DAMAGE OF 3D TUNGSTEN TARGETS IN THE COURSE OF ITER ELM-LIKE HEAT LOADS

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The damage of tungsten target under repetitive plasma loads have been studied with a quasi-stationary plasma accelerator QSPA Kh-50. The target construction was close to the ITER divertor reference design. The plasma stream parameters were relevant to ITER ELMs (surface heat load of 0.9 MJ/m^2 and pulse duration of 0.25 ms). The features of surface erosion and particle emission have been investigated in the course of increasing number of plasma pulses. The number of solid/droplet particles separated from the exposed target and their dynamics depend on the applied exposition dose. The contribution of different erosion mechanisms to the tungsten target destruction was evaluated.

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INTRODUCTION

At the present time, full tungsten divertor is accepted for ITER tokamak. The divertor components have a complicated construction including tungsten armour, heat sink and joints [1]. Plasma facing components (PFCs) will be exposed to high heat loads relevant to ITER H-regime and off-normal events. Transient off-normal events such as vertical displacement events (VDEs) and disruptions during the ITER operation will create heat loads of up to several MJ/m^2 on the PFCs during (1…30) ms. Regular H-regime of tokamaks is characterized by steady state heat loads and energy loads associated with Edge Localized Modes (ELMs) on first wall and divertor armour. The steady state heat fluxes will reach values up to 10 MW/m². In some regions, stationary heat loads will achieve 20 MW/m² for ≤ 10 s. The transient events (type I edge ELMs) will have power densities of (1…10) GW/m² for (0.2…0.5) ms [2]. The divertor components also have to withstand high H, He and neutron fluxes. Therefore, studies of the modification/damage of PFCs and heat sink joints under heat/particle plasma loads relevant to ITER are required.

The design of divertor components and its material properties are tested at different facilities and with numerical codes. In particular, the behavior of small scale mock-ups under steady-state heat loads was studied with e-beam facilities [3]. The experiments demonstrate self-castellation never appears after the 5000 cycles at 10 MW/m^2 loading. The roughening of the surface, micro/macro-cracks and eventually local melting of the roughened surface are observed only under cycles with power density of 20 MW/m^2. The experiments with tungsten cooled mock-up under plasma ($Q_0 = 0.5$ MJ/m^2 and $\tau_{pulse} \approx 0.5$ ms) and high heat flux (power density up to 10 MW/m^2) loads [4] showed the main erosion mechanisms are melt layer movement and cracks formation. The complicated manufacturing, technological supplying of experiments at facilities and analysis of tested samples make the full scale mock-up tests very difficult. Therefore, most of experiments on study of tungsten properties, erosion mechanisms are carry out using castellated W targets [4-6].

The repetitive plasma heat loads lead to the degradation of mechanical and thermal properties of ITER divertor armour material, the armour delamination from the heat sink during the reactor operation. Moreover, a possible development of molten layer on the tungsten surfaces is additional erosion of divertor components. Present work shows the behavior of castellated W target under ITER ELM-like loads and analysis of its erosion mechanisms.

1. EXPERIMENTAL DEVICE, DIAGNOSTICS AND TARGET DESIGN

The repetitive plasma exposures of castellated target have been performed using the QSPA Kh-50 [7]. The target construction is close to the ITER divertor reference design [8] (Fig. 1). Target has been manufactured from tungsten sample of EU trademark with sizes 5 × 5 × 1 cm. The size of each target element is 22x12x5 mm. The width of gaps between elements is 1 mm.

The main parameters of QSPA Kh-50 plasma streams are as follows: ion impact energy was about (0.4…0.6) keV, the maximum plasma pressure up to 0.32 MPa, and the stream diameter of 18 cm. The plasma pulse shape is approximately triangular, and the pulse duration of 0.25 ms.

The castellated tungsten target was irradiated by plasma streams with a surface heat load of 0.9 MJ/m^2 (between the melting and evaporation thresholds of tungsten as defined earlier) [9]. The surface of the target was oriented perpendicularly to the plasma stream direction. The target temperature before and between irradiating pulses corresponded to room temperature level. The maximum number of plasma impacts reached 120 pulses.

The plasma stream energy density and surface heat load were measured by the local calorimeters. The plasma pressure was measured by piezoelectric detectors. Observations of plasma interactions with exposed surfaces (Fig. 2), the dust particle dynamics and the droplets monitoring were performed with a high-speed 10 bit CMOS pco.1200 s digital camera PCO AG (exposure time from 1 μs to 1 s, spectral range from 290 to 1100 nm). The measurement scheme of ejected from the irradiated surfaces particles is similar to used earlier [6, 10].

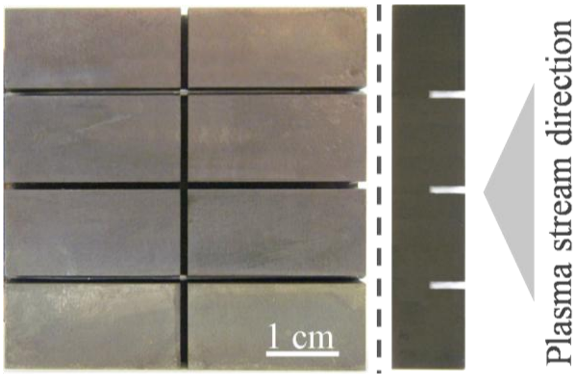

Fig. 1. Scheme of a castellated tungsten target

Surface analysis was carried out with an optical microscope MMR-4, equipped with CCD camera. Weight loss measurements were also performed.

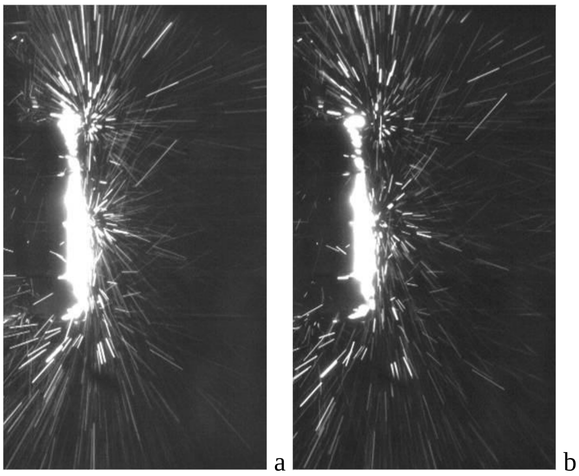

Fig. 2. The particle ejection during plasma-surface interaction (PSI). Images of droplet traces $t_{exposure}$ = 1.2 ms, t = 3.6 ms after beginning of PSI (a), t = 4.8 ms (b)

2. DAMAGING MECHANISMS OF CASTELLATED TARGETS

Droplet splashing and dust ejection during the plasma-surface interaction have been studied. The evaluation of droplet and dust contribution to the overall surface erosion was carried out via CCD camera monitoring and surface analysis. In general, the liquid particles ejection may occur due to the development of instabilities of Kelvin-Helmholtz or Rayleigh-Taylor type [11]. Elastic energy stored in stressed tungsten surface layer should be the motive force for the cracking process with following acceleration of separated solid particles [12].

2.1. STUDIES OF LIQUID/SOLID PARTICLES INJECTION

The intense particle emission is observed in the course of plasma-surface interaction (see Fig. 2). The particles fly in the upstream and downstream directions. The total number of emitted particles changed depending on number of the plasma pulses (Fig. 3).

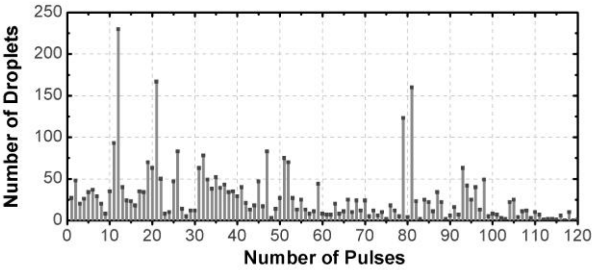

Fig. 3. Number of ejected particles vs. number of plasma pulses

The ejected particles velocity distribution in dependence on start-up time from the exposed surfaces is obtained by the analysis of camera frames (Fig. 4). The maximum velocity achieved 25 m/s. The particles started from the target in time range of (0…1.4) ms (t=0 corresponds to the beginning of plasma-surface interaction). Values of velocities of ejected particles are similar to those registered earlier [5, 6, 13]. Nevertheless, the number of emitted particles is much larger then in experiments with Ti castellated and W brush-like targets [5, 6, 13].

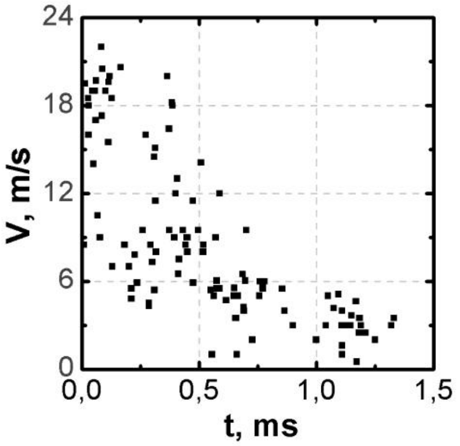

Fig. 4. Velocity distribution vs. start-up time

Presence of re-deposited particles from the structure has been revealed on the surfaces around the castellated target and on the collecting plate. The maximum size of collected particles exceeds 1 mm which is greatly exceeds the particle sizes from the flat targets [9]. Similar result was obtained in earlier experiments with brush-like target [6].

The main mechanisms of particle ejection are found to be the cracking of exposed surface and development of melt layer instabilities. In the beginning of PSI the crack edges may be a primary source of dust particles.

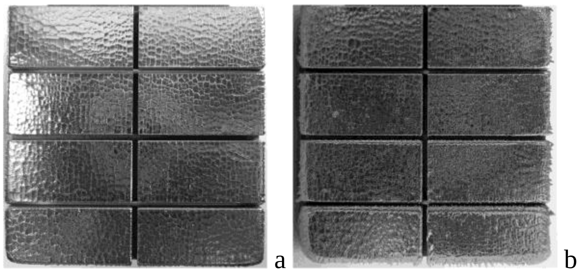

Fig. 5. General view of castellated tungsten target irradiated with 10 (a) and 120 (b) plasma pulses

2.2. EROSION FEATURES

After first several plasma pulses with applied heat loads the cracks networks and molten layer developed on the surface of castellated tungsten target (Fig. 5). The major crack network with average cell size up to 500 μm (Fig. 7,a) appeared due to DBT-effect [9, 14]. The width of major cracks is about 6 μm. In addition, re-solidification of the molten layer causes the development of the micro-cracks meshes on the background of major rack pattern (see Fig. 7,a). The micro-crack network has a cell size about 50 μm. The width of micro-cracks does not exceed 1 μm. The melt motion causes the partially filling of major cracks also.

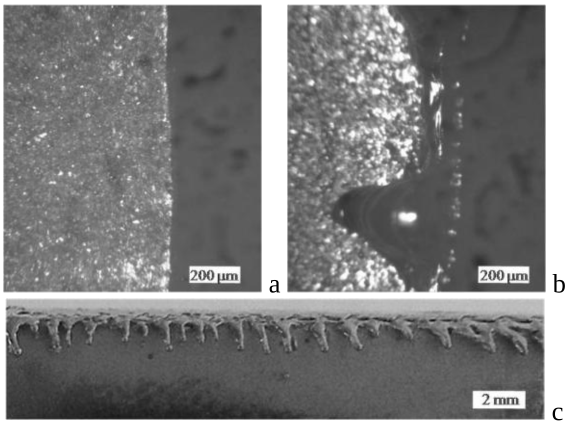

Fig. 6. Images of target edge before irradiation (a), after 20 (b) and 120 (c) exposed pulses

The Fig. 7,b demonstrates the particles along the crack edge which can be pushed away by further plasma impacts. At the same time, the crack networks increase the surface roughness which promotes the droplet splashing during the melt motion.

The molten layer, which is formed on the irradiated target, moves under the action of external forces. First of all, driving forces resulted from the pressure and temperature gradients [7]. During the plasma exposure, hydrodynamic instabilities are developing in molten layer. As result, the ripple structure on the target surface and pronounced streamlets on the target edges are formed after the solidification of molten layer (see Figs. 5, 6). So-called bridges between the elements of target as well as streamlets (see Figs. 5, 6) growth with increasing number of plasma pulses. The resolidified bridges and protuberances can be destroyed under the action of next plasma pulses and they can be a source of large particles ejected.

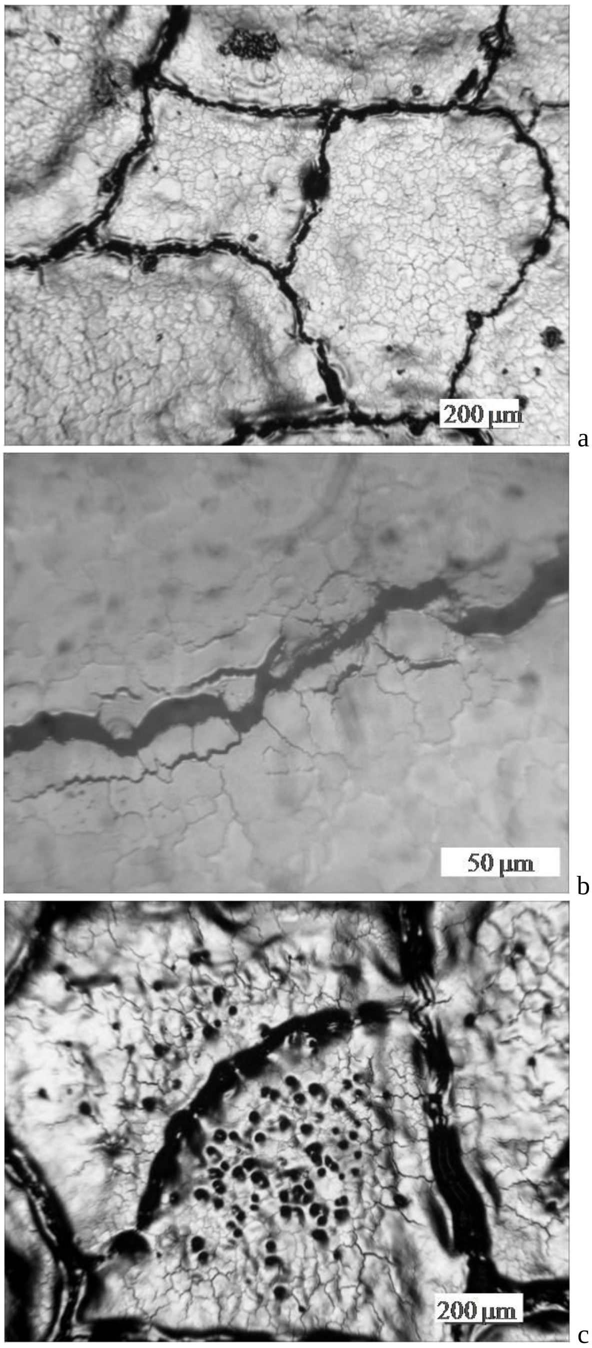

Fig. 7. Tungsten target surfaces exposed to QSPA plasma streams: micro- and major crack networks (a); example of separated particles at crack edge (b); corrugations and pits (c)

Similar to previous experiments [15] the corrugations and pits are observed on the target surface after a large number of plasma impacts (Fig. 7,c).

The maximum temperature value is realized on the edges of units. It leads to their earlier melting in comparison to surface melting. The largest streamlets are observed on the outer edge, which is the most overheated part of target. The bridges have smaller sizes, which slowly grow with increasing the number of plasma pulses.

CONCLUSIONS

Features of plasma interaction of with the castellated tungsten target (size of the structure is close to the ITER divertor reference design) have been studied at a quasi-stationary plasma accelerator QSPA Kh-50 under the repetitive plasma pulses simulating ITER ELM (surface heat load of 0.9 MJ/m^2 and pulse duration of 0.25 ms).

The plasma impacts lead to pronounced erosion of the target, which is accompanied by separation of tungsten droplets/dust from the exposed target surfaces. The number of ejected particles and their velocities depend on the irradiating dose: as the number of pulses increases, the velocities of particles decrease, whereas the start-up time increases. Both central area and edges of the irradiated targets suffer from formation of cracks and the melt motion on exposed surfaces, which depend on the number of plasma pulses.

Erosion of the castellated structures is characterized by the drastic increase in size of the ejected droplets and their lower velocities, as compared with those observed for the plane samples. It demonstrates an important influence of the droplet/dust erosion mechanism from the edges on dynamics of the erosion products. The edges erosion exceeded the erosion of the target central area considerably, and it dominated in the resulting damage of the exposed targets

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ПОВРЕЖДЕНИЕ ВОЛЬФРАМОВЫХ 3D-МИШЕНЕЙ В ЭКСПЕРИМЕНТАХ, МОДЕЛИРУЮЩИХ ELM В ИТЭР

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Изучены повреждения вольфрамовой мишени при многократном облучении плазмой в квазистационарном плазменном ускорителе КСПУ Х-50. Мишень имела конструкцию, близкую к строению компонентов дивертора ИТЭР. Параметры потоков плазмы выбраны близкими к ELM в ИТЭР (тепловая нагрузка на поверхность составляла 0,9 МДж/м^2, длительность импульса – 0,25 мс). Исследованы особенности эрозии поверхности и эжекции капель при увеличении количества плазменных импульсов. Показано, что количество пыли/капель и динамика частиц, отделившихся от облучаемой мишени, зависят от дозы облучения. Анализируется вклад разных механизмов эрозии в разрушение вольфрамовой мишени.

ПОШКОДЖЕННЯ ВОЛЬФРАМОВИХ 3D-МІШЕНЕЙ В ЕКСПЕРИМЕНТАХ, ЩО МОДЕЛЮЮТЬ ELM В ІТЕР

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Вивчено пошкодження вольфрамової мішені під час багаторазового опромінення плазмою в квазістаціонарному плазмовому прискорювачі КСПП Х-50. Мішень мала конструкцію близьку до будови компонентів дивертора ІТЕР. Параметри потоків плазми обрані близькими до ELM в ІТЕР (теплове навантаження на поверхню становило 0,9 МДж/м^2, тривалість імпульсу – 0,25 мс). Досліджено особливості ерозії поверхні та ежекції крапель зі збільшенням кількості плазмових імпульсів. Показано, що число та динаміка пилу/крапель, які відокремилися від опромінюваної мішені, залежать від дози опромінення. Визначено внесок різних механізмів ерозії в руйнування вольфрамової мішені.