CASTELLATED STRUCTURES BEHAVIOUR UNDER QSPA Kh-50 PLASMA EXPOSURES IN ITER RELEVANT CONDITIONS

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The experimental study of castellated target erosion under relevant to ITER ELMs surface heat load (i.e., energy density and the pulse duration as well as particle loads) was performed in QSPA Kh-50 quasi-stationary plasma accelerator. The damage of surface, mechanisms of solid/liquid particle ejection for different parts of castellated targets exposed to QSPA plasma streams has been studied in the course of increasing number of pulses. It is shown that melt dynamics at the structure edges, droplet splashing and molten bridges through the slits are determining processes in macroscopic erosion of castellated surface structures.

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INTRODUCTION

Tungsten is approved plasma facing material for ITER divertor because of the low sputtering rate, the high melting point and low retention of hydrogen isotopes. However divertor surface will be subjected to extremely high plasma heat loads during disruptions and Edges Localized Modes (ELMs) [1].

Some powerful test facilities are available to provide examinations of plasma-facing materials under transient ITER-like loads. Impact of ITER-relevant loads upon material surfaces are now simulated with powerful pulsed plasma guns and quasi-stationary plasma accelerators (QSPA) [2, 3], linear plasma-surface interaction (PSI) devices [4], e-beam facilities [5]. Plasma-surface interactions during transient events in ITER are also comprehensively studied with the use of the predictive numerical codes validated by experimental results obtained in different simulators [6-11].

Plasma heat load leads to creation of molten layer on exposed surfaces. The development of perturbations under the influence of different external forces and instabilities in the melt layer causes a large macroscopic erosion of the targets.

Recent results from QSPA simulations demonstrate that droplets are emitted during the plasma exposure of tungsten, and dust generation dominates after the end of plasma pulse, at the time of the following material cooling [12]. Droplets are emitted in the course of Kelvin-Helmholtz instability. A decrease of the droplet velocity with increasing surface heat load is observed. This decrease could be attributed to the growing size of the droplets for higher energy loads. Resolidification of target surface is accompanied by dust ejection driven by the cracking process [10-12].

The segmentation of divertor targets (castellation) allows mitigation of induced currents in metal surfaces during the reactor operation. The reduction of tungsten damage expected also due to minimization of the thermal stresses that is mitigation cracking of affected tungsten surface. Nevertheless, presence of sharp edges in castellated structure may lead to their enhanced erosion. The available edges will influence on energy load distribution. They would provoke the melting effects on the exposed divertor targets. Therefore, features of the erosion of castellated targets need to be comprehensively studied in ITER ELM-like simulation experiments.

Paper presents results of studies the damage of castellated targets in simulation experiments with ITER relevant conditions. Measurements of heat loads to different parts of castellated target have been also carried out.

1. EXPERIMENTAL DEVICE AND DIAGNOSTICS

The quasi-stationary plasma accelerator QSPA Kh-50 is the largest and most powerful device of this kind [13-15]. 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 energy density in free plasma 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, the dust particle dynamics and the droplets monitoring are 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).

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

Two kinds of targets were used in experiments. The targets design is shown in the Fig. 1. The tungsten castellated target consists of nine cylinders with diameter of 5 mm, height of 2 cm and minimal gap between the cylinders – 1 mm.

Because of tungsten melt is quite viscous, heavy and also due to the necessity of larger loads to achieve W melting in some appropriate surface layer, other material could be used for simulation of key dynamical effects on the castellated targets. Titanium material with well-known physical properties has been chosen to enhance the dynamics of the melt and to achieve the recognizable and measurable effects for smaller number of plasma pulses as well as to make clear the analysis of different possible mechanisms of the surface relief development. The titanium castellated target consists of nine cubes with size of 1 cm, the width of the gaps between the cubes 1 mm.

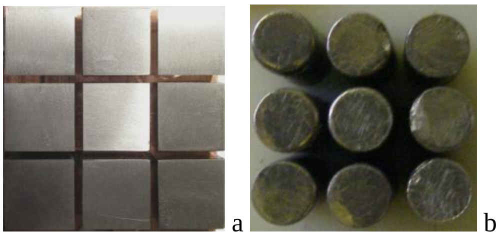

a b

Fig. 1. General view of titanium (a) and tungsten (b) castellated structures

Targets were exposed to perpendicular and inclined (inclination angle from parallel to surface incidence is 30º) plasma irradiation with various numbers of pulses.

2. EXPERIMENTAL RESULTS

2.1. THE SURFACE HEAT LOAD ON THE COMPOUND TARGET

For accurate measurements of the energy density delivered to different areas of the composite target surface a special target has been prepared, which is a set of coaxial cylinders of different diameters. Scheme of the target is presented in Fig. 2. The smallest diameter of 4 cm had the cylinder 1. Diameter of the cylinder 2 was 5.5 cm, height all these cylinders was equal 1 cm. Cylinder 3 with diameter of 7.1 cm and a height of 3 cm was used as the basis for the entire target structure.

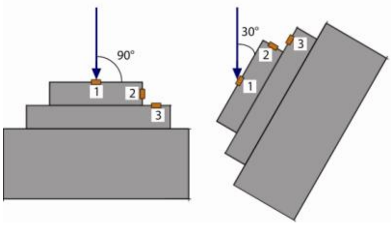
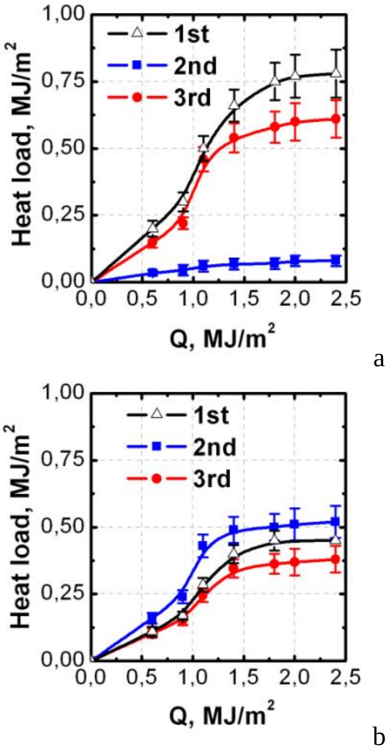


Fig. 2. Scheme of the target with installed calorimeters and direction of plasma impact

To measure the energy density delivered to the surface of the target three calorimeters were used in different places of the target. First calorimeter was located in the center of the front surface of the first cylinder. Second – was installed into a lateral surface of the cylinder 1, as it is shown see in Fig. 2. The distance from the front surface to this calorimeter was 6 mm. Third – was placed in the extended front surface area of the second cylinder at the distance of 2.4 cm from the center of the target. The measurements have been performed under 90° and 30° to incident plasma stream. Those targets were also exposed to perpendicular and inclined plasma irradiation.

For the front calorimeter (number 1) the vapor shielding of the surface begins to appear at an energy density in the incident flow above 1.5 MJ/m^2 under perpendicular irradiation (Fig. 3,a). It corresponds to the saturation of the dependence curve and indicates the evaporation influence on the energy transfer processes. With increasing energy of the incident plasma stream above 1 MJ/m^2 the energy value, which recorded by calorimeter installed to the lateral surface (calorimeter 2) saturates and it does not exceed 0.1 MJ/m^2. This value is at least 7.5 times less than the energy coming to the frontal surface at the maximal specific energy in the impacting plasma stream. The behavior of value of heat load registered by calorimeter 3 is same as for calorimeter 1. The difference between the values of heat load reaching the different parts of the combined target is due to the formation of the plasma shielding layer.



a

b

Fig. 3. Heat load to different parts of the target surface vs. energy density in plasma stream (a – for perpendicular target, b – for inclined target)

For inclined irradiation, thickness of the shielding layer is smallest at the upper edge of the sample. This layer of cold plasma is responsible for decreasing part of incident plasma energy which is delivered to the surface (Fig. 3,b). First of all, it is concern of value of heat load received with calorimeter 1 and 3. The value of heat load measured by calorimeter 2 is at least 5 times larger than the energy measured for perpendicular target. In such case calorimeter is situated closer to incoming plasma than under perpendicular irradiation.

2.2. EROSION OF THE TITANIUM CASTELLATED TARGETS

Interaction of plasma streams with heat load of 0.75 MJ/m^2 and perpendicular titanium surface is accompanied by melting of exposed surfaces. Melt motion of material targets caused formation of so-called bridges, partly filling of the gaps between the structure units. The particle ejection due to bridge destruction and growing of instabilities on the edges of the target units are also observed (Fig. 4,a).

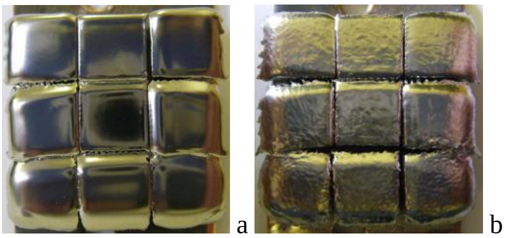


Fig. 4. Exposed surfaces after normal plasma impacts. Heat loads q=0.75 MJ/m^2 (a) and 0.9 MJ/m^2 (b)

With future increasing of heat loads and irradiation dose the ripple structure appear on exposed surfaces. More intensive melt motion, droplet ejection from the edges of the structure are registered for target irradiated by plasma with energy density of 0.9 MJ/m^2 (Fig. 4,b).

The first particles splash from the surface practically (not more 50 μs) at once beginning plasma-surface interaction. The largest number of particle ejects from the exposed surface before 0.2 ms. Maximum of droplets velocities is 22 m/s.

For inclined target, the main part of energy density of incident plasma stream delivers to the top of target. The edges of cubes are melted and molten material displaces under by the action of pressure gradient of incident plasma stream with heat load of 0.75 MJ/m^2. As result, the mountains of resolidified material appear. The melt motion leads to the formation of the bridges between the edges of the structure units (Fig. 5,a). The bridges may break away with the next plasma pulses. Droplet ejection is observed mainly from top region of target. Development of instabilities in the molten layer causes droplets splashing. The droplets fly towards the plasma stream. It may indicate the predominance of Kelvin-Helmholtz instability [9, 12]. At the same time, other instabilities develop in the melt layer on the external edges of the target. It should be mention, that the melt losses due to such instabilities are negligible.

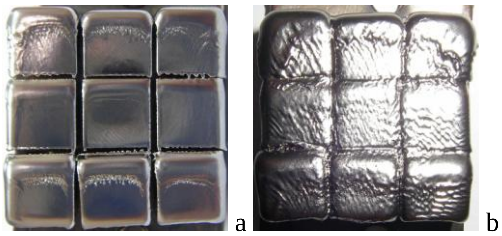


Fig. 5. Exposed surfaces of inclined target for impacting heat loads q=0.75 MJ/m^2 (a) and 0.9 MJ/m^2 (b)

The more intensive melt motion on the surface target is observed under plasma irradiation with the energy density up to 0.9 MJ/m^2. The melt motion leads to filling of the gaps between the units of target by molten metal and appearance of the ripple structure in the affected surface layer (Fig. 5,b). The main mechanisms of particle ejection are separation of the liquid metal from the solid surface (the Taylor criterion) and the Rayleigh Taylor instability [9].

Under inclined irradiation the particle start-up time from the exposed surface is in range of (0.1…1) ms from the beginning of the plasma-surface interaction. The difference between the particle start-up times from the exposed surfaces for perpendicularly and inclined can be explained by formation of non-uniform vapor shield.

2.3. EROSION OF THE TUNGSTEN CASTELLATED TARGET

Castellated tungsten target was irradiated with energy density of 0.9 MJ/m^2. The maximum number of plasma impacts – 100 pulses. The plasma pulses of such energy density caused pronounced melting of target surface. The ripple structures and cracks developed on resolidified tungsten surface (Fig. 6).

The micro-crack network is attributed to melting and following re-solidification [3, 13]. Under the action of next pulses the major cracks are partly filled by molten metal. The edges of cylinders are melted and the mountains of displaced material are formed by the action of pressure gradient with increasing of number of plasma pulses.

The large number of ejected particles flies away the target surface after 0.2 ms from the beginning of plasma surface interaction (Fig. 7). Therefore, considerable number of particles ejected in solid state [10, 12, 16]. They may break off from the crack edges during plasma impact.

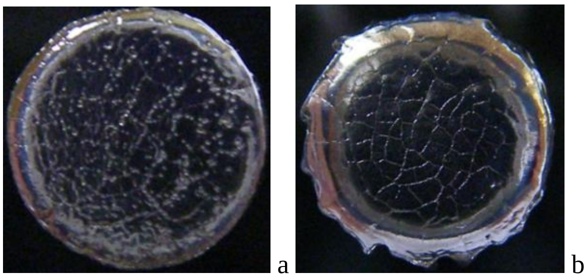


Fig. 6. Exposed surface of tungsten cylinder after 20 (a) and 100 (b) plasma impacts

The major cracks with average network size of 0.8 mm are formed due to the Ductile-to-Brittle Transition effects [3, 10]. In additional, there are particles which ejected from liquid surface [10-12]. They have smaller velocities and start-up time. It indicates the growing of instabilities on the edges of construction units. Velocity of tungsten particles was up to 20 m/s (see Fig. 7).

CONCLUSIONS

The experimental study of castellated target erosion under ITER ELM-like surface heat loads was performed in QSPA Kh-50 quasi-stationary plasma accelerator. The experiments were carried out with energy density in plasma stream of 0.9 MJ/m^2 and pulse duration of 0.25 ms. Such heat load leads to severe melting of titanium and tungsten targets. The melt layer moves by the action of pressure gradient of the incident plasma stream. As result, the bridges through the gaps between structure units and mountains of re-solidified displaced material are appear. Droplet ejection is registered from those target areas. The gaps are covered by molten metal after a large number of plasma pulses and droplet ejection decreased.

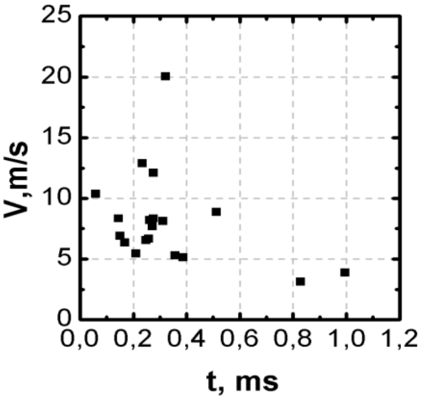


Fig. 7. Velocity distribution of ejected particles vs. particle start-up time from the exposed tungsten surface after 20 pulses. t=0 corresponds to beginning of plasma-surface interaction

The major cracks and micro cracks were observed on exposed tungsten surface. With increasing number of plasma pulses the major cracks are partly filled by molten metal. The solid particles brake away from the crack edges during the plasma impact. The droplet ejection was predominantly from the edges of castellated structures. Mountains of displaced material on the edges of constructional units are found to be a source of the splashed droplets.

Thus, it is shown that melt dynamics on the structure edges, droplet splashing and molten bridges through the slits are determining processes in macroscopic erosion of castellated surface structures.

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ПОВЕДЕНИЕ ЗУБЧАТЫХ СТРУКТУР ПОД ОБЛУЧЕНИЕМ ПЛАЗМОЙ КСПУ Х-50 В УСЛОВИЯХ, ХАРАКТЕРНЫХ ДЛЯ ИТЭР

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На квазистационарном плазменном ускорителе КСПУ Х-50 проведено экспериментальное изучение эрозии зубчатых мишеней под воздействием поверхностных тепловых (удельная энергия и длительность импульса) и корпускулярных нагрузок, характерных для режимов ELM в ИТЭР. Повреждение поверхности, механизмы эжекции частиц в твердой и капельной фазе из различных частей мишени исследованы в зависимости от количества плазменных импульсов. Показано, что динамика движения расплава на границах структур, разбрызгивание капель и появление «мостиков» расплава через зазоры между составляющими мишени являются определяющими процессами в макроскопической эрозии составных поверхностных структур.

ПОВЕДІНКА ЗУБЧАСТИХ СТРУКТУР ПІД ОПРОМІНЕННЯМ ПЛАЗМОЮ КСПП Х-50 В УМОВАХ, ХАРАКТЕРНИХ ДЛЯ ІТЕР

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На квазістаціонарному плазмовому прискорювачі КСПП Х-50 проведено експериментальне вивчення ерозії зубчастих мішеней під впливом поверхневих теплових (питома енергія і тривалість імпульсу) і корпускулярних навантажень, характерних для режимів ELM в ІТЕР. Пошкодження поверхні, механізми ежекції частинок в твердій і крапельній фазі з різних частин мішені досліджені в залежності від кількості плазмових імпульсів. Показано, що динаміка руху розплаву на межах структур, розбризкування крапель і поява «містків» розплаву через зазори між складовими мішені є визначальними процесами в макроскопічній ерозії складених поверхневих структур.