SURFACE MODIFICATION AND DROPLET FORMATION UNDER EXPOSURES OF TUNGSTEN COATINGS WITH ELM-LIKE TRANSIENT LOADS

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Features of surface modification of tungsten coatings after repetitive irradiation with QSPA Kh-50 plasma pulses are presented. Cracking, development of tungsten surface morphology and emission of droplets are studied. Targets were made from samples of steel covered by tungsten coatings of different thickness (4, 12, 40 μm). Pre-coated targets were irradiated with powerful plasma streams of heat fluxes relevant to ELMs in ITER. Mechanisms of modification and damaging of tungsten coatings under irradiation with powerful plasma streams are discussed.

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MOTIVATION

Durability of plasma facing materials (PFM) and components under steady-state and transient energy and particle loads is the key issue determining overall performance of fusion reactor ITER [1]. Transient heat loads (in the course of disruptions, Vertical Displacement Event (VDE), Edge Localized Modes (ELMs)) cause severe erosion and damages of plasma-facing materials (crack formation, melting, melt motion, droplet injection, etc.). The prospective PFMs for fusion reactors are tungsten and tungsten coatings. Therefore, particular attention should be paid to elaboration of damage features of tungsten coating as possible candidate material for divertor surfaces and first wall of fusion reactor on the base of magnetic confinement, as well as for the chamber in inertial fusion reactor.

Powerful plasma accelerators are used at present for experimental study of plasma-target interaction under transient high heat loads [2, 3]. Such devices also applied for validation of numerical models developed for ITER and DEMO [4-6]. Quasi-stationary plasma accelerators (QSPA) are characterized by duration of plasma stream, which is compared with the expected duration of ITER ELM. Therefore QSPAs became especially attractive facilities for investigations of macroscopic erosion of divertor armor materials under the plasma loads typical for ITER off-normal events.

Database accumulation and comparison of different material types (coatings, alloys and etc.) might be an appropriate basis for choosing the promising plasma facing material for fusion reactor. The main objective of this work is analysis of the specific features of macroscopic erosion of tungsten coatings of different thickness under irradiation with powerful plasma heat fluxes relevant to ELMs in ITER.

1. EXPERIMENTAL DEVICE AND DIAGNOSTICS

The experimental simulations of ITER ELMs at relevant surface heat-load parameters (i.e. the energy density and the pulse duration as well as the particle loads) were performed with the QSPA Kh-50 quasi-stationary plasma accelerator [7-9]. QSPA Kh-50 generates hydrogen plasma streams of duration of 0.25 ms and the heat loads in the range of 0.2…2.5 MJ/m^2. The plasma stream diameter is 18 cm, ion energies of (0.4…0.6) keV and maximum plasma pressure up to 0.32 MPa. The surface energy loads which were precisely measured with calorimetry, amounted to 0.45 MJ/m^2 (i.e. being below the melting threshold) or 0.75 MJ/m^2 (i.e. in between melting and evaporation thresholds).

The investigated targets (diameter of 30 mm and height of 3 mm) were made from steel and covered by tungsten coatings of different thickness (4, 12 and 40 μm). W coatings were deposited to the samples surfaces by PVD method in “Bulat" installation [10].

In order to determine the main plasma parameters (electron density and temperature) and to investigate the impurity behavior during the discharge, optical methods and piezodetectors, electric and magnetic probes were applied.

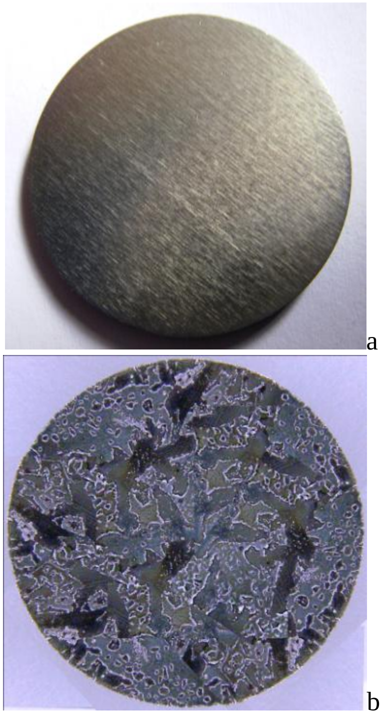
Observations of plasma interactions with exposed surfaces, the dust particle dynamics and the droplets monitoring were performed with a high-speed 10 bit CMOS pco.1200 s digital camera PCO AG (exposure time from 1 μs to 1 ms, spectral range from 290 to 1100 nm). Information from several camera frames of different duration (0.5…1.6 ms) with traces of particles flying from the tungsten surface after plasma shot allow calculation of the particles velocity and the time moment when it started from the target surface.

Surface diagnostics included optical and scanning electron microscopy, profilometry as well as microhardness, roughness and weight loss measurements.

2. EXPERIMENTAL RESULTS

2.1. SURFACE MODIFICATION OF TUNGSTEN COATINGS

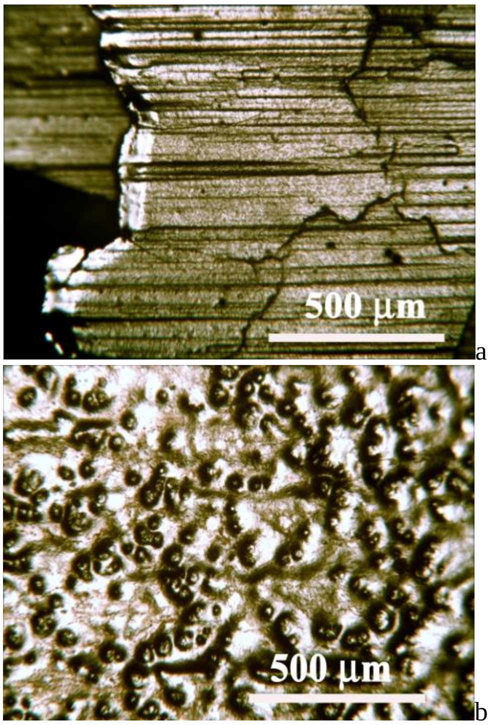
Images of target surface before and after the plasma treatment are presented in Fig. 1. Tungsten coating was partially destroyed after exposure to plasma streams. Exfoliation of surface coating layer on the separate parts of exposed surface is observed after relatively small number of plasma pulses (up 10) (for coating thickness – 12 and 40 µm). Adhesion problems under high temperature gradients (~ $10^6…10^8$ K/cm) introduced by plasma impacts cause such phenomenon. Also, particles erosion is observed from the crack edges during and after plasma impacts.



a

b

Fig. 1. General views of tungsten coating: before irradiation (a); after plasma ipacts with heat load of 0.75 MJ/m^2 (b)



a

b

Fig. 2. Different areas of tungsten coating (thickness of 40 µm): cracking (a) and surface melting (b) after plasma exposures of 0.75 MJ/m^2

Macro-cracks are observed primary in thick coatings (Fig. 2,a). Smoothing of crack edges attributed to melting and following re-solidification of material. Typical mesh size of the major cracks network in central area of the exposed surface was 0.6…1.5 mm.

The molten layer is formed in the central regions of the target (Fig. 2,b). Cracks, which became filled by the melted material are also observed. Destroy of coating occurs already under the first plasma pulses.

Microscopy observations well correlate with surface profile measurements. Corresponding changes in the profile of the surface after plasma exposure are presented in Fig. 3. Formation of cracks and melted layer cause observed changes of surface profiles. Specific surface relief is developed due to appearance of the crack meshes on the surface. Corrugated structure of hills and cracks appear after initial plasma pulses with heat load above the melting. These morphology changes are caused by surface tension effects. As result of plasma irradiation roughness of the exposed surface increased due to destroying of coating and melting of the surface. The crack width achieved 120 µm (Fig. 3,d).

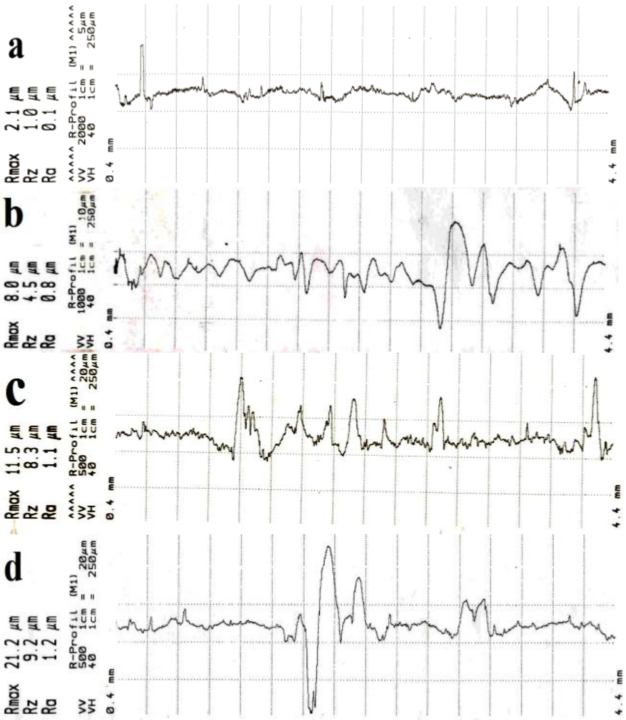


Fig. 3. Surface profiles of tungsten coating: initial (a) and after plasma heat load of 0.75 MJ/m^2 for coatings of different thickness (h): h = 4 µm (b); h= 12 µm (c); h= 40 µm (d)

2.2. DUST/DROPLET FORMATION

Plasma impacts with loads above the melting threshold cause the droplet/dust particles ejection from the surface of tungsten coating (Fig. 4). The most intense emission of the droplets is observed from coatings of 40 µm in thickness.

Tungsten cracking leads to separation of material pieces from the surface. Depending of the heat load value the eroded material could be in the form of solid dust or liquid droplets. Formation of dust particles in the course of cracking and development of sharp edges of the cracks are further accompanied by their melting under the plasma pulse because of decreased heat transfer to the bulk. Being initially solid, the separated dust particles are subjected to melting during the later stage of plasma pulse. Other surface remains non-melted in result of plasma impact.

For perpendicular plasma impact to the surface, droplets are ejected primarily with relatively small angles to the normal. Nevertheless rather large angles up to 80^0 are measured also. Analysis of droplet shows the influence of gravitational force for droplets with higher mass and smaller velocities. Due to the gravitation the resulting angular distribution of the droplets became non-symmetric [8, 12].

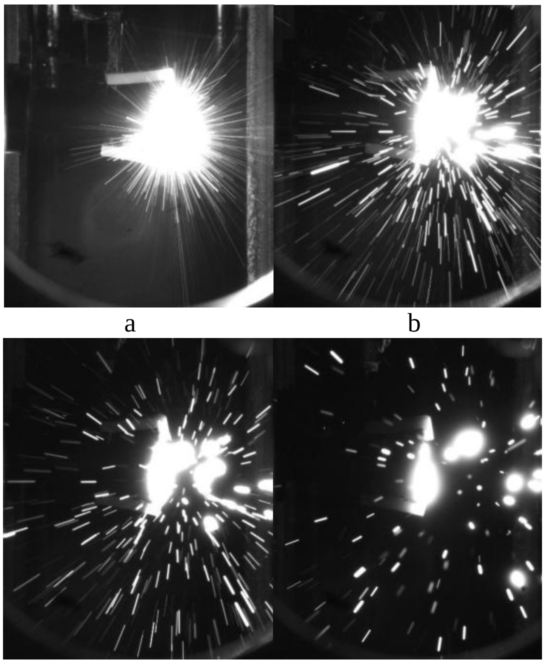


Fig. 4. Frames of the digital camera with the traces of erosion products (exposure time 1.2 ms). The camera's view is parallel to the target surface:
a – 2.4 ms; b – 4.8 ms; c – 8.4 ms; d – 15.6 ms after the start of plasma-surface interaction

The large number of ejected particles flies away the target surface after 0.2 ms after beginning of plasma surface interaction (Fig. 5). Therefore, large number of ejected particles is solid [11]. They may break off from the crack edges during the plasma impact. Some particles continue to be ejected from the surface during more than 3 ms after plasma impact. Particles velocities achieved several tens of m/s.

Fast droplets are generated at earlier time moments. Smaller velocities are observed for late stage of observation. During intermediate stage both groups of droplets with fast and lower velocities are observed. The total amount of injected droplets depends on the thickness of the coating. Number of droplets ejected from the target with coatings thickness of 40 µm is larger up to 2 times, than for the coating of 4 µm. This is due to morphological features of the target surface for thick coatings (pronounced cracking, exfoliation, etc.).

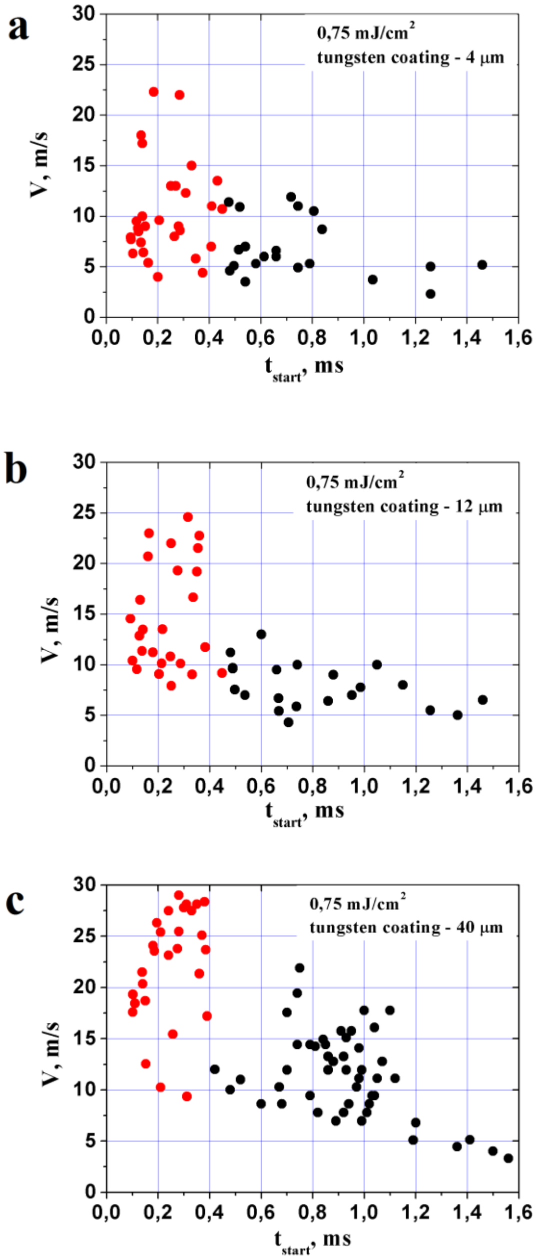


Fig. 5. Velocity distribution of ejected particles vs. their start time from the surface: a – tungsten coating 4 µm; b – 12 µm; c – 40 µm. Zero corresponds to the beginning of plasma-surface interaction

CONCLUSIONS

The recent experiments of simulations of ITER ELMs have been carried out within quasi-stationary plasma accelerator QSPA Kh-50. Targets with tungsten coating of different thickness (4, 12, 40 µm) were examined with powerful plasma impacts at heat fluxes relevant to the ELMs expected in ITER. Particular attention was paid to elaboration of damage of tungsten coating as a possible candidate material for divertor and first wall in magnetic fusion reactors and chamber materials for inertial fusion.

Destruction of the tungsten coating is studied under the influence of QSPA plasma heat loads. Major crack meshes were identified after exposures of the investigated samples. It was shown that formation the major cracks depends strongly on thickness of tungsten coatings. It is shown that tungsten coating damage during the transient events is dominated by influence of macroscopic erosion mechanisms related to the cracking development and surface melting effects. Erosion products in the form of solid dust and splashed droplets are analyzed. Performed studies demonstrate that main sources of droplets originated from crack development, resolidification process and material surface modification in the course of repetitive pulses.

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ПОВЕРХНОСТНЫЕ ИЗМЕНЕНИЯ И ФОРМИРОВАНИЕ КАПЕЛЬ ПРИ ОБЛУЧЕНИИ ВОЛЬФРАМОВЫХ ПОКРЫТИЙ В УСЛОВИЯХ ELM-ПОДОБНЫХ ПЕРЕХОДНЫХ НАГРУЗОК

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Представлены особенности модификации поверхности вольфрамовых покрытий после повторяющихся плазменных тепловых нагрузок КСПУ Х-50. Исследовано развитие трещин, изменения в морфологии поверхности вольфрамовых покрытий и инжекция капель. Мишени были сделаны из образцов стали с нанесенными вольфрамовыми покрытиями различной толщины (4, 12, 40 мкм). Подготовленные мишени облучались мощными тепловыми потоками плазмы, соответствующими ELM в ИТЭР. Особое внимание уделено исследованиям повреждений вольфрамового покрытия в качестве материала для поверхностей дивертора и первой стенки камеры реактора термоядерного синтеза. Обсуждаются механизмы модификации и повреждения вольфрамовых покрытий при облучении мощными потоками плазмы.

ПОВЕРХНЕВІ ЗМІНИ І ФОРМУВАННЯ КРАПЕЛЬ ПРИ ОПРОМІНЕННІ ВОЛЬФРАМОВИХ ПОКРИТТІВ В УМОВАХ ELM-ПОДІБНИХ ПЕРЕХІДНИХ НАВАНТАЖЕНЬ

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Представлені особливості модифікації поверхні вольфрамових покриттів після повторюваних плазмових теплових навантажень КСПП Х-50. Досліджено розвиток тріщин, зміни в морфології поверхні вольфрамових покриттів і інжекція крапель. Мішені були зроблені із зразків сталі, на яку нанесені вольфрамові покриття різної товщини (4, 12, 40 мкм). Підготовлені мішені опромінювалися потужними тепловими потоками плазми, відповідними до ELMам в ITEP. Особливу увагу приділено дослідженням пошкоджень вольфрамового покриття в якості основного матеріалу для поверхонь дивертора і першої стінки камери реактора термоядерного синтезу. Обговорюються механізми модифікації та пошкодження вольфрамових покриттів при опроміненні потужними потоками плазми.