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First tests of plasma sprayed tungsten specimens in CASTOR tokamak discharges

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Introduction

Selection of a wall surface material is an important design issue for tokamaks and other fusion devices. Plasma-sprayed coatings are among the candidates, but a knowledge base of their behaviour in high-temperature tokamak plasmas is limited. Namely, the use of plasma-sprayed tungsten-based coatings in a divertor leg of ITER comes into cosideration [1]. The tungsten erosion and redeposition was studied empirically in the ASDEX Upgrade tokamak using tungsten coated divertor tiles [2], and quantitatively by numerical simulations [3]. A different approach to coating studies will be introduced in this paper. Several different plasma-sprayed tungsten-based specimens have been manufactured at IPP Prague. They were tested under high heat fluxes by electron beam at Forschungszentrum Juelich and in small-size tokamak CASTOR plasmas at IPP Prague.

Experimental setup

Three types of specimens were prepared for the tests: plasma sprayed pure tungsten and copper-tungsten composites on copper substrates, and bulk tungsten. The plasma sprayed specimens were produced by the WSP 500 water stabilized plasma torch developed at IPP Prague [4]. In plasma spraying, the starting materials (in powder form) are introduced to the plasma jet that melts and propels them towards a substrate, where they impact, flatten and solidify, thereby forming the coating. In our case, the following powders were used: pure tungsten, and copper-coated tungsten, both with size range 100-125 μm. The coatings were applied on the convex surface of a cylindrical substrate made of copper (thickness 3 mm, outer diameter 23 mm). The following spraying parameters were used: feeding distance 60 and 70 mm, spraying distance 250 and 350 mm, carrier gas helium and nitrogen, coating thickness 0.4 mm and 2 mm for the W and W+Cu coatings, respectively.

Selected tungsten coatings were tested under high heat fluxes (up to 1 GW/m^2) at the electron beam facility JUDITH at FZJ, to simulate disruption conditions, which are not achievable at the CASTOR tokamak. The observed phenomena were the removal of oxide scale at low incident energies, surface melting at intermediate, and deep melting at high energies. The coatings were able to absorb about 0.5 GW/m^2 (2.5 MJ/m^2) in thermal shock loading without significant damage [5].

A special movable holder for two specimens allowing the change of the insertion depth on a shot to shot basis at CASTOR has been constructed. One (reference specimen) was hidden in a diagnostic port; the second one was moved into plasma from the top up to a radius r~a/3, what is deeply inside LCFS, and exposed during the L-mode CASTOR tokamak discharge ($R=40$ cm, $a=8.5$ cm, $B_T=1.4$ T, $I_p=10$ kA, $n_e\sim10^{19}$ m^{-3}, $T_e\sim200$ eV, $P_{OH}\sim30$ kW, $\tau_p\sim1$ ms, discharge length ~30 ms).

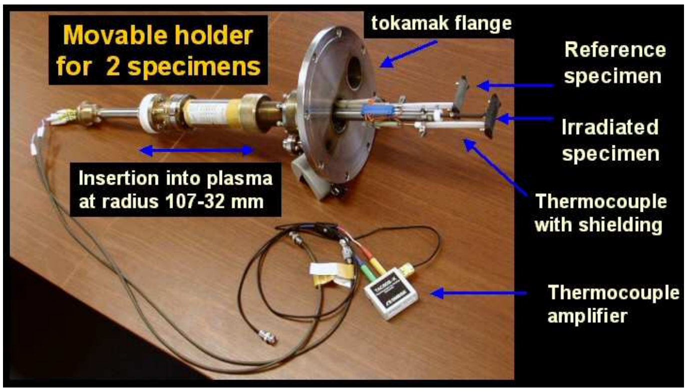

Fig.1 Movable holder for two specimens, designed for CASTOR, is electrically insulated from the flange, and physically connected to the vacuum chamber. Thermocouples monitor the temperature changes of the specimens. Specimens can be moved from the top into a tokamak chamber.

Main plasma parameters were observed simultaneously with impurity line radiation [6] measured by the imaging VUV Seya-Namioka spectrometer (50-200 nm, $\Delta\lambda\sim0.5$ nm in the first order, spatially resolved with $\Delta r\sim2$ mm; if slow CCD camera with 1 frame/s is used, time integrated over the whole discharge duration) and XUV monochromator (C V 4.03 nm, spatially and temporally resolved with $\Delta r\sim5$ mm, $\Delta t\sim200$ µs). For a single experiment with the plasma sprayed pure tungsten specimens, the fast CMOS camera monitored the output of VUV spectrometer with the temporal resolution of 1000 frames/s. The XUV monochromator was also used to check a radial position of a plasma hot core. The tungsten target was positioned in the VUV spectrometer field of view in all experiments.

Results and observations

Specimens were irradiated in CASTOR for about 30-50 shots, i.e. the total exposition was ~1s. The influence of different insertion depth on main plasma parameters changes was studied and the critical radius of insertion was estimated ($r_{crit}\sim55$ mm). At this radius $n_e\sim2*10^{18}$ m^{-3}, $T_e\sim20$ eV, what was measured by Langmuir probes. No significant changes of tokamak discharge and its radiation could be seen for $r>r_{crit}$, excluding only a local shielding effect of specimens visible by the VUV spectrometer. XUV observations confirm that feature, namely the vertical position of C V line radiation maximum (strongly centered in CASTOR) and its profile were preserved (from –40 mm to +40 mm). Deeper insertion of W+Cu specimen led to discharge disruption. Nevertheless, pure plasma sprayed W specimens could be moved deeper up to radius ~32 mm. Plasma current was partially absorbed by a tungsten surface, what was accompanied by line averaged electron density increase. The spatial chord-integrated profiles of VUV line radiation clearly show shielding effect (radiance decrease at the specimen position), and radiance increase in front of the specimen as a result of particle bombardment, ion recombination and re-emission from a solid surface.

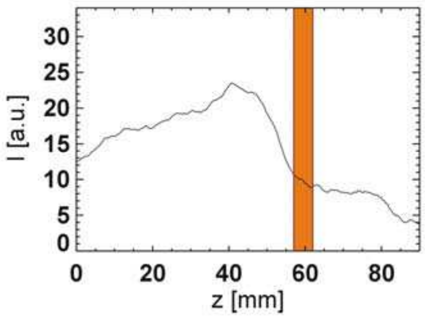

Fig.2 Radial dependence of chord-integrated intensity of H I 121.6 nm line. Plasma sprayed W specimen is located at radius of 57 mm, its width is 5 mm.

The specimen temperature increases of 0.5-1.5 K/shot corresponding to energy deposition 10-30 J/shot were measured. Heating was surprisingly slow with characteristic time 15 s. Cooling decay time of order of 40 min given mainly by thermal radiation and tokamak vacuum (10^{-3} Pa) conduction was estimated (against 15 min on air).

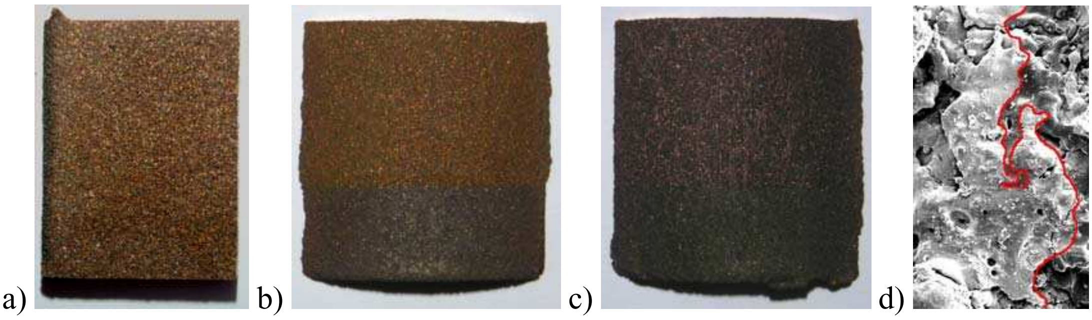

Fig.3 Plasma sprayed W(10%)+Cu(90%) specimens a) after spraying, and after removal from vacuum chamber – b) reference specimen originally located in a diagnostic port, and c) irradiated specimen. A lower part of specimens b) and c) was modified afterwards with respect to following surface tests. d) detail of the irradiated W surface (SEM image, 500x zoom), showing the smooth metallic surface of the bright “branch” on the right.

After specimen removal from the vacuum vessel, a strong surface oxidation resulting in a surface color change was observed in a few minutes. The most visible effects were seen on the surface of W+Cu specimens. It led to a green shade of original color on the reference specimen, and black violet shades of original color of the irradiated specimen. In the case of pure W plasma sprayed specimens, the oxidation processes were not so strong, however, black blue tint of the irradiated specimen could be seen. Small bright “branches”, nearly perpendicular to I_p direction, were observed on all irradiated plasma sprayed specimens.

Afterwards, the specimens were cut into electron (opposite to I_p direction) and ion (in I_p direction) sides and a central part. On all parts, compositional changes were measured by Rutherford Backscattering Spectrometry (RBS) and Elastic Recoil Detection Analysis (ERDA) at Institute of Nuclear Physics in Rez. Results for pure W coating show hydrogen implantation into the surface for both inserted specimens. Nevertheless, content of oxygen decreases for irradiated one. Carbon content shows no clear trend.

Surfaces were also imaged by scanning electron microscopy (SEM). No traces of deep erosion or local melting were observed. However, few isolated microscopic surface holes and cracks on the irradiated W+Cu specimen were detected.

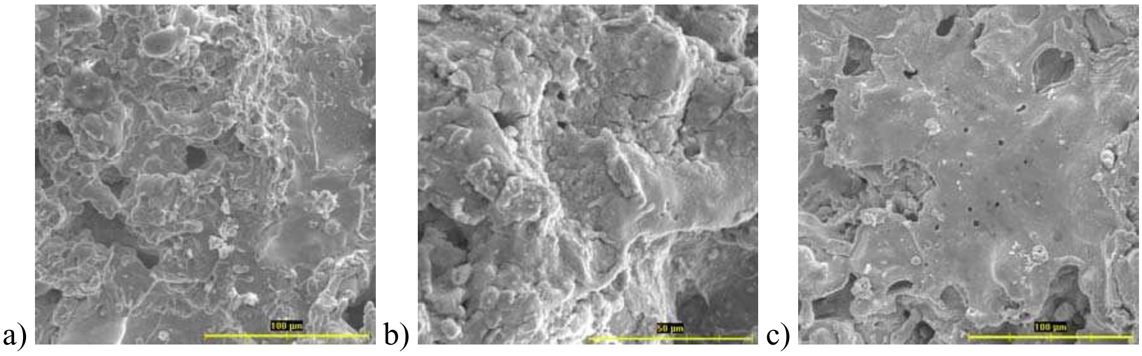

Fig.4 Plasma sprayed W+Cu specimens imaged by SEM a) after spraying, b) reference specimen hidden in a diagnostic port, c) irradiated specimen.

Conclusion

The pure tungsten specimens can be used in high-temperature tokamak plasmas up to T_e~ 20 eV, where high power local events (more than 0.5 GW/m^2) are not present. Only traces of tungsten emission in UV range were seen at CASTOR, therefore, tungsten biasing experiments are planned and visible spectroscopy above 400 nm (W I lines) will be used.

Acknowledgement

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