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Journal of Nuclear Materials 337–339 (2005) 1019–1023

journal of nuclear materials

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Modification of tungsten layers by arcing

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Abstract

Numerous traces of arcs have been found on W-covered graphite tiles of ASDEX Upgrade after exposure. The distributions of number density, lengths and orientation are calculated and compared to pure graphite tiles at comparable locations. It was established that arcs perforate a 1 μm tungsten layer down to the carbon substrate. The amount of removal should rise with arc current, but a surface fraction of about 8% is eroded at 10 A already. At tiles of the divertor baffle the layer is continuously removed along the entire track pointing to higher currents. The carbon of the stripped parts is subject to subsequent erosion processes. The distribution of materials in and around arc tracks was investigated by sputter depth profiling (SIMS and AES) and the characteristic geometry was studied using an electron microscope. Observations are interpreted using results from laboratory vacuum arcs on the same material.

PACS: 52.80.Mg; 52.80.Vp; 52.40.Hf; 52.55.Fa
Keywords: Arcing; Erosion/Deposition; Tungsten-coated carbon; Wall materials

1. Introduction

Arcs embedded in the scrape-off layer (SOL) of fusion plasmas belong to the most interesting physics phenomena of plasma–surface interaction (e.g. [1]). Arcs are confirmed post mortem by the remnants of the cathode spot on the solid surfaces. Cathode spots are μm regions where currents with densities of about 10^{11} A/m^2 cross between plasma and solid and explosive melting and evaporation takes place as the elementary step of the non-linear and non-stationary process of arc burning. In an external magnetic field arcs move into the non-Amperian direction (called retrograde motion [2]), that can be modified further by the Robson drift if the field is inclined to the surface [3,4]. Arc tracks are common to all plasma facing materials [5–7]. The observed strong analogy between tracks on plasma facing components and traces on cathodes of vacuum arc discharges confirms that the cathodic processes are fully determined by the self-produced arc plasma. Relying on this analogy, results from laboratory vacuum arcs can be used to interpret arc tracks found on plasma-facing

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doi:10.1016/j.jnucmat.2004.10.056

components made of the same material. Arcs as an important source of impurities in the SOL have been ruled out for calm stationary scenarios. Unfortunately, two new facts seem to invoke new discussions of arcing phenomena: (i) high-confinement scenarios (H modes) in contemporary tokamaks show systematic MHD instabilities at the edge (ELMs) as a basic ingredient, and (ii) the application of layered materials for plasma facing components rises the problem of coverage of the substrate instead of the overall erosion rate.

2. Observations on plasma facing components

Inspecting the tokamak ASDEX Upgrade (IPP Garching) numerous arc tracks have been identified by naked eye at several locations in the machine (Fig. 1). One of the favoured places are plates of the so-called divertor baffles (Fig. 2). As part of the tungsten program in ASDEX Upgrade (see [8,9]) some of these graphite tiles have been coated by a 1 μm W layer.

Using digital images most tracks could be identified and statistical information about the average track density (Fig. 3) and the distributions of track lengths and track angles (Fig. 4(a) and (b)) was obtained. To compare with tiles made from pure graphite, the same statistics was carried out for a comparable set of divertor baffle tiles situated at exactly the same poloidal positions but toroidally adjacent. The number of tracks found on graphite was about 10–15% lower than on the tungsten coated tiles. The distribution of the track lengths follows an exponential law, thereby defining a characteristic length that is 12 and 6.3 mm for the two different W-covered tiles, respectively, and 8.1 and 5.6 mm for the pure graphite tiles. The vast majority of the tracks are strait lines and their orientation can be described by the angle between the track and the plane of the poloidal cross-section. The total magnetic field is almost parallel to the surfaces of all tiles so that the arcs move generally in the poloidal direction. The observed distributions of track angles have well-pronounced single maxima. Differences in the mean angle between tiles at different positions can be due to different orientation with respect to the magnetic field. Investigations of the tile surface with an electron microscope revealed that a typical arc track erodes the 1 μm W layer on its full length (Fig. 5). Comparing EDX spectra taken at the bottom of the track with those from the surrounding undisturbed layer demonstrates that the layer is removed completely and the graphite substrate is exposed (Fig. 6). At the rims of the track clean W surfaces are seen (without a C overlayer) demonstrating that some fraction of the removed tungsten stays very locally building up banks along the track.

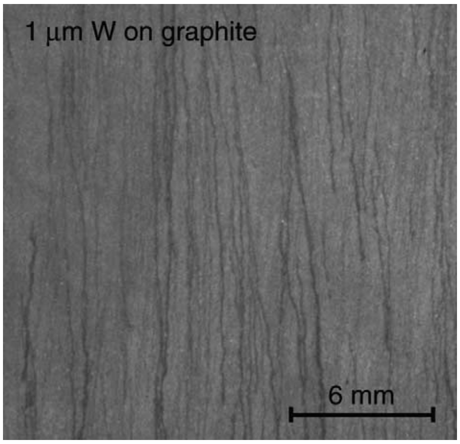

Fig. 1. Arc tracks on a lower W-coated (1 μm) tile of the divertor baffle of ASDEX Upgrade.

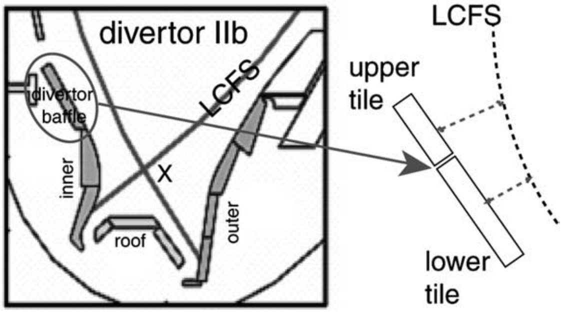

Fig. 2. Left: schematic poloidal cross-section of the divertor IIb of ASDEX Upgrade. Right: upper and lower tiles of the divertor baffle together with a typical last closed flux surface (LCFS).

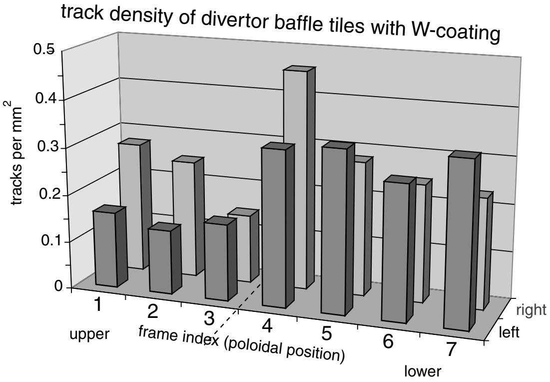

Fig. 3. Density of arc tracks found by analysing a left and a right column of three and four digital images for upper and lower W-coated tiles, respectively.

3. Laboratory experiments

Bipolar vacuum arcs were ignited between a Mo wire as anode and a W-coated sample as cathode in a labora-

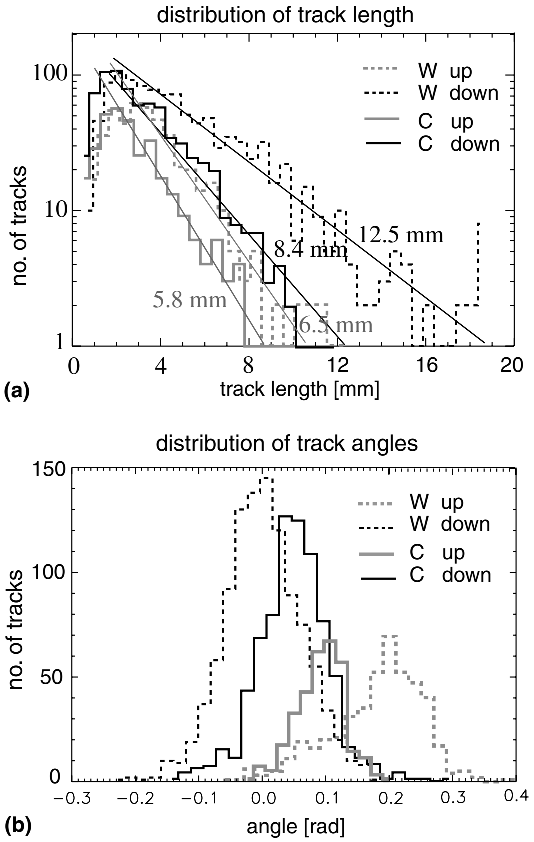

Fig. 4. Distribution of (a): track lengths (b): track angles with respect to the poloidal plane for upper and lower tiles of pure and W-coated graphite.

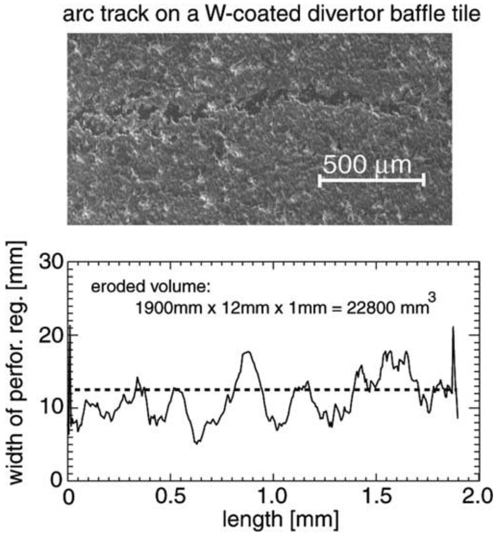

Fig. 5. Example of an arc track at a divertor baffle tile together with the variation of the track width along the track.

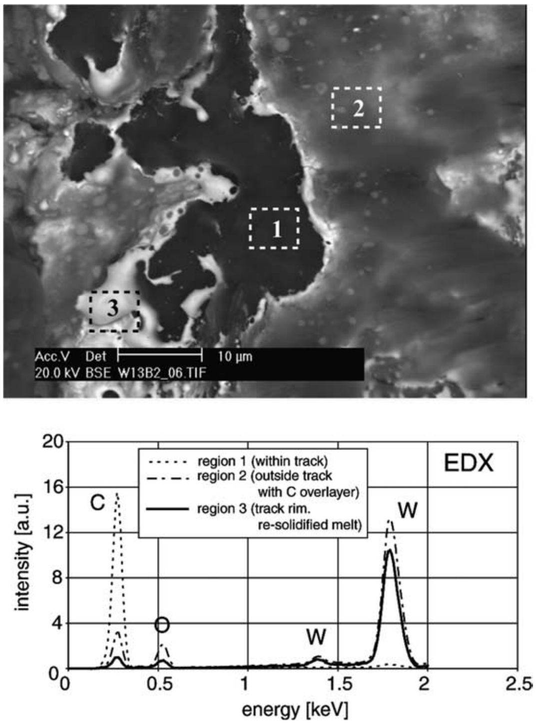

Fig. 6. Eroded region from an arc track at a baffle tile (regions of EDX analysis are indicated) together with the EDX spectra.

tory vessel under UHV conditions (no plasma) applying 0.4T externally parallel to the sample surface. The capacitor bank had 400 µs time constant and allowed arc currents up to 15A [10]. Using frame series of a high-speed camera an arc velocity of 290 m/s was estimated. The arc tracks consist of scattered holes perforating the W layer locally and the degree of perforation of the layer was found to vary along a bundle of laboratory arcs. The fraction of the area perforated was about 8% at a current of about 10A. Through the perforation substrate carbon was available to all erosion processes. This is demonstrated by sputtering experiments in the track region exhibiting a carbon enrichment throughout the layer as compared to regions without arcs (Fig. 7). Combining the sputter rates for pure W and C with the observed W flux in the virgin layer and the C-flux deep in the substrate a coverage of 4% was estimated. To investigate the transport of the eroded tungsten a chain of depth profiles perpendicular to the arc track bundle was laid out. In the depth profiles a re-deposited layer was clearly silhouetted against the underlaying W layer by its peaking C content. The accompanied re-deposited W content is also detectable but small. An uncertain determination of the transition from the re-deposited to the W layer will result in a large systematic background in re-deposited W but will have only minor consequences for the determination of re-deposited C. For

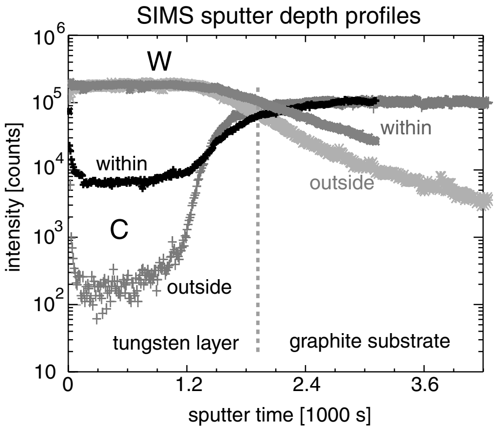

Fig. 7. SIMS sputter profiles of W and C for two locations on a W-coated graphite sample used in laboratory experiments. One location was within an arc track the other one outside.

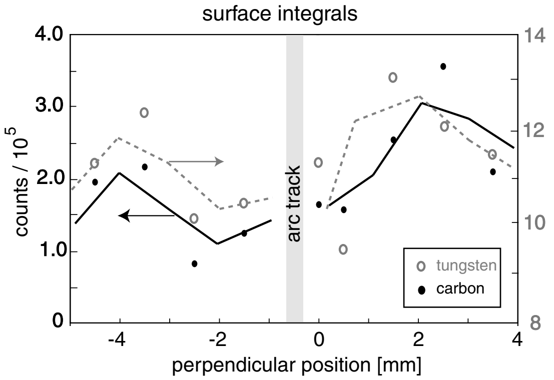

Fig. 8. Profiles of the W and the C content in the surface peak of SIMS sputter depth profiles perpendicular to a track bundle on a W-coated graphite sample used in laboratory experiments.

both elements an enhanced deposition was observed at a distance of about 3mm to both sides of the track (Fig. 8).

4. Discussion and conclusions

Arcs burning on W-coated graphite PFCs perforate this layer down to the substrate and expose the graphite to all subsequent erosion processes. In laboratory SIMS profiling the constant contribution of carbon to the sputtered flux throughout the depth of the W layer is within a factor two given by taking the fraction of holes in the exposed surface as a graphite surface part (see Fig. 7). Even small currents like 10A are sufficient to perforate the 1 μm layer (the minimum current is approximately 8A) and currents of several 10–100A are estimated for the continuously perforated tracks on the divertor baffle tiles. The number of tracks is higher for tiles closer to the LCFS (the lower tiles, see Fig. 2). Comparing W coated and pure graphite tiles the different exposure times in the machine, different detectabilities on different material, and systematic errors must be taken into account. Although staying for two campaigns in the machine the number of tracks on the pure graphite was about 15% lower than numbers on W-coated tiles exposed for one campaign. Hence the difference in ignition rate is about a factor of two not more. From the characteristic length of the arc tracks a lifetime of the arc can be deduced using the arc velocity from the laboratory. This is reasonable because the velocity is a property of the cathode spot producing its own very dense and cold plasma almost independent of any embedding plasma and because the known saturation of the velocity with rising magnetic field is almost reached at 0.4T (see [11]). Arcing on the lower W-coated tile took typically 45 μs, on the upper 23 μs, slightly longer than the 30 and 20 μs for the respective tiles consisting of pure graphite. This shows that arcs on tiles closer to the plasma are not only more numerous but also burn longer. From the single-peaked distributions of the track angles it can be concluded that during the arc lifetime no fast changes of the direction of the local magnetic field happened and that most arcs belong to the same phase of the discharge (for other possibilities see [12]). The small poloidal component of the field vector results in a deviation that is different for tiles having different orientation. But the fact that differences in mean angles on upper and lower tiles are larger for the W-covered tiles indicates a contribution of the Robson drift (the relation between Robson drift angle and field inclination depends on material). Combining track numbers, lengths, and widths and assuming a complete removal of the 1 μm layer it was calculated that a volume of about 1/3 mm^3 of tungsten was eroded by arcing at the two baffle tiles during one campaign. But from the analysis of the deposition layer in the neighbourhood (see Fig. 8) of the tracks in laboratory experiments it can be estimated that in the absence of an embedding plasma most of the eroded tungsten would be re-deposited on the same tile. Of course the rather poor accuracy of those estimates allows for a small difference amount that can escape to the plasma. Depth profiles from the neighbourhood of tracks on divertor baffle tiles do not add up to such a clear picture but point to a strong influence of the embedding SOL plasma on transport and re-deposition of W. A comparison of the amounts of W eroded by arcing and sputtering will be done if the necessary data are available.

Acknowledgment

The authors thank the ASDEX Upgrade team for providing the divertor baffle tiles.

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