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Arcing at B_4C-covered limiters exposed to a SOL-plasma

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Abstract

Plasma sprayed B_4C-layers considered as wall coatings for the W7X stellarator have been studied during and after exposure to TEXTOR and after arcing experiments in vacuum. Arcing through the B_4C layer occurred favoured by high power fluxes and not restricted to less stable phases. But this arcing implies an especially noisy scrape-off layer (SOL). Instead of moving retrograde in the external magnetic field, the arc spot on the B_4C-layer sticks to the same location for its whole lifetime. Consequently, the arc erodes the entire B_4C layer, finally burning down to the Cu substrate. In the neighbourhood of craters the surface contains Cu originating from those craters. This material, hauled to the surface by the arc, is subject to subsequent erosion, transport, and redeposition by the SOL-plasma. The behaviour of arcs on B_4C is most probably caused by the peculiar temperature dependences of the electrical and heat conductivity of B_4C.

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Keywords: Scrape-off layer; Plasma facing materials; Boron carbide; Arcing; Erosion/deposition; Limiter

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1. Introduction

To passivate the plasma facing surfaces of the actively cooled steel segments building up the first wall of the W7X stellarator a plasma sprayed B_4C-layer of about 170 μm thickness is proposed [1]. This very hard low-*z* ceramics material has a high melting temperature, stands substantial power fluxes and shows low physical and almost no chemical sputtering [2]. But for a successful application as a wall-material in a fusion device mechanical and power-deposition tests [3,4] have to be supplemented by the exposure of mock-ups to relevant plasmas.

B_4C is a rather sophisticated material with an electrical resistivity that decreases with increasing temperature. Hence, the behaviour of B_4C in contact with the near-wall plasma in a fusion device is difficult to forecast. This makes test exposures desirable, too.

Massive B_4C as a limiter material has already been tested with little satisfaction [5]. Also an attempt has been made to investigate if massive B_4C-limiters can offer an effective way of permanent in situ boronization, but this has been proven insufficient [6]. In a few cases B_4C-layers on limiters and divertor plates have also been used temporarily [7,8].

2. Exposure experiments

Using the limiter-locks installed at TEXTOR a number of B_4C covered massive Cu-limiters have been

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consecutively exposed to the scrape-off layer (SOL) plasma generally defined by the toroidal ALT-II main limiter. The additional limiters had either semi-spherical or desk-roof shape and carried a B_4C-layer of about 150 μm thickness. They could be put to variable radial positions ($r = 475$–455 mm), even to those comparable to or slightly inside the radius of the ALT-II belt limiter ($r = 460$ mm). After a typical exposure campaign lasting for about 50 discharges the limiter was retracted and taken out for ex situ inspection of the B_4C surface. During few exposures the limiter surface has been extensively diagnosed in situ by optical methods and the integral current flowing from the limiter to the wall of the machine was measured with a time resolution ≈1 ms. Almost the entire limiter was observed optically by a far-distance microscope. A fast (100 μs) IR-diode and a slower (1 ms) pyrometer signal were used to deduce the power flux to the foremost limiter part. A side-view of the limiter silhouette was taken in the light of the BII-line (412 nm) by a CCD-camera.

The discharges had line-averaged central densities between 2 and 6×10^{19} m^{-3}, the plasma current was 340 kA and the toroidal magnetic field 2.25 T. Auxiliary heating power of up to 2.9 MW was injected by neutral beams.

Analysis methods of the limiter surface after exposure included optical and electron microscopy, EDX, SIMS, AES, RBS, PIXE, as well as laser profilometry and metallographic techniques. To study the behaviour of arc type discharges laboratory experiments with vacuum arcs in magnetic fields have been supplemented (B_4C covered Cu-cathode, Mo anode, 0.4 T).

3. Results and discussion

Numerous light spots with extensions of about 100–200 μm were spread over the limiter surface during exposure to TEXTOR discharges as revealed by the far-distance microscope (Fig. 1).

The spots stuck to fixed locations and some of them existed throughout the whole discharge (≈5 s). Generally, the number of spots was larger if the power deposited onto the limiter was larger. It is worth mentioning that even for a quite low power flux of 200 kW/m^2 (which compares to the design value for the first wall of W7X) the spots did not vanish completely, although their number was diminished. There have been several examples of spots that kindled at locations on the surface where spots burned already in previous discharges.

Time series of the current from the whole limiter and the integral IR-emission both showed large fluctuations during shots characterised by numerous light spots (Fig. 2) whereas they stayed calm in shots where spots were rare. Although, during one individual discharge, periods with few or many spots did not clearly correspond to less or more spiky currents, respectively.

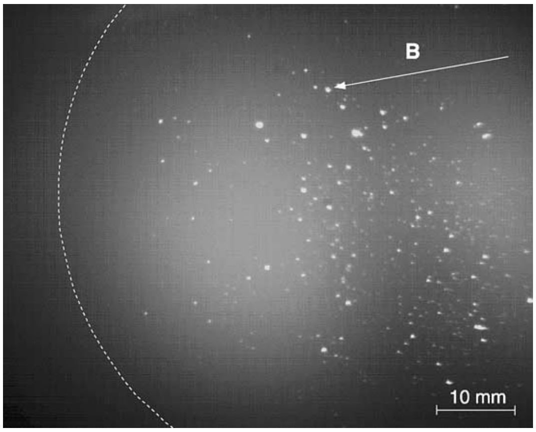

Fig. 1. Light spots distributed over the B_4C-covered surface of the semi-spherical limiter ($r = 455$ mm) in TEXTOR shot #91191 after $t = 1.72$ s observed by the far-distance microscope (cut-out sector covering about 70% of the surface, exposure time 50 ms, spatial resolution 50 μm).

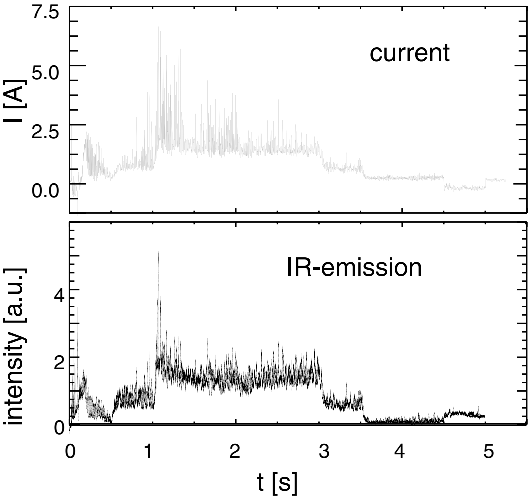

Fig. 2. Temporal evolutions of the integrated current flowing from the limiter to the liner (top) and the spatially integrated IR-emission from the limiter observed by a fast diode (bottom) during TEXTOR shot #91214.

The inspection of the limiter surface after exposure revealed the creation of a number of remarkable localised erosion craters on the B_4C-surface consisting of cylindrical holes of 25–150 μm diameter surrounded by bulges of obviously re-solidified melt and equipped with short appendixes in the form of a furrow (Fig. 3).

Some of the larger crater locations could be clearly related to bright light spots that appeared in the course of past discharges so that arcing suggests itself as the

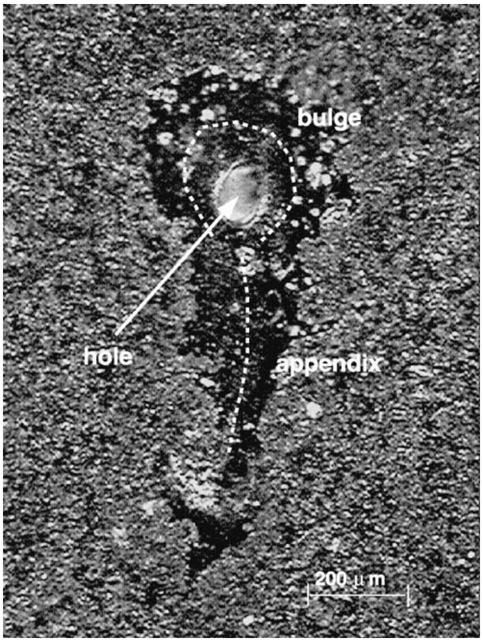

Fig. 3. Crater on the B_4C-covered limiter surface consisting of the cylindrical crater hole (∅ ≈ 100 µm) surrounded by a bulge of re-solidified molten material and equipped with an furrow-like appendix (length ≈ 0.5 mm).

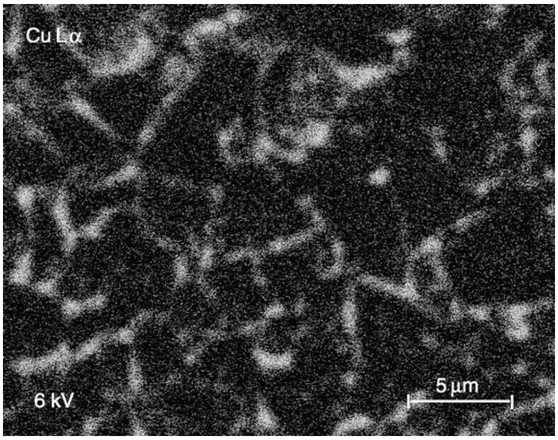

Fig. 4. SEM (EDX)-picture of a segment of the crater bulge using the intensity of the Lα-line of Cu (beam electron energy reduced to 6 keV for improvement of the lateral resolution).

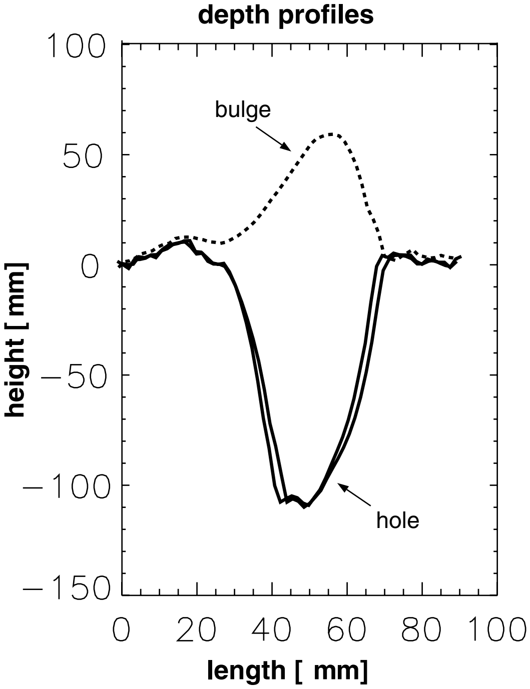

Fig. 5. Line-profiles across a crater on the desk-roof limiter from a laser profilometer.

natural explanation of the phenomenon. However, the absence of the expected characteristic retrograde motion of the arc spot in the external magnetic field as well as the peculiar geometry of the craters required further investigation (for general arc behaviour see [9]). The crater hole is an almost perfect cylinder extending down to the substrate exposing the Cu-metal at its bottom. The inner mantel of the hole as well as the bulge at the surface consist of re-crystallized B_4C containing about 5–8 at.% Cu that was pushed off the crystals into the grain-boundaries creating a metallic network (Fig. 4).

Laser profiles of typical large craters confirmed that they are deep holes and demonstrated clearly that not all of the material ejected from the hole was re-collected in the bulge (Fig. 5). Consequently, Cu could be identified as a contribution to the deposition layer covering the immediate neighbourhood of the crater (Fig. 6). PIXE analysis along lines on the limiter surface (Fig. 7) as well as SIMS depth profiles distributed over the crater surroundings (Fig. 8) identify the craters to be an essential source of Cu.

To pin-down the arc-nature of the phenomenon laboratory arcing experiments have been carried out in vacuum on samples of the same material (170 µm B_4C on Cu) in an external magnetic field of 0.4 T. They demonstrated that motionless cathode spots leaving behind deep cylindrical holes reaching onto the substrate are the typical habits of arcs on B_4C-layers. Additionally, these experiments showed that the arc current was exceptionally calm as compared to arcing on metals. Taking into account that the erosion of a large amount of B_4C took place at the beginning of an arc event, the coincidence of a localised BII-line emission on the limiter surface with spikes appearing on the limiter current signal relates current-peaks to early stages of the arc

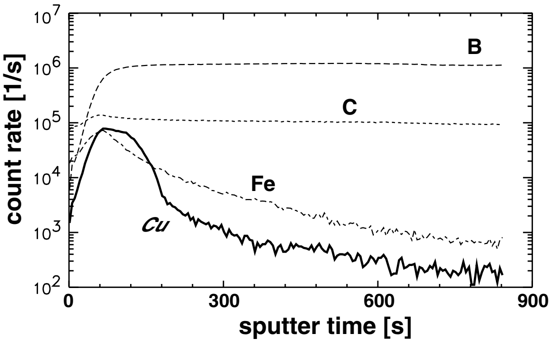

Fig. 6. SIMS depth-profile of the layer re-deposited in the neighbourhood of a crater region (10 keV O_2^+-beam of 100 nA).

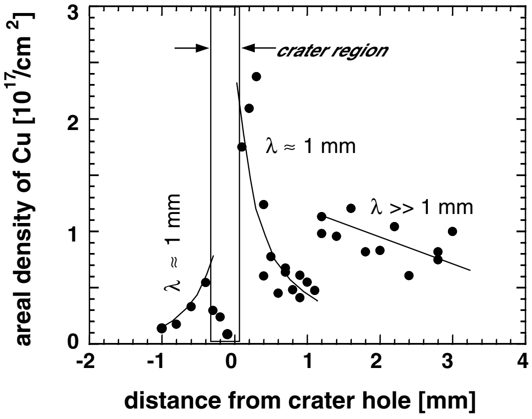

Fig. 8. Areal density of Cu along a line crossing a crater obtained by integrating SIMS depth profiles (calibrated for PIXE and AES results).

event. Consequently, the arc events on the limiter are thought to consist of an early bipolar phase, where the current flows mainly along magnetic field lines across the surrounding SOL-plasma, later falling into an unipolar phase with a current path that closes in the neighbourhood of the crater on the limiter itself. From the unexpectedly good correlation (>90%) between the current signal and both the fast IR-diode and the pyrometer measurements can be concluded that at least the early (bipolar) phase has a global influence on the limiter as a whole. Fast observations of plasma parameters in the SOL away from the limiter added the fact that the SOL-plasma was noisy as long as the B_4C-covered limiter was exposed and arcing occurred at its surface [10].

One important consequence of the melting and re-solidification of the plasma-sprayed B_4C as well as the intruding substrate-Cu was the change of the electrical resistivity of the surface with respect to the substrate. Using an exfoliated flake from the layer it was found experimentally that the resistivity is by a factor of 200 higher than that for massive bulk B_4C. This factor was gained in conductivity if, as e.g. for the crater appendix, the sprayed layer melted and re-solidified as bulk B_4C. Conductivity was improved further by incorporating substrate Cu forming a percolatively conducting network. The measured resistivities differed remarkably: 2–3 kΩ in the appendix and 200 Ω to 1 kΩ on the bulge compared with 40–160 kΩ far away from the crater. This irreversible change of layer properties in the vicinity of a crater will be of course experienced by every future plasma coming in contact with the limiter surface.

4. Conclusions and consequences

Light spots occurring at the surface of a B_4C-covered limiter during a tokamak discharge and craters eroded through that covering layer are due to arcing. Peculiarities of the arcing process on B_4C is caused mainly by the temperature dependence of thermal and electrical conductivities as will be discussed elsewhere [11]. The observation of the limiter current and the IR-emission from the limiter shows that this arcing has global effects on the limiter influencing the surrounding plasma locally. But, as additional observations far away from the

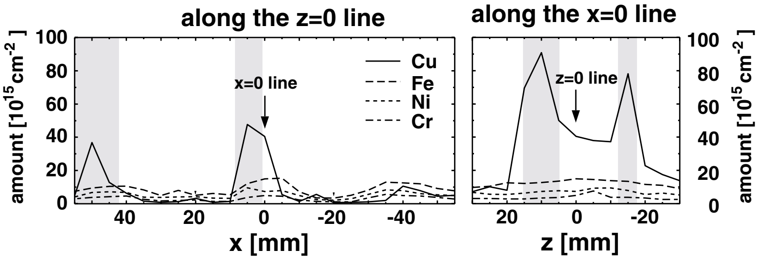

Fig. 7. Line-scans of the areal densities of metals along poloidal as well as toroidal lines on the limiter surface measured with PIXE (1.5 MeV proton beam, lateral resolution 5 mm). Locations of nearby craters are indicated by grey shadows.

limiter show, bipolar phases of the arcs life act also on the plasma further away making a noisy SOL. As a proof can be taken that a sufficiently large destruction of the B_4C-layer calms the SOL and the IR-emission down completely [10].

The second major problem introduced by the arcs is the local erosion of substrate material in the crater holes and its subsequent transport and re-deposition on the surface surrounding the crater. This material, generally supposed to be covered from plasma influences by the layer, is now available for further erosion processes. Copper concentrations found on the surface after multi-shot exposures are of course the result of a dynamical balance of deposition and re-erosion processes. Consequently, the Cu amount found around the craters on investigated limiters is about a factor of 2.5 lower than that observed at samples from laboratory arcing without any embedding and eroding plasma.

The irreversible changes of the conductivity of the layer in the neighbourhood of craters explain the observed re-ignition of arcs at locations of former arcing. On the one hand the erosion of a given site is prolonged in subsequent discharges but, on the other hand, the number of newly developed crater locations is possibly restricted. Generally it seems desirable to improve the conductivity of the plasma sprayed layer to reduce the arc-ignition probability.

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