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Influence of surface tension on macroscopic erosion of castellated tungsten surfaces during repetitive transient plasma loads

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This paper is focused on the analysis of surface tension contribution to the erosion features of tungsten resolidified surfaces and resulting material response to large number of repetitive transient hydrogen plasma impacts. Experimental investigations of erosion processes on castellated tungsten surfaces in conditions relevant to uncontrolled ITER ELMs have been performed within powerful quasi-stationary plasma accelerator QSPA Kh-50. The surface energy load measured with a calorimeter was varied between melting (0.6 MJ/m^2) and evaporation (1.1 MJ/m^2) thresholds, the plasma pulse duration was 0.25 ms. Observations of plasma interactions with exposed W surfaces, analysis of dust particle dynamics and the droplets monitoring have been performed with a high-speed digital camera. Repetitive plasma loads above the melting threshold led to formation of melted and resolidified surface layers. Networks both macro and intergranular cracks appeared on exposed surfaces. Cracks propagate to the bulk mainly transversely to the irradiated surface. The splashing of dust/liquid particles has been analyzed in the course of repetitive plasma pulses. It was revealed that mountains of displaced material at the edges of castellated units are primary source of the splashed droplets due to development of instabilities in melted layer. The solid dust ejection dominates by cracking processes after the end of pulse and surface resolidification. Due to the continuously growing crack width (from value of sub-µm till tens µm) with increasing number of pulses the initially uniform melt pool on the castellated units became disintegrated into a set of melt structures separated by cracks. After large number of exposures the progressive corrugation of the surface occurred due to the capillary effects on exposed W surfaces. Results of simulation experiments for castellated targets and developed surface structures are compared with repetitive plasma exposures of flat tungsten surfaces.

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1. **Introduction**

Understanding of plasma-surface interaction (PSI) effects during the transient events in future fusion reactors requires dedicated R&D activity in plasma simulators used in close connection with material characterization facilities as well as with numerical modeling [1]. Castellated geometry of Plasma-Facing Components (PFC) is considered as reference design for the ITER divertor surface [1, 2]. A castellated surface of monoblock is to be used in order to reduce the influence of electric currents induced upon the metallic surfaces during the reactor operation, as well as to minimize thermal stresses, which might be caused by the formation of macro-cracks meshes and the resulting tungsten erosion. Material melting (especially edges of monoblocks) can occur under ELM heat loads and disruptions [3]. Subsequently, the edges of the castellated PFCs of the ITER divertor can be a source of enhanced erosion, i.e., the emission of molten/solid dust particles which can be ejected into the plasma region. Thus the detailed experimental studies of threshold values for the damaging processes: roughening, crack formation, droplets/dust generation, melting of the PFC, under ITER or DEMO relevant loading scenarios are required for evaluation of the materials performance under the transient events.

The energy density (~0.5 MJ/m^2 (controlled) and up to 4 MJ/m^2 (uncontrolled)), the duration (0.25-0.6 ms) of ITER Edge Localized Modes (ELM) as well as particle loads (up to 10^{24} ions$\times$m$^{-2}\times$s^{-1}) [1] can be well reproduced with Quasi-Stationary Plasma Accelerators (QSPA). Melt motion effects, driven by external forces such as gradients of both plasma pressure and recoil pressure of evaporating material, surface tension, and Lorentz forces, have been investigated in previous studies with QSPA Kh-50 and QSPA-T in experiments simulated the expected ITER transient events [4-9]. It should be mention, that plasma pressure in QSPA plasma streams is large in compare with expected for ITER disruption and ELMs. Nevertheless, increasing the pressure of the impacting plasma stream allows one to clarify the contribution of the plasma pressure gradient to the melt motion, even for a QSPA plasma pulse of 0.25 ms duration, and to approach the melt velocities as those expected for ITER disruptions [5]. Whereas in ELMs simulation conditions the influence of melt motion on the surface profile becomes evident only with large number of pulses [4-7]. Experimental results from the castellated targets exposed to pulsed plasma streams would be of great interest for the numerical simulation of surface damage effects which are caused by the material melting [9–11] and dust production [12-14]. It should be noted that a MEMOS code, based on the shallow water approximation, has been well developed [7, 8]. An experimental analysis of the dominating erosion mechanisms in 3D geometry, which contribute to the material performance, can be used for the validation of a 3D version of the MEMOS code which is now available [15].

This paper is focused on the analysis of surface tension contribution to the erosion features of castellated tungsten resolidified surfaces and resulting material response to large number of repetitive plasma impacts. It could provide input to studies of PFC erosion in ITER and DEMO-like conditions.

2. Experimental device, sample 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 carried out with a quasi-stationary plasma accelerator QSPA Kh-50 [4-7] that is largest and most powerful device among Quasi-Stationary Plasma Accelerators. The main parameters of the hydrogen plasma streams are as follows: ion impact energy about 0.4 keV, maximum plasma pressure 0.32 MPa (that is larger than plasma pressure (up to 0.01 MPa) relevant to ITER), and the stream diameter 18 cm. It should be note, that driving force for melt motion is quite small $F=\nabla P_{QSPA}<0.2$ MN/m^3 (D≈5 cm near axis). The surface energy load measured with a calorimeter was 0.9 MJ/m^2 (relevant to unmitigated ITER ELMs Type I) i.e. above the melting (0.6 MJ/m^2) and below the evaporation (1.1 MJ/m^2) thresholds of tungsten [7] (i.e. plasma load is near to plasma load relevant to ITER ELMs). The plasma pulse shape is approximately triangular, pulse duration 0.25 ms.

Target has been manufactured from sintered tungsten sample of Plansee AG trademark with sizes of 5 × 5 × 1 cm with slits (Fig. 1 a). The size of each target unit is 24x12x5 mm, that is comparable to momoblocks in ITER. The width of gaps between elements is 1 mm. The surface of the target was oriented perpendicularly to the impact plasma stream. The target temperature before and between irradiating pulses corresponded to room temperature level. The maximum number of plasma impacts achieved 200 pulses.

As on 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 at the exposure time ranging from 1 μs to 1 s, spatial resolution 12×12 μm^2 and within the spectral range from 290 nm to1100 nm [16, 17]. Optical methods of diagnostics were used for determination of the main plasma parameters (electron density and temperature) and studies of the impurity behavior during the time of discharge. Surface analysis was carried out with an optical microscope MMR-4 equipped with a CCD camera. Measurements of weight losses and microhardness of the surface were performed also.

3. **Experimental results**

3.1. Castellated target exposure by 100 plasma pulses.

The results of experiments on tungsten irradiation with 100 exposures with the surface heat load of 0.9 MJ/m^2, performed earlier [17], can be briefly summarized as follows. The plasma impacts lead to pronounced erosion of the target, which is accompanied by separation of tungsten droplets/dust from the exposed target surfaces (Fig. 2a). The number of ejected particles and their velocities depend on the irradiating dose: as the number of pulses increases, the velocities of particles decrease (Fig. 3), 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.

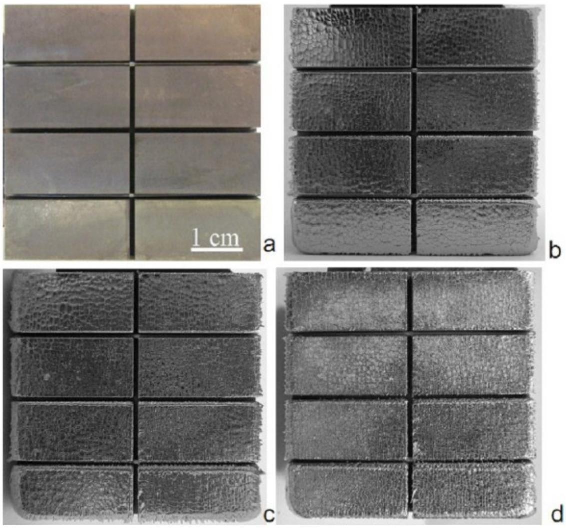

Fig. 1. General views of castellated target. Initial (a) and surfaces exposed by 80 (b), 150 (c) 200 plasma pulses

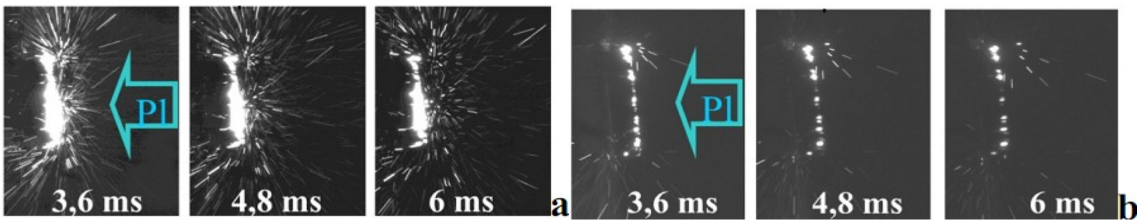

Fig. 2. The particle ejection during plasma-surface interaction (PSI). Images of droplet traces $t_{exposure}$ = 1.2 ms, after 80 (a) and 150 pulses for t = 3.6 ms (left), 4.8 ms (middle), 6 ms (right)

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 (Fig. 4a) [16, 17]. The edges erosion exceeded the erosion of the target central area considerably, and it dominated in the resulting damage of the exposed targets. Major crack network with average cell size up to 500 μm appeared after 100 pulses. Width of major cracks ≈ 6 μm. The micro-crack network has a cell size about 50 μm. Width of micro-cracks does not exceed 1 μm (Fig. 1, 5).

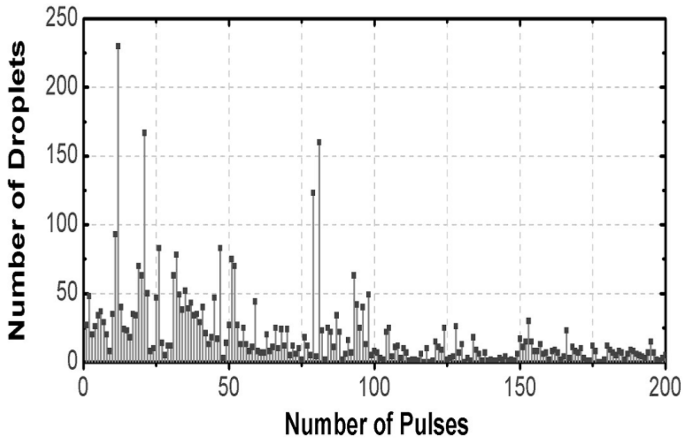

Fig. 3. Number of ejected particles vs. number of plasma pulses

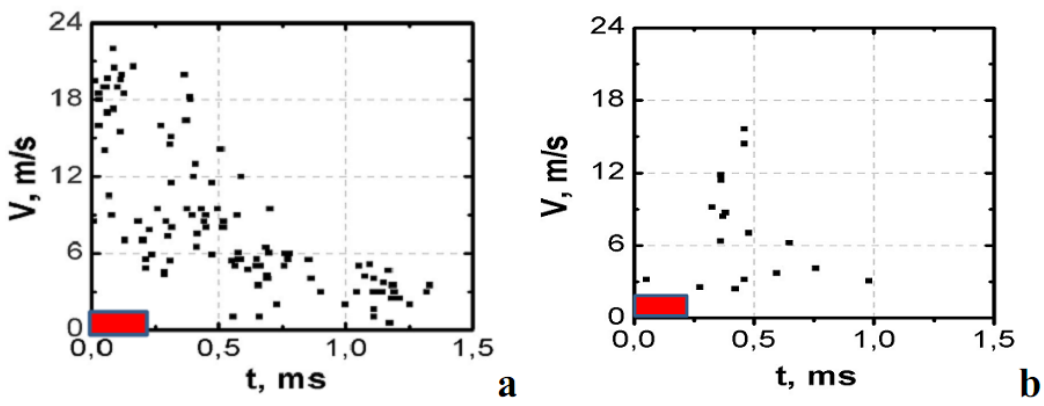

Fig. 4. Velocity distribution of ejected particles v.s. particle start-up time from the surface after 80 (a) and 150 (b) plasma pulses. Duration of plasma pulse marked shaded rectangles.

3.2. Castellated target exposure by 200 plasma pulses.

In recent experiments we applied additional 100 exposures of the castellated tungsten target with target analysis after 50 and 100 pulses. Thus, the total number of exposures achieved 200. Number of ejected particles essentially decreased after hundred plasma pulses (Fig. 3). Maximum velocity of ejected particles is 23 m/s. The melt layer re-solidifies completely 0.25 ms after the start of interaction of plasma with target surface [14]. Velocity of ejected particles decreased with increasing pulse number (Fig. 4). Elastic energy stored in stressed surface layer of tungsten should be the motive force for the cracking process with following acceleration of separated solid particles. The solid dust ejection dominates by cracking processes after the end of pulse in the course of surface resolidification [13, 14]. Mountains of displaced material, accumulated at the edges of castellated units are found to be the primary source of the splashed droplets (Fig. 1). After 200 pulses the surface significantly damaged by crack meshes (Fig. 5).

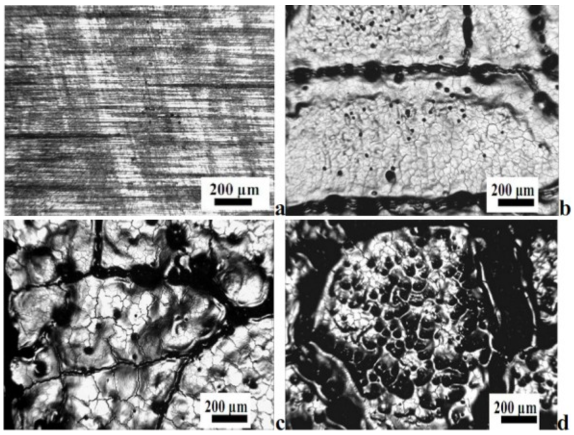

Fig. 5. Images of initial surface (a) and after different: 80 (b), 150 (c), 200 (d) plasma pulses

4. Discussion and conclusion

Repetitive plasma loads above the melting threshold led to formation of melted and resolidified surface layers. Networks both macro and intergranular cracks appeared on exposed surfaces (Fig. 5). Cracks propagate to the bulk mainly transversely to the irradiated surface [4-6]. The splashing of dust/liquid particles has been analyzed in the course of repetitive plasma pulses. It was revealed that mountains of displaced material at the edges of castellated units are primary source of the splashed droplets. The solid dust ejection dominates by cracking processes after the end of pulse and surface resolidification.

Due to the continuously growing crack width (from fraction till tens μm) with increasing number of pulses the initially uniform melt pool on the castellated units became disintegrated into a set of melt structures separated by cracks (Fig. 5). As result, a number of ejected particles essentially decreased after first hundred plasma pulses. Further increase of repetitive plasma impacts (above 200) led to considerable qualitative changes of surface morphology. Each cell of the crack network is strongly subjected to the surface tension that minimizes melt pool area. After large number of exposures the progressive corrugation of the surface occurred due to the capillary effects on exposed W surfaces.

Rayleigh–Taylor instability leads to bridges formation between neighboring castellated units (Fig. 6). Growth of radius of edge convex prevents fast formation of bridges. Thus surface tension stabilizes the growth of Rayleigh– $R_{RT} \geq \frac{0.53 V_m^2 \rho_m^{1/3} \tau_m^{4/3}}{\sigma^{1/3}}$ Taylor instability R_{RT} critical edge convex radius; τ_m - time of intense melt motion; σ- surface tension; ρ_m- density of melted material; V_m -velocity of melt motion. If $R > R_{RT}$ growth of instability and the bridges between the units do not occur [8,9].

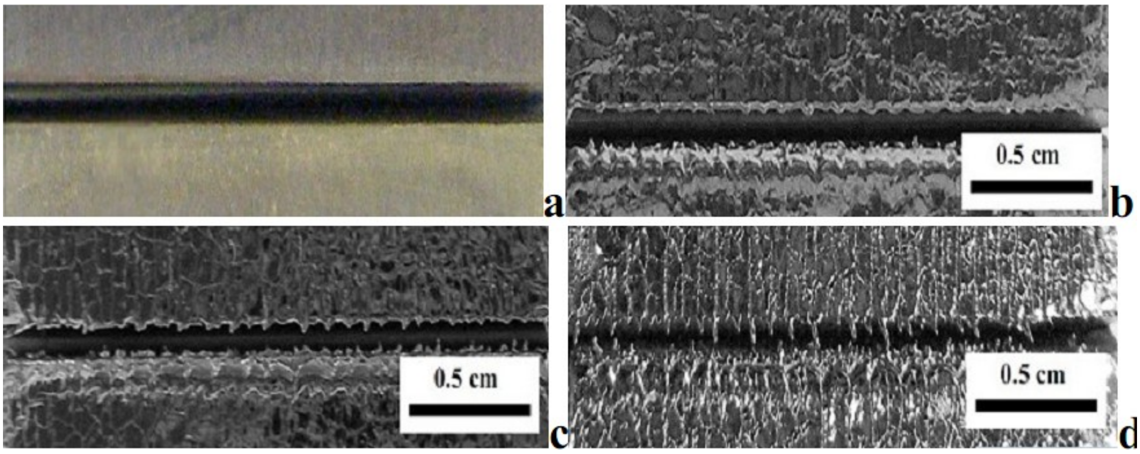

Fig. 6. Bridges between the units appeared after different plasma pulse: Initial (a), after 80 (b), 150 (c) and 200 (d) plasma pulses

Break away condition for RT instability ξ - value of perturbation $\xi \geq \frac{1}{\gamma_{RT}} \sqrt{\frac{6\sigma}{r_{RT} \rho_m}}$; r_{RT} radius of droplets; γ_{RT} maximum instability increment; σ- surface tension; ρ_m- density of melted material. If $\gamma_{RT}\tau_m$ <1 growth of RT waves is negligible [8,9]. The protuberances (length up to 0.2 cm) appear at the edges due to the motion of molten layer and developed Rayleigh–Taylor instability (Fig. 7).

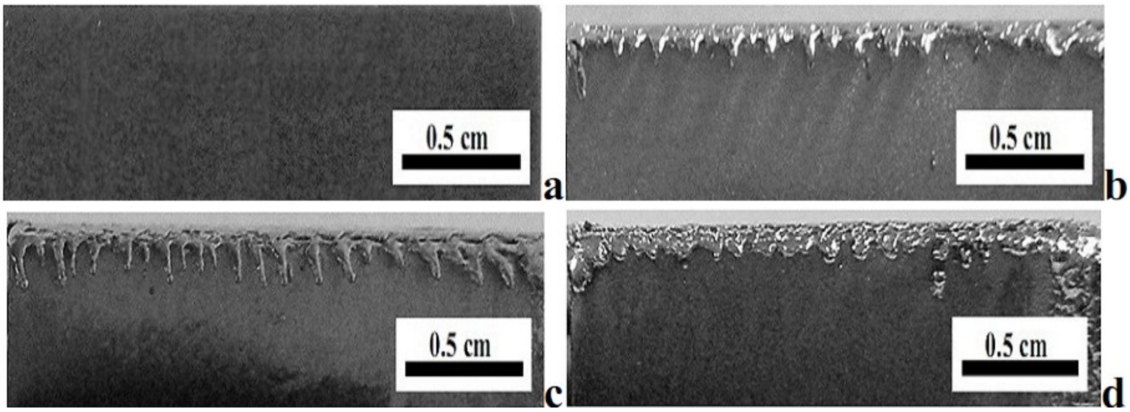

Fig. 7. Images of initial (a) outward unit edge and after different: 80 (b), 150 (c), 200 (d) plasma pulses

The length of protuberances decreased to halve after 200 pulses. The length of protuberances agreed with estimation value of RT perturbation (ξ).

Results of simulation experiments for castellated targets and developed surface structures are compared with repetitive plasma exposures of flat tungsten surfaces [4, 19]. As it shown early in experiments simulated ITER disruption [5, 7, 19], the melt layer motion driven by plasma pressure results in erosion crater formation with rather large mountains of the resolidified material at the crater edge. In present experiments a small pressure gradient does not produce pronounced melt motion, this allows to evaluate contribution of surface tension to W erosion.

Surface damage under heat load above melting threshold at increase of plasma pulses could be summarized in the following way (Fig. 8). Networks of cracks appeared on exposed surfaces (Fig. 8a). The melt motion causes the partial filling of cracks (Fig. 8a). Increased depth and width of the cracks and negligible melt motion on small brush surface are observed Fig. 8c). Each cell of the cracks network is strongly subjected to the surface tension that minimizes the cell surface area. Surface tension is responsible for the shape of melted areas between cracks (Fig. 8d). Suppression of droplets splashing after repetitive pulses (Fig. 3) is due to surface tension effects.

Nevertheless as, it was shown in simulation with MEMOS for ITER relevant conditions, at violent melt motion with the melt velocity of 1 m/s the sharp edge leads to a fast growth of the RT instability and the intense droplet splashing can occur at the brush edges with $R < 0.001$ cm [8].

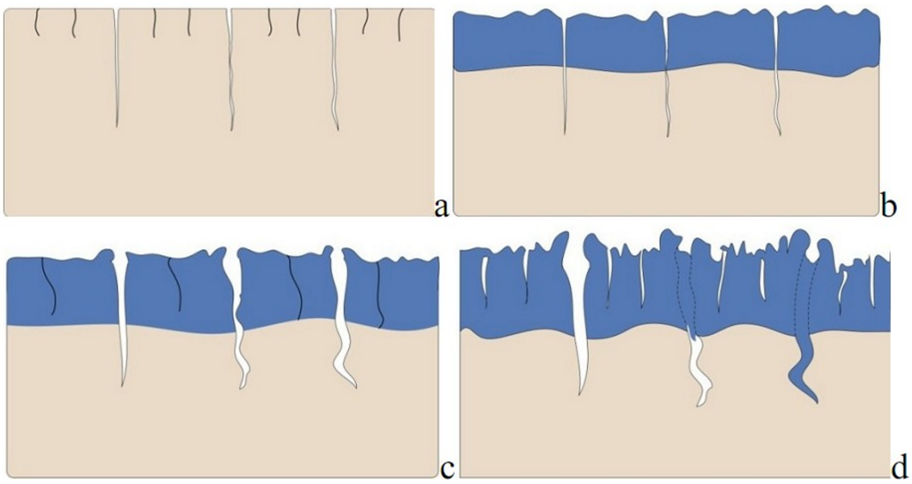

Fig. 8. Scheme of contribution of surface tension in suppression of droplets splashing

Thus, experimental investigations of erosion processes on castellated tungsten surfaces in conditions relevant to ITER ELMs have been performed within powerful quasi-stationary plasma accelerator QSPA Kh-50. Networks both macro and intergranular cracks as well as melt motion are observed on exposed castellated W surfaces in result of repetitive plasma loads with energy density above the melting threshold. Each cell of the crack network is strongly subjected to the surface tension that minimizes melt pool area. After large number of exposures the progressive corrugations of the surface developed due to the capillary effects. Surface Tension prevents fast formation of bridges between units and essentially suppresses droplets ejection from exposed surfaces for growing number of repetitive QSPA plasma impacts.

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