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Behaviour of a tungsten coated molybdenum poloidal limiter in FTU tokamak

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Abstract

A tungsten coated molybdenum poloidal limiter has been tested in the FTU tokamak. The evidence of no deterioration of macroscopic plasma parameters in standard sawtooth discharges, with respect to other medium and high Z materials, has been confirmed by post-mortem analysis of the limiter. Negligible traces of erosion by sputtering or thermal loads were found in the limiter regions not interested by abnormal events. A large part of the macroscopic damages around the outer and inner equatorial plane is believed to be caused by runaway electron fluxes during disrupting discharges.

Keywords: FTU; Limiter; High Z wall material; Physical erosion

1. Introduction

Tungsten is presently one of the candidate material for high heat flux plasma facing components to be employed in the ITER divertor. Despite the very low high Z impurity concentration allowed in the plasma core of a fusion reactor, tungsten is one of the most attractive materials because of the negligible erosion by plasma neutrals and ions at the low electron temperature expected in ITER divertor, resulting in a very long component life-time as compared to any other material considered [1]. The experimentally confirmed high probability of prompt redeposition [2] further reduces the net erosion of tungsten components. Moreover the very low rate of evaporation allows high operating temperature, eventually limited by the onset of thermoelectron emission.

The main drawback of tungsten is its brittleness even at high temperature (the ductile–brittle transition temperature DBTT ranges between 373 and 673 K), which make machining and welding difficult and thermal shock resistance rather poor. Therefore, in addition to the bulk material, tungsten coatings have been considered, which moreover allow "in situ" repairs to be carried out [3].

In this work the performance of a tungsten coated molybdenum (TZM) poloidal limiter in the FTU tokamak is analyzed with emphasis on the behaviour of the material with respect to erosion and microstructural modifications.

2. Experimental

In the summer of 1994, just before the beginning of the long shutdown during which a molybdenum (TZM) full toroidal limiter [4] was going to be mounted on the inboard side of the FTU vacuum chamber, a tungsten poloidal limiter was tested within an experimental program devoted to the study of plasma performance with different limiter materials (Si, Ni, Mo and W) [5].

As usual, the limiter consisted of two halves, an inner and an outer one (at the same toroidal location), poloidally covering about 150° and 90° degrees respectively. Each half consisted of a massive stainless steel/inconel (inner/outer) structure supporting tungsten coated TZM mushroom shaped tiles. Tungsten coatings with a thickness of 2 mm were prepared by vacuum plasma spray (VPS) at Metallwerke Plansee, Austria (Fig. 1). The coating declared density was 92% of the theoretical one and the main impurities of the feedstock powder were molybdenum and oxygen (600 and 350 ppm by weight). The substrate temperature during coating deposition was in the range of

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Fig. 1. Etched cross-section of a tungsten coated TZM mushroom of the inner half of the FTU limiter. Melted region on the top and the drilled hole (the last part, 1 mm radius, is no longer visible, owing to the polishing) for thermocouple insertion can be observed.

1000–1200°C. The thickness of TZM substrate ranged from 1 to 3 cm, depending on the mushroom size, the smallest and largest diameter being 3.4 and 6 cm, respectively.

The limiter operated for about 120 plasma discharges, with 2/3 of them ending in a disruption, often associated with high hard X-ray and neutron signals. Plasma current, electron density and toroidal field varied between 0.4 and 0.7 MA, 0.5 and $2.5 \cdot 10^{20}$ m^{-3} and 3 and 6 T respectively, deuterium being the working gas. The limiter temperature at the discharge onset was always well below the DBTT, as a result of the FTU cryogenicity and a low duty cycle.

At the end of the experimental campaign, the limiter was removed from the vacuum vessel and analyzed by several techniques, including profilometry, optical metallography, SEM, EDX and activation measurements. To the purpose of comparison, an 'as received' coated mushroom not employed in FTU was analyzed too.

3. Results and discussion

The discharge integrated energy load on the limiter was monitored by means of a set of mineral insulated type K thermocouples embedded within the head of some mushrooms, with the hot junction located at 4 mm beneath the surface. Specific energy load as high as 3 MJ/m^2 during steady state discharges were estimated, with a poloidal asymmetry reflecting, at least partially, the non-perfect match between mushroom tip envelop and last closed magnetic surface (LCMS). As far as disruptions are concerned, only some rough estimation of the thermal load profile on the limiter could be made by comparing discharges quite identical but for the current termination (soft landing or disruptive), as done in Ref. [6]. In this way the contribution from the disruptive portion only of the discharge could be extracted. The limiter temperature increase by disruptions peaks around the inboard and outboard mid-plane. From the amount of molten material in these zones a lower limit for the deposited energy flux, corresponding to the missing material being considered removed by external forces rather than evaporated, was estimated to be ~ 6.5 MJ/m^2; for a heat flux incident time of 5 ms, corresponding to the typical overall duration of a hard disruption this results in an average power load larger than 1 GW/m^2. In a previous campaign, by using a single spot IR detector, power fluxes as high as 500 MW/m^2 and 200 MW/m^2 were measured during the 100 μs lasting thermal quench and the a few ms lasting magnetic quench, respectively, in limiter regions far from the equatorial plane [6].

Deuterium fluxes calculated assuming typical values of $30 \cdot 10^{-3}$ s for the particle confinement time and 1 cm for the particle flux e-folding length λ_{Γ}, ranged between 0.3 and $1.5 \cdot 10^{23}$ m^2 s^{-1}, depending on the electron density, corresponding to a total average fluence ranging between $2 \cdot 10^{24}$ m^{-2} and $9 \cdot 10^{24}$ m^{-2}. Local measurements of Dγ brightness give a value of 10^{22} m^{-2} s^{-1} for the deuterium flux with $\bar{n}_e = 0.5 \cdot 10^{20}$ m^{-3}, in satisfactory agreement with the calculated value [5]. These very large, reactor relevant particle fluxes result from the high density and the small limiter area characterizing the FTU machine.

Spectroscopic evidences of tungsten presence in the bulk and edge plasma of FTU are lacking because of both intrinsic (weakness of visible emission lines, always below the background level) and instrumental problems (UV and soft X-ray radiation out of the range of the dedicated spectrometers). Nevertheless an indication of tolerable tungsten erosion in standard sawtoothing discharges can be inferred from the main plasma parameters (electron peak temperature, total thermal energy and energy confinement time) which do not show any deterioration with respect to operation with other limiter materials such as Si, Ni and Mo. Z_{eff} and total radiation values are low too, the radial profile of radiated power suggesting no tungsten impurity accumulation in the plasma core. More details can be found in Ref. [5].

At a visual inspection the damage pattern on the tungsten limiter looked like the usual one recognized on all previous limiters: melting and ablation of mushroom surface was concentrated around the outer and inner equatorial midplane, the other parts appearing, in this case, to have suffered no damage at all by plasma fluxes (surface traces by grinding were as visible as on the 'as received' mushroom). Profilometry carried out on the mushrooms in these 'untouched' zones showed no macroscopic surface modification, when compared to measurements made before the employment on FTU, but device sensitivity (1 μm) is not sufficiently accurate to rule out any erosion of the tungsten coating. On the other hand quantitative method of erosion measurements based on in situ spectroscopy or weight losses were not available in this case. Evidences of surface morfological modifications induced by sputtering were looked for by SEM analysis of the mushroom heads. Only very shallow indications of sputtering action could be recognized, to be compared with the highly textured surface of a plasma sprayed tungsten implanted with a deuterium beam having the same order of total fluence, but energy corresponding to the peak of the sputtering yield versus ion temperature curve for tungsten [7]. Notice that the additional contribution from self-sputtering was absent in that case. Even if in a qualitative way this confirms the weak erosion by sputtering at the low electron temperature characterizing the FTU scrape-off layer (T_e ranges between 12 and 40 eV with no clear dependence on density for $\bar{n}_e$ between 0.22 and $2.5 \cdot 10^{20}$ m^{-3} [8]).

On the other hand, concerning the thermal shock resistance of the coating, a homogeneously distributed net-like crack pattern was found on the otherwise intact mushrooms (Fig. 2), resembling similar characteristics found in high heat flux tests of bulk tungsten [9]. This is not surprising taking into account the brittleness of tungsten at the very low operating temperature in FTU. Temperature gradients, perpendicular to the surface, set up by steady state heat flux lasting 1 s or more are not sufficient to exceed the ultimate strength of tungsten and to crack the coating surface, due to the good thermal conductivity of tungsten, reduced in plasma sprayed coatings by a factor not larger than 2 [10]. So the crack pattern probably results from fast heat fluxes during disruptions or runaway electron (RAE) fluxes, not strong enough to melt tungsten surface, but sufficient to install high compressive stresses in a thin surface layer, exceeding the threshold for crack initiation. As an example, by using semi-infinite solid approximation to calculate temperature distribution inside the 2 mm thick tungsten coating (related thermal diffusion time $\sim 40 \cdot 10^{-3}$ s), a temperature gradient sufficient to exceed the ultimate strength of tungsten can be set up by a heat flux of 200 MW/m^2 for $3 \cdot 10^{-3}$ s, a specific energy load reachable during disruptions also in the FTU limiter regions far from the equatorial plane [6].

Mushroom cross-sections etched with Murakami's reagent (10 g $K_3Fe(CN)_6$, 10 g NaOH in 200 ml of distilled water) were analyzed with both optical microscopy and SEM. VPS tungsten coating of both 'as

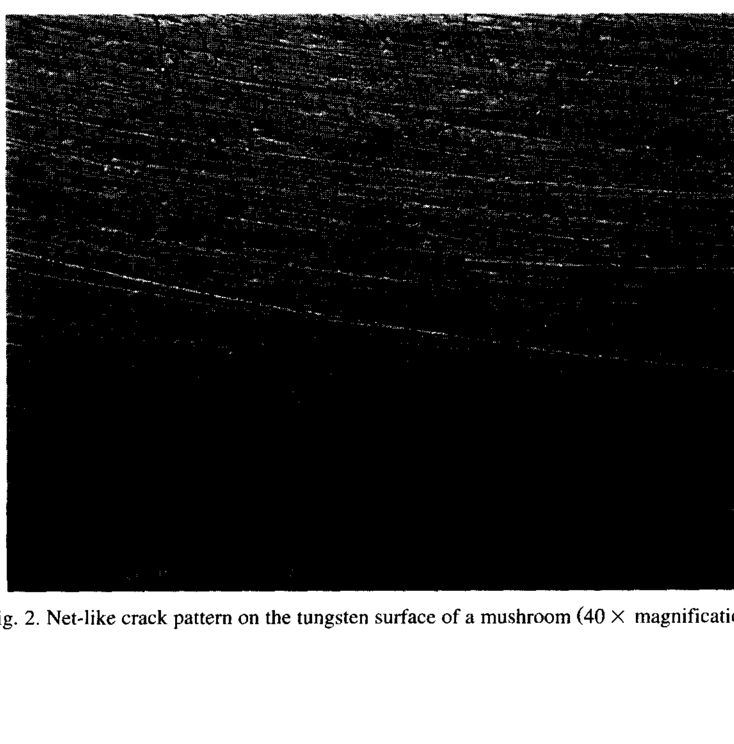

Fig. 2. Net-like crack pattern on the tungsten surface of a mushroom (40 × magnification).

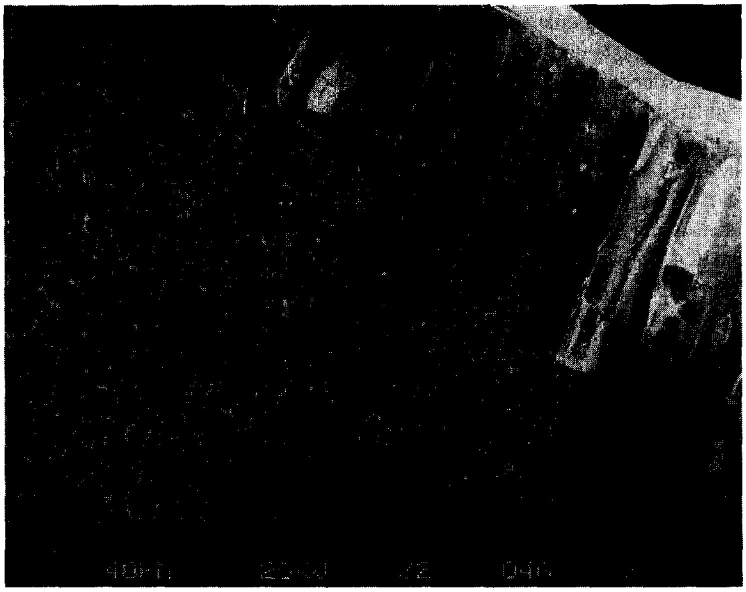

Fig. 3. Scanning electron micrograph at 60 × magnification of the cross section through melted zone of the mushroom located on the outer equatorial plane.

received' and plasma exposed samples revealed the dense microstructure typical of the coatings deposited on substrate above the recrystallization temperature, rather than a splat morphology [11]. Except for severely damaged mushrooms where, in some zones, coating was missing completely, the bonding between tungsten deposit and TZM substrate appeared to be quite good, with no enhanced porosity at the interface. No impurity was detected by EDX, the concentration of the declared ones being below its resolution limit. No evident grain growth, with respect to the 'as received' sample, was found on plasma exposed samples, except on cross-sections throughout melted regions, where the typical columnar microstructure is well visible (Fig. 3). More dramatic was the grain growth in the TZM substrate in correspondence with severely heated or melted surface regions of the coating. In some cases, for example beneath the coating in Fig. 3, abnormal grain growth led to the formation of very large monocrystals. In these zones, preliminary EDX analysis [12] revealed the presence of a relatively high amount of small ZrO and TiO inclusions. It is therefore possible to make the hypothesis that grain growth occurs owing to a depletion of Zr and Ti concentration in the matrix, so that grain boundary pinning by Ti and Zr carbide precipitation is no longer operative. Oxygen from the plasma discharge could diffuse through the melted zone and cracks of the coating. As a matter of fact, very deep cracks are visible in these regions of the coating, often propagating through the entire thickness of the TZM substrate, probably as a result of the high tensile stresses associated with the solidification of melted coating.

A few days after the removal of the limiter, activation measurements were carried out on some mushrooms of both inner and outer limiter by using a GeLi spectrometer. Several radioisotopes were identified, resulting from type (γ,n) or (γ,p) photo-reactions with threshold energies between 5 and 17 MeV. Almost all of these radionuclides originate from atoms in the TZM substrate, probably because the tungsten coating (where it is not even partially or completely ablated) is thin with respect to the length of material traversed by photons of energy above the threshold of the possible photoreactions in tungsten. In Fig. 4 the measured γ-radioactivity, corrected as to the time of the last operation day, is reported as a function of the poloidal angle for the ${}_{41}Nb^{91m}$ isotope resulting from the photo-

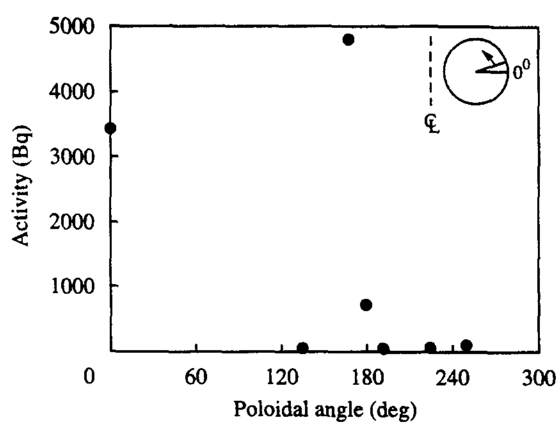

Fig. 4. γ-radioactivity for the ${}_{41}Nb^{91m}$ isotope as a function of the poloidal angle, corrected as to the time of the last operation day. Each point represents a mushroom.

reaction ${}_{42}Mo^{92}(\gamma,p)_{41}Nb^{91m}$ (threshold energy 7.5 MeV). No correction was made for taking into account the different mass of the mushrooms, the depth of the activated zone as well as the amount of ablated material being unknown. Besides the usual one on the outer limiter [13], activation was detected on the inner part of the limiter too. This activation is believed to derive from that fraction (the least energetic) of RAE generated during a disruption, at the end of the thermal quench, that is forced towards the inner limiter following the dump of the plasma column on the inboard side of the vacuum chamber, that always characterizes the current decay phase of plasma disruptions in FTU. Signals from hard X-ray and neutron detectors show large increases during the decay of the plasma current (sometimes characterized by a midway hesitation, see Fig. 5). Unfortunately, both the outer and the inner limiter being located at the same toroidal location, the source of γ-rays and photoneutrons could not be discriminated. The radioactivity being closely associated with the melted and/or ablated zone, we believe that a large part of the macroscopic damages on the inner limiter are originated by the impact of the RAE during disruptions. As a matter of fact, the very high stopping power of tungsten for high energy electrons leads to a large part of the energy being released inside the coating. By using an analytical model [14] to calculate the energy deposition profile in a tungsten semi-infinite absorber for a 20 MeV electron at normal incidence, all the energy results to be released within a 1.5 mm thick layer. Actually incidence angles of RAE on mushroom surface range from 0° to 20° at the most, moving 3 mm outward from the tangency point of LCMS. This causes more energy to be deposited near the surface, volumetric heating, usually characterizing high energy electron impact at normal incidence, becoming, in one way, similar to surface heating. On the other hand, at very grazing incidence angles, multiple scattering could cause a large fraction of electrons to be reflected, thus reducing the amount of deposited energy. However, the presence of a strong magnetic field (in the inboard and outboard side of the vacuum chamber $B_T = 9$ and 4 T respectively for $B_T(0) = 6$ T), nearly parallel to the material surface, bends back electrons into the surface and further reduces their penetration depth, as a result of the electrons orbiting the embedded magnetic field lines [15].

4. Conclusions

Post-mortem analysis of the tungsten coated molybdenum limiter used for two weeks in the FTU tokamak during the summer of 1994, confirmed the results from plasma diagnostics [5], which suggest high Z materials like W (or Mo) to be compatible with a reactor operative scenario. Negligible traces of erosion by sputtering or evaporation during steady state discharges were found. Severe damage around the outer and inner midplane are to be ascribed to runaway fluxes during disruptions. The low operating temperature of the FTU limiters represents a drawback for withstanding thermal shocks, ductile–brittle transition temperature of tungsten being well above the room temperature.

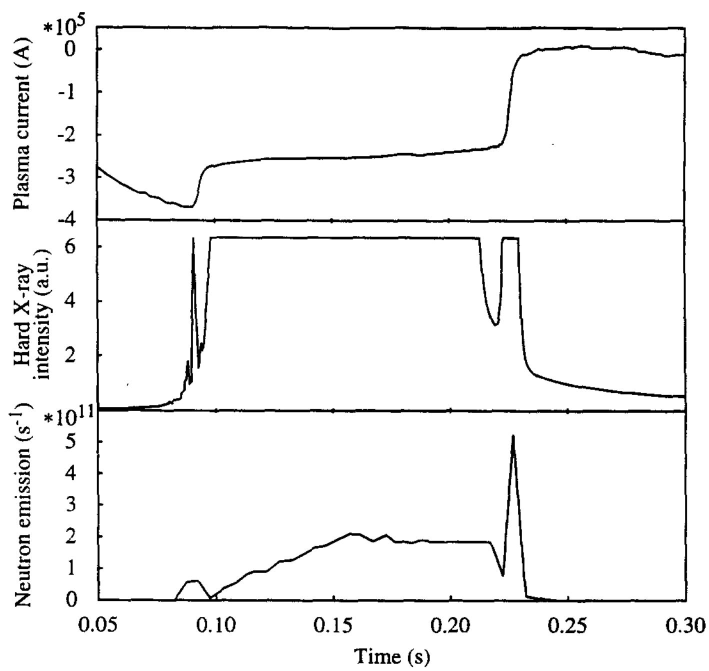

Fig. 5. Plasma current decay showing a midway hesitation (a), correlated to strong hard X-ray emission (b) and neutron production (c).

The short experimental campaign carried out in the summer of 1994 cannot be considered exhaustive with reference to both plasma behaviour and material performance. New tests of tungsten in FTU should be planned, by replacing the tiles of the outer poloidal limiter, provided with an under vacuum removal system and/or by using the sample introduction system [16], now being operated, which allows up to ten samples a day to be exposed to the plasma in the scrape-off layer.

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