Investigation of plasma-tungsten interaction with pre-melted (damaged) layers of ITER–like tungsten divertor tiles on Globus-M tokamak

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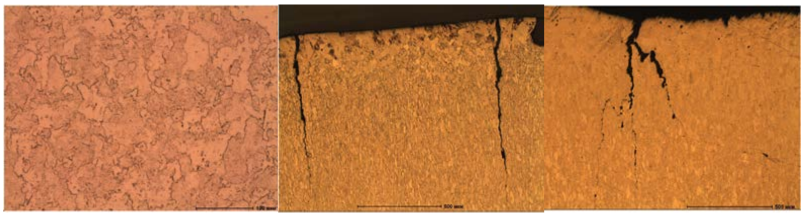
The requirements on plasma facing materials in future reactors will go far beyond those of the modern machines. ITER-plasma parameters are not achievable at the existing tokamaks. But investigations of materials under high repetition and intense fusion-relevant pulses with the help of tokamaks, mirror machines, plasma focus/guns, ion/electron beam have to be performed, e.g. [1]. As tungsten became main plasma facing material in ITER, research programs of plasma – tungsten wall interaction on ASDEX and JET tokamaks were performed, e.g. [2]. They produced significant but not sufficient information about tungsten behaviour under severe loads. Principal reason is that modern tokamaks cannot create wall loads with energy densities sufficient to melt tungsten. At such circumstances the plasma-wall interaction with pre-melted tungsten layers may be investigated at the existing machines. Such experiments must be concentrated on the study of properties of damaged (melted) W layers, layer dynamics and possible flaking formation.

Four ITER–like tungsten tile mock-ups (Fig. 1a) consisting of 20.5×23.9×10 mm W-tiles brazed to 2 mm copper substrate were manufactured in Efremov Institute [3]. To simulate ITER thermal loads tungsten mock-ups were damaged by the electron beam and by plasma jet of coaxial gun at the load compared with transient ITER event (ELM) power depositions. To achieve temperatures close to those expected in ITER and avoid oxidation, electron beam treatment of mock-ups was performed with active cooling and in the vacuum chamber. Electron beam "Tsefey-M" facility (Efremov Institute) [4] produced e-beam with P_e = 195 kW and 18 mks duration which was enough to provide the local tungsten melting. After each pulse the beam was shifted to undamaged area and switched again. Each cycle of melting was finished when the total mock-up area was covered (scanned by e-beam melts). Totally 1000 and 2000 cycles of tungsten mock-up re-melts were performed (see Figs. 1b and 1c).

a) b) c) d)

Fig. 1. ITER–like W divertor tile mock-ups: a) initial; b) after 1000 re-melt cycles with e-beam; c) after 2000 re-melt sycles with e-beam; d) after 100 shots (right) and 1000 shots (left) with plasma gun

Technological equipment Struers were used to prepare surface of W samples for microscopic examination. Metallographic investigation of W surface were carried out using inverted microscope OLYMPUS GX51 and high-resolution stereo microscope OLYMPUS SZX16 . Initial W samples had uniformly distributed grains without cracks while pronounced cracking was observed in W after 1000 and 2000 remelts (Fig. 2).



a) b) c)

Fig. 2. Optical images of W samples: a) initial; b) after 1000 re-melt cycles, c) after 2000 re-melt cycles

Chemical composition and surface morphology of the W samples after e-beam treatment were studied by electron probe microanalysis on a microanalyzer Camebax (Cameca, France) equipped with a Si(Li) energy dispersive spectrometer and scanning electron microscope. Structure of the W samples was investigated by means of X-ray diffraction (XRD) using copper irradiation (λ_{Cu} = 0.154 nm).

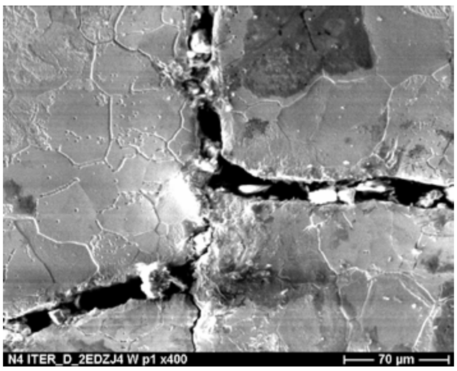


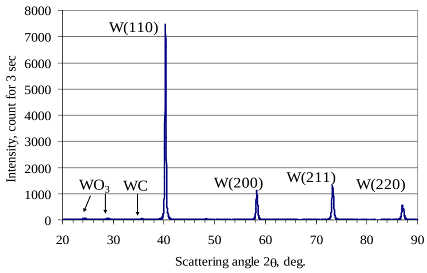
Fig. 3. Micrograph of W surface after 1000 re-melt cycles

Surface layer melted under electron beam irradiation and well wetted solid tungsten. During solidification the melted layer cracked and at near room temperature the cracks propagated inside the metal up to 2.4 mm. The cracks formed practically square net with size of about 1 mm. There were 100-300 grains of recrystallized tungsten in each cell (Fig. 3). After 2000 re-melts the cell size increased by 20%.

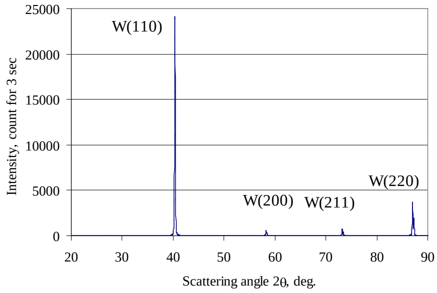
Surface layer ~1 μm thick of initial W sample contained about 1 wt.% of carbon and oxygen that entered into tungsten carbide (WC) and oxide (WO_3) (Fig. 4a). Mean size of tungsten grains calculated according to Scherrer's equation was equal to 50 nm.

After solidification the surface layer was enriched by carbon and oxygen. The tungsten oxide (WO_3) thicknesses were about 40 and 80 nm after 1000 and 2000 re-melts, respectively.

Melting and subsequent solidification of upper layers resulted to increasing of grain sizes to 30-100 μm after 1000 re-melts and then to decreasing ones after 2000 re-melts. According to XRD data a preferred texture with axis of <110> normal to the surface was formed in the recrystallized layer (Fig. 4b).

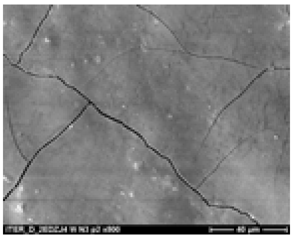


a)

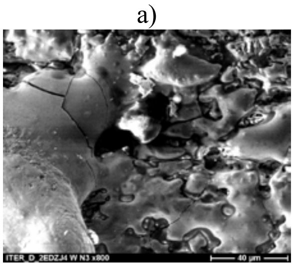


b)

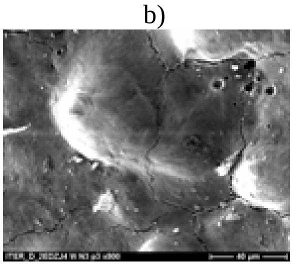
Fig. 4. XRD data for initial W surface (*a*) and after 2000 re-melts (*b*)



a)



b)



c)

Fig. 5. Micrographs of three areas of the W sample after irradiation in the plasma gun by 1000 shots: a) center; b) and c) different edges

Prior to installation in Globus-M one of these four W mock ups was irradiated by the plasma gun at the Ioffe Institute (Fig. 1d). The device could generate plasma jet up to energy density ~1 MJ/m^2. The plasma gun pulse duration was ≤ 15 μs [5].

Three micrographs of different areas of the W sample after irradiation with the plasma gun by 1000 shots are presented in Fig. 5. As seen the irradiation effects were more severe at the sample edges than in the center.

After hydrogen plasma irradiation the intensities of all W lines decreased considerably (Fig. 6) due to relief development. In 6 μm thick layer the crystallites underwent strong deformation that it is probably attributed to hydrogen saturation of the sample.

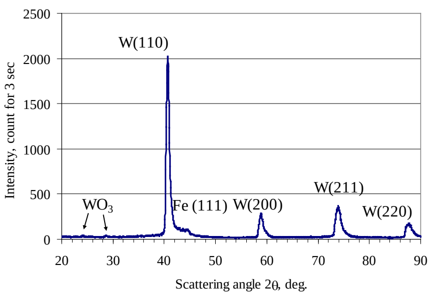


Fig. 6. XRD data for W after plasma gun irradiation by 1000 shots

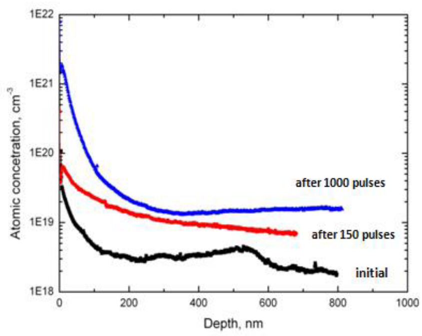


Fig. 7. In-depth distribution of H in W samples after plasma gun treatment

In-depth distribution of hydrogen in tungsten was determined by dynamical SIMS technique. Profiling was carried out using a magnetic-sector instrument CAMECA IMS 7f. The primary beam of $^{133}Cs^{+}$ ions with 4 keV kinetic energy was scanned over 200×200 μm^2 area of the sample biased by – 3 kV. $^{1}H_2^{-}$ secondary negative molecular ions and $^{184}W^{-}$ secondary ions were collected from a central 60 μm diameter area of the bottom of a sputtering crater. Quantification of the SIMS data was done using relative sensitivity factors [6] determined by using implanted standards. Crater depths were measured by an AMBIOS XP-1 surface stilus profilometer. The in-depth distributions of hydrogen in the tungsten samples: initial, irradiated by 150 plasma pulses, and irradiated by 1000 plasma pulses are presented in Fig. 7.

The protection graphite tiles arranged in the third sector of the lower divertor of Globus-M tokamak were removed and replaced with the sector of W tiles during the shutdown in September 2013. The sector consists of 4 ITER-like W tile mock-ups and 18 plates of 3 mm tungsten sheet which was attached to the existing stainless steel substrate (Fig. 8). Only at the positions of the Langmuir probes graphite tiles used. Radial dimension of the sector is 83 mm.

Fig. 8. W tiles in low divertor of the Globus-M tokamak

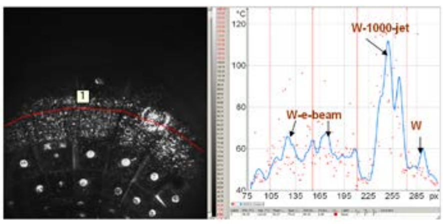


Fig. 9. A temperature field measured by IR camera

The temperature and heat flux distribution at the divertor plate were measured using IR camera Flir SC 7300M. The first results have demonstrated that after current disruption the pre-irradiated surface had a non-uniform temperature field, probably indicating the presence of loose layer under the damaged surface (Fig. 9).

Results of this report have been obtained with the help of the unique scientific device the Globus-M tokamak. The work is supported by the RFBR grant № 13-08-00370.

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