of castellation on both sides of Slice 2 (a) and deposition profiles of deuterium and boron (b) and carbon (c). The deposition belts near the top of the gap on Side A and Side B are marked with arrows.