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Journal of Nuclear Materials 313–316 (2003) 67–71

journal of nuclear materials

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Performance and erosion of a tungsten brush limiter exposed at the TEXTOR tokamak

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Abstract

To examine the performance of a castellated structure under plasma loading, a hemispherical solid tungsten brush limiter was exposed to the plasma in the TEXTOR-94 tokamak. Due to the thermally isolated column of W segments, IR camera showed a non-uniform temperature distribution. The maximum incident power density was calculated to be about 35–40 MW/m^2. Concerning impurity generation, the structure did not show any particular effects. During plasma exposure, only some minor cracks developed in one of the columns, however, the crack propagation was interrupted by a groove. It can be concluded that the W brush limiter had comparable performance and superior mechanical behaviour compared to a solid W limiter. To study erosion and long-range transport of W atoms, a graphite limiter was exposed simultaneously with the brush limiter. As a result, the deposited W atoms via long-range transportation were estimated to be 10^{15} cm^{-2} shot^{-1} at 46.5 cm from the plasma centre of TEXTOR.

Keywords: Tungsten; Castellation; Tokamak; TEXTOR; Finite element method; Erosion deposition

1. Introduction

Tungsten is an attractive candidate material as a plasma facing material in future fusion devices because of the low erosion rate and the high melting point [1]. However, W is brittle at room temperature, hence, the operation temperature of W tiles should be above its ductile brittle transition temperature (DBTT) in order to avoid serious cracking [2–4]. Recently, castellated structures of solid W have been developed [5] and tested in laboratories [6]. The results showed a good performance of the component up to heat loads of 13.7 MW/m^2. Thermally induced surface stresses caused by the temperature gradient have been reduced significantly and helped to prevent the crack propagation.

In the present work, a castellated solid W module so-called macro brush limiter was exposed to the TEXTOR plasma to examine the performances. In addition, long-range transport of eroded W atoms was also studied by

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PII: S0022-3115(02)01334-X

exposing a graphite limiter simultaneously at a different position.

2. Experimental

The macro brush tungsten limiter is 12 and 8 cm long in toroidal and poloidal directions with a spherical face of a radius of 7 cm. The brush structure was manufactured by casting 4 solid W plates (2 cm in thickness, purity: 99.9%) with Cu (purity: 99.99%) at 1180 °C. After the casting process, a brush structure with the column size of 1 cm × 1 cm with 0.4 mm grooves was prepared by spark erosion techniques (Fig. 1(a)).

The brush limiter was exposed to about 30 density ramping discharges at 45 cm from the plasma canter (1 cm inside of the last closed flux surface (LCFS)). The density ramping discharges were typically operated with electron density of $2–6 \times 10^{13}$ cm^{-3}, 330 kA plasma current, neutral beam heating with the power of 1.7 MW and 6 s plasma duration. The bulk temperature of the test limiter was monitored at 3 mm below the interface of W and Cu by thermocouples. The thermocouples showed that the initial bulk temperature of the limiter was around 100 °C. The surface temperature of the brush limiter was observed by an IR camera and a pyrometer. W release was monitored by the measurement of the WI (401 nm) line intensity in 2D images with a spatial resolution of 0.25 mm.

In addition to the brush limiter, a graphite limiter (the spherical face of a radius of 7 cm) was exposed simultaneously at a plasma radius of 46.5 cm from the centre (5 mm outside of the LCFS). The graphite limiter was located at a position 135° toroidal and 180° poloidal direction from the brush limiter. In the last phase of the experiments, the limiter was exposed without the W source (after the removal of the brush limiter). The WI line had been observed by a spectrometer in order to examine the long-range transport and the deposition of eroded W atoms from the brush limiter. The schematic view is shown in Fig. 1(b).

After the exposures, the brush limiter was studied by metallography and surface analyses were carried out on the graphite limiter. The details of the surface analysis procedures are described elsewhere [7].

3. Results and discussion

3.1. Performance of the W brush limiter

The IR camera showed a non-uniform temperature distribution for the individual columns of the brush structure (Fig. 2(a)). This temperature profile was not only in accordance with the radial power profile in the plasma edge and with the curvature of the limiter surface [8]. It indicated additional effects by the brush structure. These effects pronounced near the limiter top where magnetic field lines intersect the limiter surface at grazing angles. Jumping of temperatures between two columns was observed at the groove (Fig. 2(b)). By using finite element method (FEM), the temperature distribution and displacements due to thermal expansion were calculated taking into account temperature dependent physical parameters [9] and angular dependent energy reflection coefficients [10]. As a result, the calculations generally reproduced the non-uniform temperature distributions. It was revealed that the temperature distribution was caused by the thermal isolation of the individual columns. The mean incident power deposition

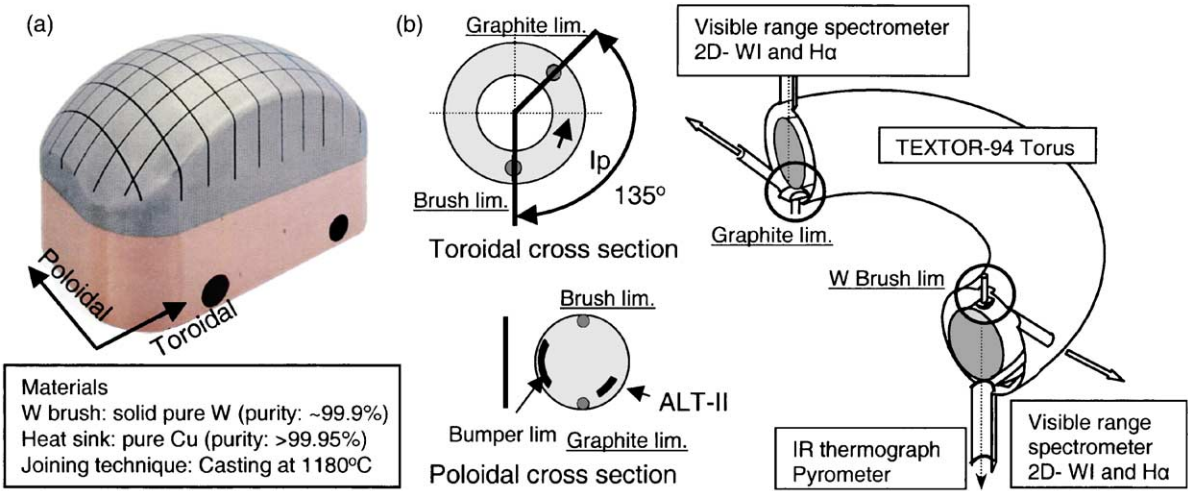

Fig. 1. (a) The tungsten brush limiter used in this experiments, (b) schematic view of the experimental set-up. The brush limiter and a fresh graphite limiter were simultaneously exposed in the different position in TEXTOR.

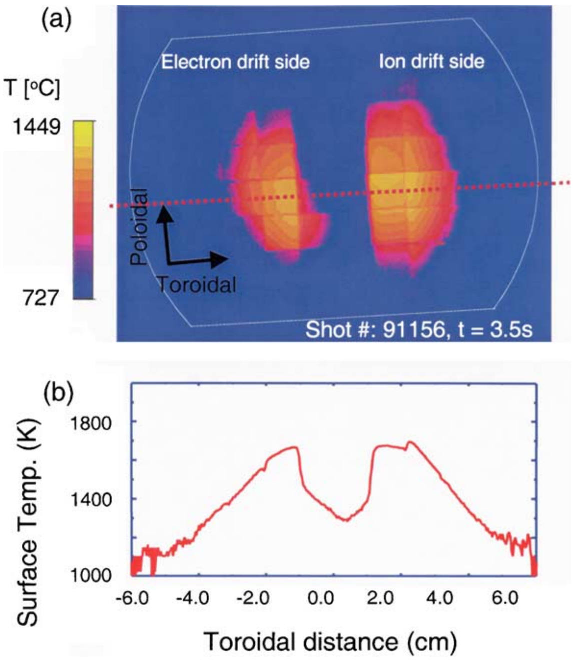

Fig. 2. (a) Non-uniform temperature distribution during a discharge. Shot no. 91 156, $t = 3.5$ s. (b) A temperature profile along the toroidal direction.

was estimated to be 35–40 MW/m^2 (the absorbed power density: 6.5–7.5 MW/m^2). The FEM analysis showed a steep temperature gradient of approximately 600 °C/cm near the loaded surface. In spite of such high heat loads, the columns in this area did not show any visible defects. One might expect that the edges of the protruded columns would be a strong impurity source, if the columns displaced significantly due to the thermal expansion. According to the FEM analysis, the displacement of the columns in the radial direction was 0.06 mm in the maximum at the highest loading point during discharge compared with the position before the shot. One can conclude that the displacement in the radial direction is not significant under the plasma loading. And the total displacement of the brush limiter was estimated to be 0.5 mm at the highest loading point and 0.7 mm at the edge mainly because of the thermal expansion of the Cu part (heat sink). For this analysis, the energy reflection coefficient was referred from a literature [10], the actual energy reflection coefficient with electric sheath during plasma loadings is one of the interesting issues. In this point, further calculation is necessary to understand the detailed temperature profile across the columns and grooves.

One might expect that the groove walls can be a strong impurity source due to arcing and sputtering. The local groove effects with respect of W release were observed by WI (401 nm) line intensity in 2D images with a special resolution of 0.25 mm (Fig. 3). In the figure, one can see the high intensity area that is corresponding to the intensive loading area (see Fig. 2), however, pronounced local impurity generations such as intense line emission or spark due to the structure, were not observed in the experiments.

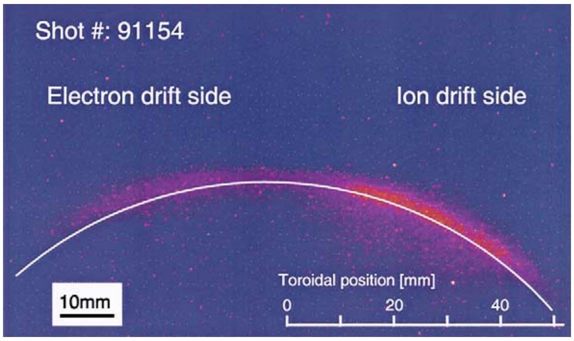

Fig. 3. 2D distribution of WI (401 nm) intensity with a special resolution of 0.25 mm. Shot no. 91 154, $t = 2$ s (averaging over 0.2 s).

After the exposure, post-mortem inspections were carried out. The initial temperature of the W brush limiter was around 100 °C (below the DBTT) at the beginning of the experiments. Under these conditions, serious cracking was always observed in the solid W limiters [2,3], however, no serious damages over the entire surface were observed in the W brush limiter. In fact, small cracks developed in the perpendicular direction at one column at the edge of the brush limiter and the crack was stopped within a column by a groove (Fig. 4(a)). This shows that the brush structure could effectively prevent the crack propagation. The cracks were studied further by metallography (Fig. 4(b)). It shows that the cracks were created at the grain boundaries and propagated along the grain boundaries, as is often observed in solid W materials [4]. Another remarkable event was observed in a discharge. Melted Cu suddenly came up on the top surface of the brush limiter. By a

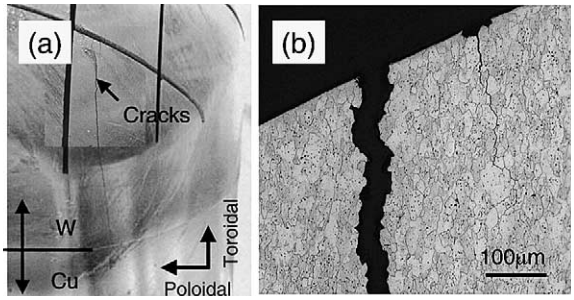

Fig. 4. (a) Cracks in a column at the edge of the brush limiter. (b) Microstructure of the cracks in a W column.

metallographic inspection, it was found that the source of the Cu was the remained Cu just beneath the top surface during the manufacture process. The heat sink can be excluded as a source of the Cu. This event was obviously caused by error in the manufacture. It can be avoidable by precise manufacture.

In conclusion, in comparison to a solid W limiter, the W brush limiter behaves similar to solid W limiter under plasma loading and superior mechanical behaviour. Therefore, this structure is one of the promising structures for plasma facing components.

3.2. Erosion and deposition of W atoms on the graphite limiter

The WI (401 nm) line was carefully observed on a fresh graphite limiter during the experiment. Fig. 5 shows the normalized WI intensity measured in front of the graphite limiter as a function of the shot number. The WI intensity was associated with the W atoms from the W brush limiter. The figure showed that the WI intensity, i.e. the amount of W reached on the surface, was in a quasi steady state. It means that the erosion and deposition from the W brush limiter and the re-deposition of W atom on the graphite limiter were balanced. After the extraction of the W brush limiter, the intensity decreased due to erosion by a factor of 6 (Fig. 5). The erosion phase was divided into two phases corresponding to the radial position. The ratio of the erosion rates of two phases (E_2/E_1) was about 1.8. The ratio was identical to the D flux ratio at the different limiter positions (2.1×10^{19} cm^{-2} s^{-1} at $r = 46$ cm and 1.2×10^{19} cm^{-2} s^{-1} at $r = 46.5$ cm). This indicated the erosion was dominated by the sputtering due to the particle flux.

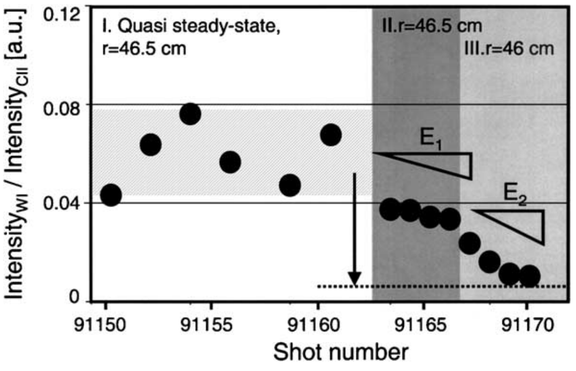

Fig. 5. Evolution of the normalized WI (401 nm) intensity. WI intensity was measured between 1.15 and 1.25 s in short flat top phases and normalized by CII (392 nm) intensity that represented the background plasma. The radial positions of the brush limiter (r_W) and the graphite limiter (r_C) in the different three phases: (I) $r_W = 45$ cm, $r_C = 46.5$ cm; (II) extracted, $r_C = 46.5$ cm; (III) extracted, $r_C = 46$ cm.

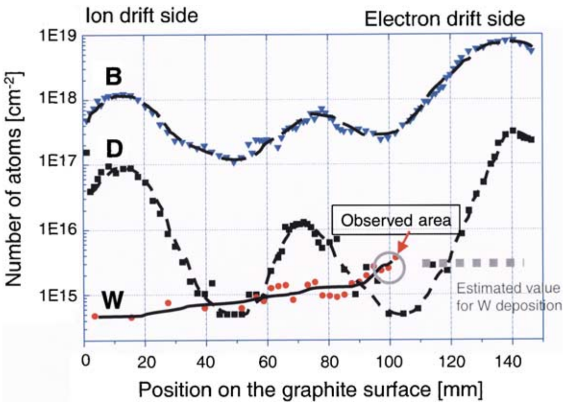

Fig. 6. W, D and B distribution on the graphite limiter. The circle in the figure shows the area observed by spectroscopy.

Fig. 6 shows the W, D and B distributions on the graphite surface. The estimated W content is shown in the figure because the quantification of W content was disturbed by a huge amount of Cu deposition originating from the molten Cu on the surface of the brush limiter. The W atoms had toroidally asymmetric distribution on the limiter. As shown in Fig. 6, there were differences between the profiles of W and the others (D and B). In fact, D and the other impurities such as B that were introduced during wall conditioning and distributed in the whole chamber, on the contrary, W source was only one local position. This could cause the differences in the profiles. Nevertheless, toroidally asymmetric distributions were observed in all case. The distribution, especially clear in the cases of D and B, seemed to be a general impurity transport in the scrape of layer. This asymmetry is caused by the difference of the connection length and not by the position of impurity sources. The connection lengths in the experiments were about 12.5 m at the electron drift side and about 2.5 m at the ion drift side. Hence, the longer connection length is associated with greater amount of deposition and vice versa.

The W content in the observed area is shown with a circle in Fig. 6. The amount of W atoms was about 2×10^{15} cm^{-2} at the observed area. This is the remained W atom after two net erosion phases shown in Fig. 5. Using the results by the spectroscopy and the surface analyses, one can roughly estimate the amount of the deposited W atoms in the quasi steady state. The amount of W atoms in the quasi steady state was estimated to be about 1.2×10^{16} cm^{-2}. The net erosion rates was calculated to be $E_1 = 1 \times 10^{15}$ cm^{-2} shot^{-1} and $E_2 = 2 \times 10^{15}$ cm^{-2} shot^{-1}. Since the net erosion and net deposition in a quasi steady state should be balanced, the net deposition rate due to the long-range transport will be in the order of the net erosion rate E_1, therefore, the net deposition rate was calculated to be approximately 1×10^{15} $cm^{-2}\,shot^{-1}$ at 46.5 cm from the plasma centre.

4. Summary

To investigate the effect of castellation of W, a macro brush W limiter was studied in TEXTOR. A non-uniform temperature distribution was observed. It was caused by thermal isolation of the individual columns. FEM analysis indicated that the incident power density onto the limiter was estimated to be 35–40 MW/m^2 (the absorbed power density: 6.5–7.5 MW/m^2). The displacement due to thermal expansion during a discharge could be negligible. No clear indications of enhanced erosion, such as arcing in grooves and intense sputtering at the edge of columns, were observed. Although, the starting temperatures was below the DBTT, cracking over the entire limiter surface was not observed. Instead of large cracks, only minor cracks developing perpendicularly were observed and the further propagation of the cracks was terminated by the grooves. In conclusion, the brush limiter showed comparable performance under plasma exposure and superior mechanical behaviours comparing to a solid W limiter.

The WI line was observed on the surface of a graphite limiter, which shows the long range transportation of W atoms from the brush limiter. The evolution of the WI intensity indicated that the content of W atoms on the surface was in a quasi-steady state and the long-range transport of the W atom was estimated to be approximately 1×10^{15} $cm^{-2}\,shot^{-1}$ at 46.5 cm from the plasma centre.

Acknowledgements

Authors would like to thank Dr A. Gervash in Efremov Research Institute, St Petersburg, Russia, for discussions on the manufacturing of the tungsten brush limiter.

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