PLASMA-SURFACE INTERACTION AND MECHANISMS OF DUST PRODUCTION IN ITER ELM SIMULATION EXPERIMENTS WITH QSPA Kh-50

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Experimental simulations of ITER transient events with relevant surface heat load parameters (energy density and the pulse duration) were carried out with a quasi-stationary plasma accelerator QSPA Kh-50. The several mechanisms of dust generation from tungsten surfaces were identified. The major cracks development and it bifurcation led to generation dust particles with sizes up to tens µm. Melting of surface and development of fine meshes of cracks along the grain boundaries are accompanied by resolidified bridges formation through the fine cracks. Such bridges produce nm-size dust. Appearance of sub-micron and nanometer-size cellular structures under plasma irradiation can leads to the intensification of the dust formation.

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INTRODUCTION

Plasma-surface interaction processes with large plasma heat load and particle fluxes are the most important issues for International Thermonuclear Experimental Reactor (ITER) and next-step fusion devices [1, 2]. Erosion of Plasma-Facing Components (PFC) restricts the divertor life time due to ejection of eroded material from exposed surface. A substantial amount of the material dust can also appear. Dust transport in the vessel deserves special attention because the grains can deeply enter the core plasma [1-4].

Observations with impurity diagnostics (fast cameras, laser beam scattering) of the grains in present-day tokamaks are quite problematic for the high energy fluxes and in fact don't allow robust predictions for ITER [3, 4]. For this reason, the simulation experiments are carried out by using powerful pulsed plasma guns [5], quasi-stationary plasma accelerators (QSPAs) [5, 6] and e-beam facilities [7], which are capable of simulating, at least in part, the loading conditions relevant to ITER. The dynamics of erosion products, the impurities transport in the impacting plasma, the vapor shield in front of target and corresponding heat transfer to the material surface under normal plasma irradiation were also studied [8-11]. However, tungsten dust generation under different heat load relevant to Edge Localized Modes (ELM) in ITER requires further studies

This paper presents recent results of ELM-simulation experiments with the quasi-stationary plasma accelerator QSPA Kh-50. The experiments include study of plasma-surface interaction under inclined plasma impact, the observation and collection of dust of different kind.

1. EXPERIMENTAL SET UP AND DIAGNOSTICS

Experimental simulations of ITER transient events with relevant surface heat load parameters (energy density and the pulse duration) as well as particle loads were performed with the QSPA Kh-50 quasi-steady-state plasma accelerator which is the largest and most powerful device of this kind [5].The main parameters of QSPA plasma streams were as follows: ion impact energy about 0.4…0.6 keV, the maximum plasma pressure 3.2 bars, and the stream diameter about 18 cm. The plasma pulse shape is approximately triangular, pulse duration 0.25 ms and the energy density varied in the range 0.2…2.5 MJ/m^2.

The energy density in plasma and surface energy load and its changes were measured by a calorimeter. The energy density in the shielding layer was measured by displacing the calorimeter through a hole in the center of the sample. The calorimeter could be moved into the near-surface plasma up to the distance of 5 cm from the target.

The erosion products flying from the tungsten target have been registered using a high-speed 10 bit CMOS digital camera PCO·1200 s from PCO AG with a space resolution of 1280×1024 pixels and frame duration of 1.2 ms. A surface analysis was carried out with an MMR-4 optical microscope equipped with a CCD camera and Scanning Electron Microscopy (SEM) of the JEOL JSM-6390 type.

2. EXPERIMENTAL RESULTS

2.1. FEATURES OF POWERFUL PLASMA–SURFACE INTERACTION WITH INCLINED TARGETS

Calorimetric measurements demonstrated that even for QSPA Kh-50 plasma exposures which do not result in tungsten melting ($q<0.6$ MJ/m^2), the absorbed heat load is below 60% of the impact plasma energy (Fig. 1). The energy density increases with an increasing distance from the target surface. For the normal incidence, the energy density saturates at some distance from the surface (2–4 cm, depending on the energy density in the plasma stream) reaching the energy density of the incident plasma. This shows that only a part of the plasma stream energy is transferred to the target through the shielding plasma layer [8].

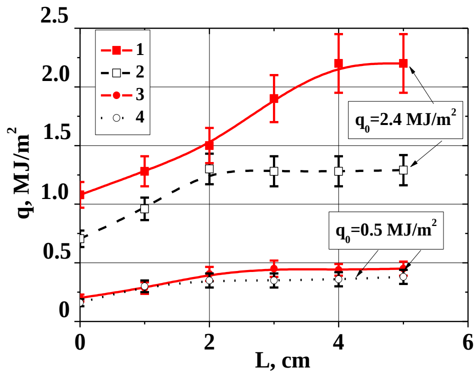

Fig. 1. The energy density (q) distributions in the shielding layer vs. the distance from the target surface (L) for a normal (1, 3) and an oblique plasma irradiation (45°) (2,4). Energy density of impact plasma achieved q_0

Fig. 2. Frame of the digital camera with the traces of erosion products corresponding to the start of plasma–surface interaction (t_{exp} =0.25 ms). q_{surf} = 0.75 MJ/m^2

For the inclined irradiation, the energy density in shielding layer is increasing with the growing the distance from the target surface in the same way as the normal impact. However, saturation of energy density is observed at the distance of 2 cm from the surface. Even at the greatest of the possible distances (5 cm) from the exposed surface the measured energy density is less than the energy density in the incident plasma stream. Thus a calorimeter placed in this position is still within the shielding layer. A non-uniform distribution of the energy density along the target surface is observed under the inclined irradiation [10, 12]. The example of the high speed image of QSPA Kh-50 plasma interaction with the inclined tungsten target is shown in Fig. 2.

2.2. MECHANISMS OF DUST PRODUCTION

At the heat load corresponding to the cracking threshold only several dust particles traces are registered. Plasma impacts with loads above the melting threshold cause the melting/dust particles splashing from the tungsten surface (see Fig. 2). Particles velocities may achieve several tens m/s. Fast droplets are generated at earlier time moments (Fig. 3). Smaller velocities are observed for late stage of observation. During intermediate stage both groups of droplets with fast and lower velocities are observed [8, 11, 13]. It was show that at least more than 95% of particles started from solid surface [11].

For a plasma impact perpendicular to the surface, droplets are ejected primarily with small angles to the normal. For inclined plasma irradiation the largest numbers of particles are also flying towards impact plasma (see Fig. 2). 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 [11].

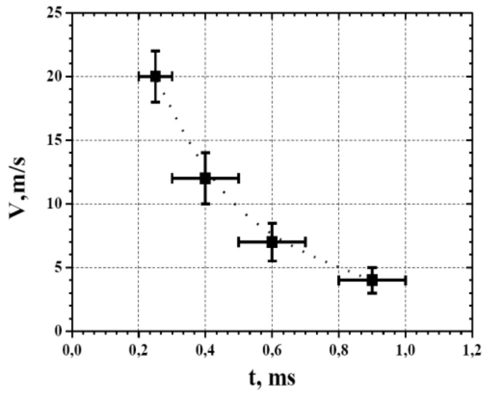

Fig. 3. The dependence of particles velocity flying from the tungsten target after irradiation in the QSPA Kh-50 facility from the start time. Zero is the time of plasma arrival at the target surface. q_{surf} = 0.6 MJ/m^2

Major cracks network develops after first plasma impacts of heat load above cracking threshold (Fig. 4,a).

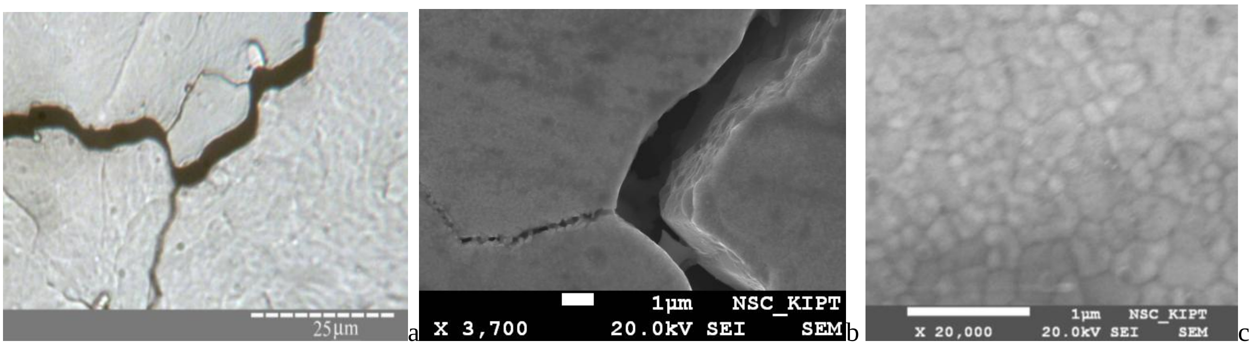

Fig. 4. Development of major crack and its bifurcation (a), bridges formation through the fine cracks (b), some ordered submicron cellular structures (c) on exposed tungsten surface

Dust particles with sizes up to 30 μm can ejected from the surface due to the cracking development and major cracks bifurcation (see Fig.4,a.) Solid particles may split from the crack edges during its rupture [13].

Melting of surface and development of cracks along the grain boundaries are accompanied by formation of resolidified bridges through the fine cracks (see Fig. 4,b). That is caused by melt motion and capillary effects. With next impacts (even without melting) resolidified bridges can produce nm-size dust. After a lot of plasma pulses, networks of both major and intergranular cracks as well as blisters and bubbles develop on exposed surface [5, 9, 13]. Some balls of the sizes of (0.01…1) μm are collected inside both voids of blisters and cracks' volumes [9]. Surface modification of tungsten and development of ordered submicron cellular structures in the course of repetitive plasma pulses also contributes to the nm-dust generation (see Fig. 4,c)

CONCLUSIONS

Influence of the target inclination on the material response to the repetitive plasma heat loads up to 1.1 MJ/m^2 lasting 0.25 ms, which are relevant to ITER Type I ELMs has been analyzed. Studies of dust generation under such energy loads have also been performed.

Dust particles with sizes up to tens μm could be ejected from the surface due to the cracking development and major cracks bifurcation.

Melting of the surface and development of fine meshes of cracks along the grain boundaries are accompanied by resolidified bridges formation through the fine cracks in the course of melt motion and capillary effects. With the next heat pulses (even without melting) such bridges produce submicron- and nm-size dust.

Surface modification of tungsten target after the repetitive plasma pulses with development of some ordered submicron cellular structures creates conditions which provide significant nm-size dust generation after following plasma pulses.

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ПЛАЗМО-ПОВЕРХНОСТНОЕ ВЗАИМОДЕЙСТВИЕ И МЕХАНИЗМЫ ОБРАЗОВАНИЯ ПЫЛИ В ЭКСПЕРИМЕНТАХ, МОДЕЛИРУЮЩИХ ITER ELM В КСПУ Х-50

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Экспериментальное моделирование ИТЭР переходных явлений с соответствующими параметрами тепловых нагрузок на поверхность (плотности энергии и длительности импульса) выполнены в квазистационарном плазменном ускорителе КСПУ Х-50. Были идентифицированы несколько механизмов генерации пыли с поверхности вольфрама. Развитие макротрещин и их бифуркация привели к генерации частиц пыли размером до десятков микрометров. Плавление поверхности и развитие сетки мелких трещин по границам зерен, сопровождаются образованием перезатвердевших мостов через мелкие трещины. Такие мосты создают наноразмерную пыль. Появление субмикронных и наноразмерных ячеистых структур при облучении плазмой может интенсифицировать образование пыли.

ПЛАЗМО-ПОВЕРХНЕВА ВЗАЄМОДІЯ І МЕХАНІЗМИ УТВОРЕННЯ ПИЛУ В ЕКСПЕРИМЕНТАХ, ЩО МОДЕЛЮЮТЬ ITER ELM В КСПП Х-50

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Експериментальне моделювання ІТЕР перехідних явищ з відповідними параметрами теплових навантажень на поверхню (густини енергії і тривалості імпульсу) виконані в квазістаціонарному плазмовому прискорювачі КСПП Х-50. Були ідентифіковані декілька механізмів генерації пилу з поверхні вольфраму. Розвиток макротріщин і їх біфуркація привели до генерації частинок пилу розміром до десятків мікрометрів Плавлення поверхні і розвиток сітки дрібних тріщин по границях зерен супроводжуються утворенням перезатверділих мостів через дрібні тріщини. Такі мости створюють норозмірний пил. Поява субмікронних і норозмірних стільникових структур під час опромінення плазмою може інтенсифікувати утворення пилу.