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Performance of tungsten coatings as plasma facing components used in ASDEX Upgrade

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Abstract

Tungsten coated graphite tiles were mounted in the divertor of the ASDEX Upgrade tokamak and exposed to approximately 800 plasma discharges with varying average heat fluxes of up to 6 MW/m^2. After the experimental campaign, cracks were detected on almost all tiles in accordance with results of electron beam tests. The W-coated tiles in the inner divertor were found to be covered by deposited layers of low-Z material with thicknesses in the μm range and only a few percent tungsten remaining on the surface. In contrast the outer divertor is dominated by erosion. Here, the tungsten concentration at the surface was found to be close to the initial level. The global W-migration pattern was determined by analyzing the deposition of tungsten on a complete poloidal set of plasma facing wall components. Both divertor regions display broad deposition peaks with deposited layers at least one order of magnitude thicker than the main chamber values.

1. Introduction

Owing to its favorable physical properties, tungsten is considered as an attractive plasma facing material in fusion devices [1,2]. In order to investigate the suitability of tungsten as a divertor target plate material, ASDEX Upgrade was equipped with tungsten coated divertor target tiles for a full experimental campaign (≈800 plasma discharges). Major points of interest were the investigation of erosion and deposition processes and the transport of tungsten into and within the plasma, which were summarized elsewhere [3]. In this paper we present results obtained from technological investigations of the tungsten coated tiles after the experimental campaign and results from electron beam tests carried out concurrently. Furthermore, results of erosion and deposition measurements, which were completed after the experimental campaign, are reported.

2. Technical performance of the tungsten coatings

The design criteria for tungsten as plasma facing material on the divertor target tiles in ASDEX Upgrade were defined by the expected heat loads, the size and geometrical shape of the tiles and the compatibility of the tungsten components with the former technical divertor I concept. The preceding technological evaluation procedures are reported elsewhere [4,5]. These tests led to the selection of a high-density plasma spray coating on fine grain graphite substrate. An intermediate layer was applied to act as bonding medium (Plansee AG) and to suppress excessive tungsten carbide formation, which could limit the lifetime of the coatings due to embrittlement and cracking.

The dimensions of the plasma facing surface of the divertor tiles were approximately 160 × 80 mm^2 (poloidal × toroidal direction), with a tile thickness of ≈30 mm. The edges were rounded and shadowed by slight tapering in toroidal direction in order to avoid hot spots. The graphite EK98 was chosen, despite its low coefficient of thermal expansion (3.8×10^{-6}/K) which does not well match that of W (4.6×10^{-6}/K at room temperature), since a wide experience in its thermomechanical behavior existed from the former employment as target tiles. The coating had to be applied on the

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plasma facing surface and the rounded edges. After physical vapor deposition (PVD) of the intermediate W-Re multilayer, the tiles were baked at 1000°C followed by plasma spraying of the tungsten layer. Finally, the tiles were baked again at 1300°C in order to achieve a homogeneous, recrystallized structure of the coating. After cooling, bowing of the tiles occurred as a result of the different thermal expansion of graphite and coating. The density of the plasma-sprayed coating was approximately 92% with only slightly reduced values of thermal conductivity and mechanical strength compared to those of bulk tungsten. Depending on their position in the divertor, the tiles were either clamped or screwed to the sub-structure.

Parallel to the tungsten divertor experiment performed in ASDEX Upgrade, electron beam tests were carried out at the FE-200 electron beam facility in Le Creusot (France) [6] using identical tiles with different coating thicknesses (200, 500 μm) and with a tungsten–rhenium coating (500 μm) with 10 wt% Re, respectively, manufactured in the same way. The heat flux profile during these tests was adjusted to match an ASDEX Upgrade reference profile with a full width at half maximum of 19.4 mm. The pulse duration was 2 s and the peak of the profile was adjusted to the nominal strike point position in ASDEX Upgrade. After performing 200 cycles with a power load of 7 MW/m^2, the peak position was shifted by both ±10 mm and another 100 cycles were performed on each position. Finally, the peak was moved back to the nominal strike point position, and another 100 cycles at a power load of 9 MW/m^2 were carried out.

Due to the higher porosity of the W10Re coatings and the reduced thermal conductivity of W10Re in comparison to pure W, the W10Re coatings showed significantly higher surface temperatures than the W-coatings at identical heat fluxes. At 7 MW/m^2 the increase of the surface temperature was 530°C for the 500 μm W-coatings, 610°C for the 200 μm W-coatings and 900°C for the 500 μm W10Re coatings. The starting temperature was 150°C in all cases.

After 400 cycles (200 at nominal position, each 100 at ±10 mm) at 7 MW/m^2 power load, a distinct crack pattern had formed on the 500 μm W-coated tile. Along the length of the loaded zone, a crack extended almost over the whole width of the tile (toroidal direction) and propagated through the whole bulk of the graphite. In lateral direction (poloidal direction) small cracks were also visible on the surface. After the cyclic load with 9 MW/m^2 the tiles had more cracks, but the pattern did not change. In contrast to these results, the 200 μm W-coatings loaded at 7 MW/m^2 had only a few microcracks within the tungsten layer, which did not propagate into the graphite. However, after the 9 MW/m^2 cycles the tiles showed macrocracks only in the region which had received the highest power load. At the edges of the zone with the highest heat load, the macrocracks branched out and diminished with increasing distance. Additionally the toroidal crack also occurred at the rounded edge. The 500 μm W10Re-coatings exhibited the best results in these tests. On tiles cycled at 7 MW/m^2 no macrocracks were present, similar to the 200 μm W-coatings. Further, no additional macrocracks were observed after loading with 9 MW/m^2.

In the tungsten divertor experimental campaign, tiles with 500 μm W-coating were installed in the ASDEX Upgrade divertor. A total of nearly 200 tiles were employed covering 90% of the divertor strike point zone. Approximately 800 plasma discharges with varying average heat fluxes up to 6 MW/m^2 were performed during the campaign.

The measured surface temperatures corresponded fairly well to those from the electron beam tests at comparable heat fluxes and pulse lengths. Throughout the discharge period the surface temperature stayed below 700°C. An intermediate inspection of the tiles, which was performed after 3 months and approximately 200 discharges with power densities below 5 MW/m^2, revealed that fine cracks had already developed on single tiles but most of the tiles were still intact. After termination of the discharge period, larger cracks were detected on almost all tiles. This is in accordance with the results found on tiles with identical coating in the electron beam test, which were still intact after loading with 50 cycles at 7 MW/m^2. Despite the large cracks in the divertor tiles, no influence on the plasma performance and the measured W-concentrations in the plasma was found [3].

In Fig. 1, the heat load distribution on the divertor tiles and the crack pattern are shown schematically. The toroidal crack always started from the thicker edge of the tapered tiles, which was exposed to the heat load, and propagated through the bulk of the graphite. Surface analysis of the cracks revealed that failure started at the rounded edge within the graphite near the interface between graphite and coating. In that region, the rounded edge gives rise to a stress concentration. The other major cracks in the coating had poloidal orientation. It can be assumed that they originate from the mismatch in thermal expansion. It is not clear whether the observed poloidal cracks in the coating occurred because of thermomechanical stresses or thermal fatigue. The presence of fatigue is also in contradiction with previous tests [4,5].

At the interface between graphite and coating no carbide formation due to the thermal loading was found, as could be expected from the relatively low temperatures on these tiles during operation. Within the first tungsten layer, nearest to the graphite in the multilayer, zones of WC and W2C were found which had already been formed by the thermal treatment during the manufacturing of the coating. On the tiles installed in the

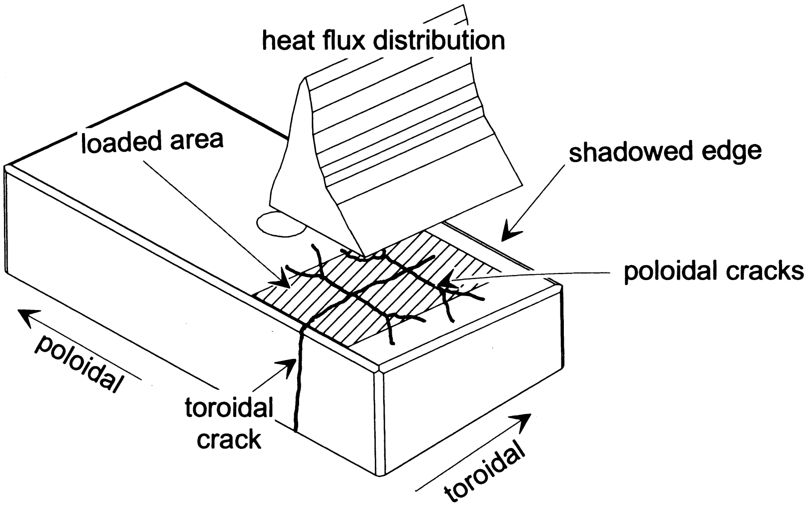

Fig. 1. Heat load distribution and crack pattern on ASDEX Upgrade divertor tiles.

divertor as well as on the tiles which had undergone the electron beam tests, this carbide zone was not wider than on tiles which had not been loaded. In the subsequent tungsten layers within the multilayer, no carbides were present as well.

3. Erosion and deposition measurements

The impact of plasma ions on the divertor target plates can lead to sputtering of tungsten atoms. Time resolved profiles of the tungsten sputtering flux across the inner and outer target plates during plasma discharges were obtained by spectroscopic observation of line radiation of neutral tungsten in the visible range [7].

Time integrated spatial profiles of the tungsten erosion in the outer divertor plate were determined by exposing test tiles for one or several subsequent discharges using a manipulator system [8]. As expected, significant tungsten erosion occurred only under discharge conditions with high divertor plasma temperatures such as low density Ohmic discharges or H-mode discharges with ELMs [8,7]. But even under these conditions the energy of the incident D ions is too low to account for the observed erosion. Carbon ions produced at the plasma facing graphite components in the main chamber can impact the target plate with much higher energies due to their higher charge state and the correspondingly increased sheath acceleration. Using sputtering yields of carbon impacting on tungsten from laboratory ion beam experiments [9] and adopting a 1% fraction of C^{3+} ions [3] one obtains good agreement with the measured erosion fluxes.

A small fraction of the sputtered tungsten atoms ($\approx$1%) could migrate to the upstream scrape-off layer plasma [10] and eventually reach the vessel walls because of cross-field diffusion processes. By measuring the poloidal distribution of deposited tungsten atoms, it was possible to obtain a global long-term migration pattern. A complete poloidal set of plasma facing wall components was analyzed by Particle Induced X-ray Emission using a 1.5 MeV proton beam. The amount of deposited tungsten was derived from the integral over the respective L_β doublet line at 9.68/9.96 keV.

All main chamber components exhibited roughly the same low level of tungsten contamination (see Fig. 2(a)). By comparing our measured values with previous results, where some tungsten test tiles had already been installed in the divertor, one obtains an upper limit of 10^{15} W-atoms/cm^2 deposited within a total plasma discharge time of $\approx$3000 s.

The tungsten deposition on the lower divertor plates exceeds the main chamber results by a factor of up to 50–80. Redeposition in the tungsten coated region was determined by analyzing thermography tiles, which were employed for thermographic measurements of the surface temperature and therefore had not been replaced by tungsten coated tiles. Fig. 2(b) and (c) display the radial distribution of the tungsten deposition for the inner and outer target plate, respectively. The peak positions coincide with the maxima of the average deuterium fluence to the target plates as determined from Langmuir probe measurements [4]. The overall maximum was found at the deposition dominated inner divertor plate (Fig. 2(b)) with a less pronounced broader maximum on the erosion dominated outer target plate. A secondary peak could be found in the private flux region of the outer divertor, which originates from tungsten sputtered near the outer strike point being transported along the magnetic field lines.

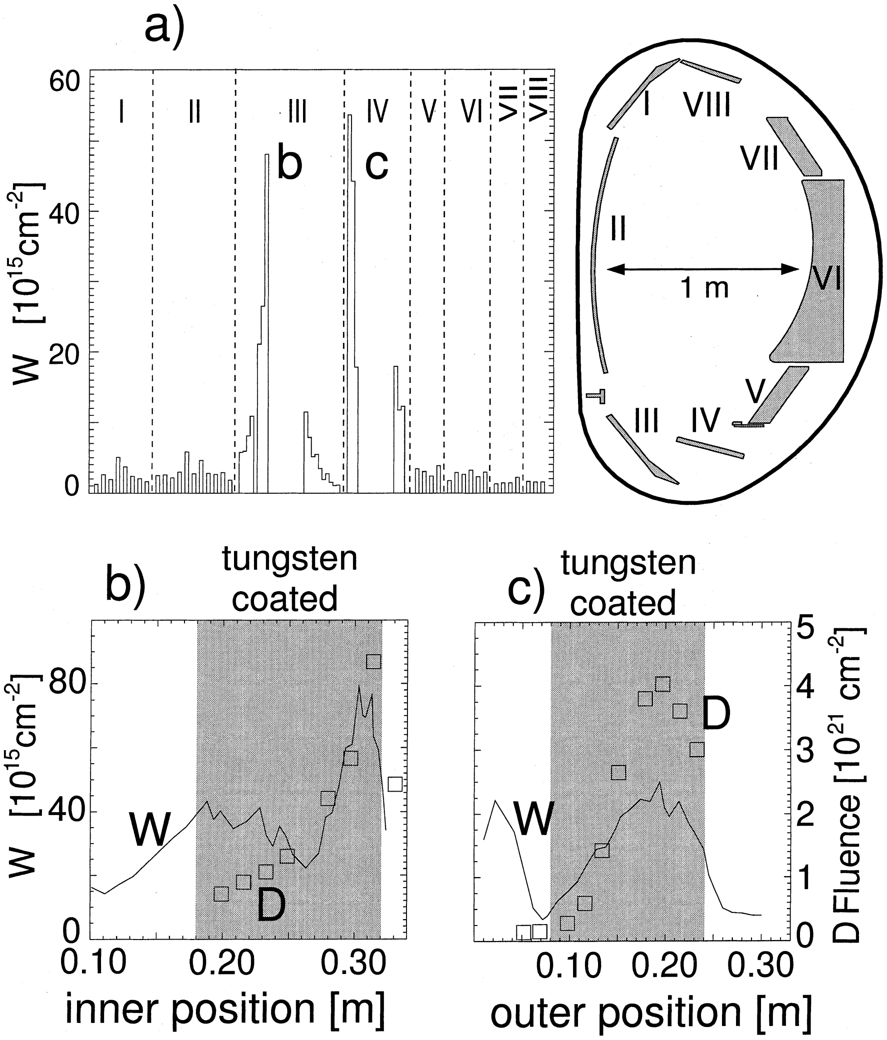

Fig. 2. (a) Poloidal distribution of tungsten deposition on plasma facing vessel components. The data in the tungsten coated area were obtained from graphite thermography tiles; (b) inner target; (c) outer target. (b) and (c) also show the integrated D fluence.

Apart from sputtering, the carbon impurity ions impacting onto the tungsten target tiles can also be deposited or implanted and therefore cause long term surface modifications.

Samples from both the inner and outer divertor target area were analyzed by various ion beam techniques. The composition of the target surface was determined by X-ray Photoelectron Spectroscopy (XPS) and was found to consist apart from tungsten mainly of boron, carbon and oxygen with varying percentages (see tables in Fig. 3). Rutherford backscattering (RBS) was used to determine the depth distribution of tungsten within the deposited layers. Fig. 3 shows tungsten depth profiles from strike point samples of the inner divertor (a) and the outer divertor (b), respectively. At the inner target area, we find deposited layers of low-Z material with a thickness of up to several μm and with only a few percent of tungsten remaining at the surface. In contrast to this deposition pattern, erosion dominates the outer target area, where the fraction of tungsten was found to be close to the initial level.

Distinct shadowing effects from the tilted surface geometry of the tungsten tiles could be observed with both analysis methods. In particular, we find for the inner divertor that the layer in the plasma wetted zone of the tungsten tiles is significantly thicker than in the shaded area. The difference is, however, much less pronounced on the outer target plate. This can be explained by the dominance of deposition in the inner divertor, which leads to layer buildup roughly proportional to the

Element	B	C	N	O	W
	percentage				
inner divertor					
wetted	34	38	2	24	2
shadowed	10	76	0	12	2
outer divertor					
wetted	13	12	3	51	21
shadowed	11	9	0	55	25

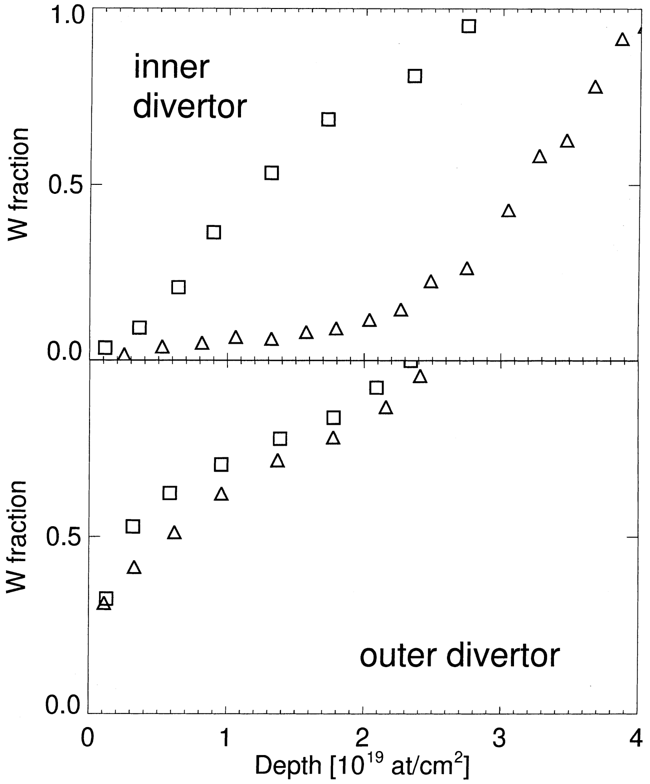

Fig. 3. Depth profiles of tungsten in the strike point area of inner and outer divertor measured by 2 MeV proton RBS. The RBS spectra were measured in both the plasma wetted zone (triangles) and in the shadowed region (squares) of the tilted tiles. Depth profiles were obtained from the spectra by assuming a mixture of tungsten and carbon to model the surface composition. The table shows the near-surface amounts of low-Z material and tungsten determined by XPS measurements.

incident particle flux. In contrast, the dominance of erosion in the outer divertor inhibits any formation of deposited layers.

4. Summary and outlook

To investigate the feasibility of tungsten in a divertor tokamak under reactor relevant conditions W coated divertor tiles were mounted in the ASDEX Upgrade tokamak. They consisted of a high-density plasma spray coating (500 μm) on fine grain graphite. During the experimental campaign these coatings were exposed to approximately 800 cycles with varying average heat fluxes up to 6 MW/m^2 for 2 s, and up to 5 s at lower power densities. The maximum surface temperatures reached 700°C.

After termination of the discharge period, cracks were detected on almost all tiles in accordance with the results found on similar tiles in electron beam tests. Due to stress concentration, toroidal cracks always started at the edge of the tile, which was exposed to the highest heat load, and propagated through the bulk of the graphite. The cracks observed in the poloidal orientation only extended throughout the coating and can be assumed to originate from the mismatch in thermal expansion of coating and substrate. At the interface between graphite and coating no carbide formation due to the thermal loading was found.

The erosion of tungsten was investigated directly by exposing thin film probes in the outer target area and by spectroscopic observations. The results agree with predictions using sputtering yields as obtained in laboratory ion beam experiments. For typical divertor plasma temperatures the tungsten erosion is mainly due to low-Z impurities.

After the experimental campaign a complete poloidal set of graphite tiles was analyzed. The graphite tiles from the main chamber show only very small amounts of deposited tungsten ($\leqslant 10^{15}$ W-atoms/cm^2); the tungsten deposition on the lower divertor plates is larger by at least one order of magnitude. The peak positions of the deposition coincide with the maxima of the plasma fluence to the target plates. Finally, the tungsten coatings at the inner target area were found to be covered by deposited layers of low-Z material with thicknesses in the μm range with a nonzero tungsten concentration on the surface. In contrast to this deposition pattern erosion dominates the outer target area, where the surface tungsten content was found to be unaltered compared to the initial surface composition.

For application on plasma facing components loaded with high particle and low heat fluxes, alternative tungsten coatings are being developed. They consist of tungsten applied by PVD with significantly lower thicknesses (below 5 μm). Emphasis is put on matching the thermal expansion of the graphite substrate and the coating in order to reduce crack formation. Additionally, for high heat flux components on the heat shield, W-coatings on carbon fiber reinforced graphite (CFC) substrate are currently under development. Due to the anisotropic thermal and mechanical properties of the CFC, the adhesion strength and thermomechanical performance of these coatings are expected to be reduced. Heat shield tiles of representative geometry (coated surface approximately 90×90 mm^2) are manufactured for each type of coating on different substrates. These specimens will be exposed to heat fluxes comparable to the power load conditions in ASDEX Upgrade in order to determine the damage threshold load and thermomechanical behavior of the composites. If the results prove the technical suitability for in-vessel installation, coating of parts or even of the complete heat shield of ASDEX Upgrade is envisaged.

References

[1] C. Garcia-Rosales, J. Nucl. Mater. 211 (1994) 202.

[2] D. Naujoks, K. Asmussen, M. Bessenrodt-Weberpals, S. Deschka, R. Dux et al., Nucl. Fusion 36 (1996) 671.

[3] R. Neu, K. Asmussen, K. Krieger, A. Thoma, H.-S. Bosch et al., Plasma Phys. Controlled Fusion 38 (1996) 165.

[4] S. Deschka, C. García-Rosales, W. Hohenauer, R. Duwe, E. Gauthier et al., J. Nucl. Mater 233–237 (1996) 645.

[5] C. García-Rosales, S. Deschka, W. Hohenauer, R. Duwe, E. Gauthier, et al., Nucl. Fusion Technology, accepted.

[6] M. Diotalevi, M. Febvre, P. Chappuis, in: Fusion Technology 1996, Proceedings of the 19th Symposium on Fusion Technology, vol. 1, 1996, North-Holland, Lisbon, pp. 491–494.

[7] A. Thoma, K. Asmussen, R. Dux, K. Krieger, A. Herrmann et al., Plasma Phys. Controlled Fusion 39 (1997) 1487.

[8] K. Krieger, J. Roth, A. Annen, W. Jacob, C.S. Pitcher et al., J. Nucl. Mater. 241–243 (1997) 684.

[9] W. Eckstein, C. García-Rosales, J. Roth, W. Ottenberger, Rep.IPP 8/82, Max-Planck-Institut für Plasmaphysik Garching, 1993.

[10] K. Krieger, H. Maier, V. Rohde, M. Balden, D. Coster et al., in: M. Schittenhelm, R. Bartiromo, F. Wagner (Eds.), Europhysics Conference Abstracts, Proceedings of the 24th EPS Conference on Controlled Fusion and Plasma Physics Berchtesgaden 1997, vol. 21A, part IV, 1997, EPS, Geneva, pp. 1421–1424.

[11] P. Franzen, H. Maier, D. Schleußner, R. Behrisch, M. Balden et al., in: M. Schittenhelm, R. Bartiromo, F. Wagner (Eds.), Europhysics Conference Abstracts, Proceedings of the 24th EPS Conference on Controlled Fusion and Plasma Physics Berchtesgaden 1997, vol. 21A, part IV, 1997, EPS, Geneva, pp. 1429–1432.