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ORIGINAL PAPER

Transient plasma loads to the ITER divertor surfaces: simulation experiments with QSPA Kh-50

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Abstract. Experimental simulations of International Thermonuclear Experimental Reactor (ITER) transient events with relevant heat load and particle load parameters have been performed with a quasi-stationary plasma accelerator QSPA Kh-50. Pulsed plasma guns PPA and IBIS were also used for comparative studies of surface damages appearing under varying plasma parameters and sorts of plasma ions. Particular attention is paid to the material erosion due to particles ejection from the tungsten surfaces both in the form of droplets and solid dust. Generation mechanisms of the dust in the course of ELM-like plasma impacts to the tungsten surfaces are discussed.

Key words: plasma accelerator • transient loads • tungsten • dust • fusion reactor

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Introduction

The anticipated regime of the tokamak ITER is the ELMy H-mode. The edge localized modes (ELMs), intrinsic for this regime, produce short periodic pulses of heat flux to the divertor armor, being the most heat loaded part of the tokamak. The disruptions can also occur, despite of mitigation schemes such as the massive gas injection and others. The expected transient events determine the erosion rate and the lifetime of PFCs (plasma-facing components), being one of the most important issues that influence the tokamak performance [6, 7].

The energy range of ITER disruptions and ELMs will be clearly higher than in the existing tokamaks. Taking into account the laboriousness of the experiments on plasma-surface interactions (PSI) in these devices, experimental investigations have to be performed with other powerful plasma sources able to reproduce the energy and particles loads during the transients [1, 2, 5, 10, 11, 13].

This paper presents the results of simulation experiments with powerful plasma impacts on the tungsten and carbon surfaces that are ITER relevant PFMs (plasma-facing materials), analysis of residual stresses in tungsten and cracking development as well as erosion mechanisms resulting in particles ejection from the exposed surfaces.

Experimental setup

The simulation experiments aimed at comparative studies of PSI issues and materials damage were carried out

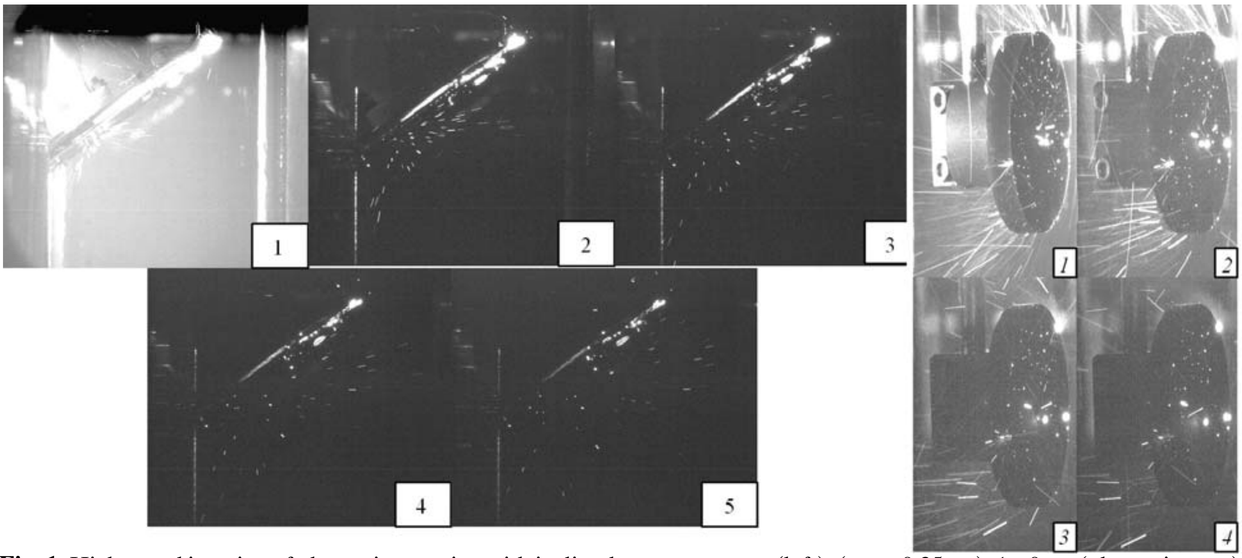

Fig. 1. High speed imaging of plasma interaction with inclined tungsten target (left), (t_{exp} = 0.25 ms): 1 – 0 ms (plasma impact); 2 – 1.16 ms; 3 – 2.32 ms; 4 – 3.48 ms; 5 – 4.64 ms; Q_{surf} = 0.75 MJ/m^2. Exposures of graphite target (right), inclined at 45° in vertical plane (t_{exp} = 1 ms): t_1 = 1 ms; t_2 = 2 ms; t_3 = 3 ms; t_4 = 4 ms after pulse; Q_{surf} = 0.5 MJ/m^2.

with QSPA Kh-50 (quasi-stationary plasma accelerator) [2, 4] and PPA (pulsed plasma gun) [11–13] in Ukraine and RPI-IBIS (multi-rod plasma injector) facility in Poland [5, 10].

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 which correspond to the ELM impact in ITER. The plasma stream diameter is 18 cm, the ion energy is varied in the range of (0.4–0.9) keV, and a maximum plasma pressure achieves 3.2 bar [3, 14].

The pulsed plasma accelerator PPA generates plasma streams with ion energy up to 2 keV, plasma density (2–20) × 10^{14} cm^{-3}, a maximum specific power of about 10 MW/cm^2 and plasma energy density varied in the range of (5–40) J/cm^2. The plasma stream duration was 3–6 μs. Either helium or hydrogen were used as working gases [12, 13].

Deuterium plasma streams with a power density of 1–5 MW/cm^2 and pulse duration of 1–5 μs, generated by RPI-IBIS were used for comparative studies and determination of an initial stage of evaporated impurity dynamics during plasma-surface interaction as well as features of surface damage under varied plasma parameters [5, 10].

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). In order to determinate the main plasma parameters (electron density and temperature) and to investigate the impurity behavior during the time of discharge, optical methods of diagnostics were used. The spectroscopic measurements were performed by means of a two different spectrometers that provide with a good space- and time resolution. Particularly, a Mechelle®900 spectrometer equipped with a CCD-camera and operated in the wavelength range (300–1100 nm) with different exposition times was in use [5, 10]. A surface analysis was carried out by scanning electron microscopy (SEM). Residual stresses were measured with XRD by the $\sin^2\psi$ method.

Experimental results

Figure 1 shows the high speed imaging of QSPA Kh-50 plasma interaction with the inclined tungsten target. First frame corresponds to the plasma pulse time, and the next images show dynamics of the tungsten droplets and solid W dust in front of the target surface.

Information from several frames with detected traces of particles flying from the W surface after the plasma shot allows calculation of the velocity of particles and the time moment when they started from the target surface. Tungsten particles registered in the experiment have velocity up to 20 m/s for earlier instants. For the latter moments, the velocity decreased to several m/s. Analysis of the obtained experimental results and comparison with the numerical simulation [4] allows conclusion that the generation of W particles in the form of droplets may occur only during the plasma pulse and (as latest) few tens microseconds after the pulse end. Thus, in spite of the energy load to be sufficient for melting, only first traces are attributed to the fast W droplets. Other traces are formed by the ejected solid dust. Generation of dust is registered also during exposures of the graphite targets (Fig. 1).

Dust generation mechanisms for tungsten are associated with W cracking. Figure 2a shows the cross-cut of the target and also the exposed W surface with major cracks and intergranular micro-crack meshes. Major cracks are attributed to ductile-to brittle transition effects, while micro-cracks are due to resolidification of the surface layer. Solid particles may split from the crack edges during the rupture. Elastic energy stored in stressed tungsten surface layer is the motive force for the cracking process [8].

Results of residual stresses measurements are presented in Fig. 2b. Similar level of residual stresses is obtained also for short pulse hydrogen exposures in PPA and for helium plasma pulses. The main part of the elastic energy is spent for the cracking itself and the rest of the elastic energy remaining after splitting the particle is transformed to the particle acceleration. Such a mechanism is obviously important for micro-particles

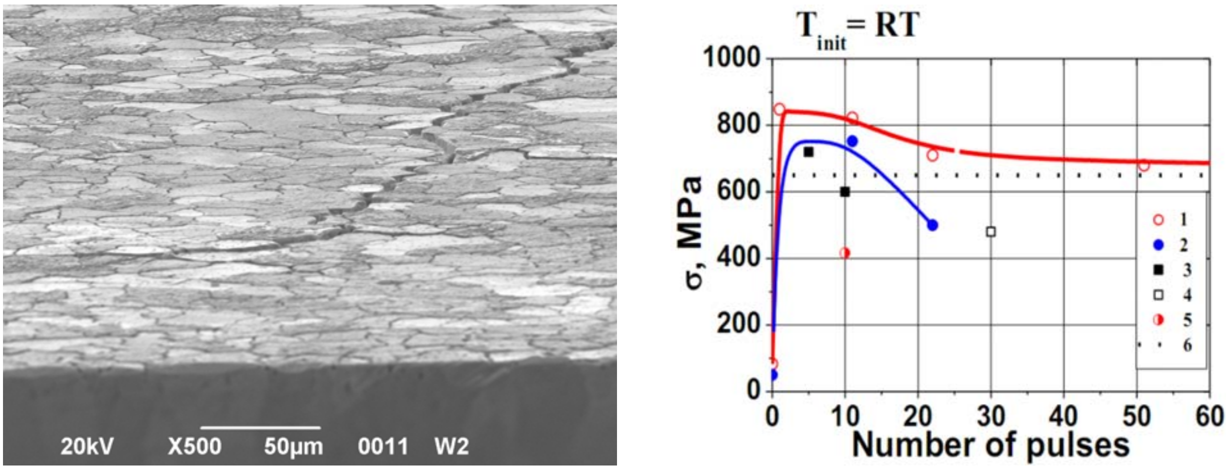

Fig. 2. Exposed W surface with major and micro-cracks after QSPA plasma impacts (a), residual stresses (b) vs. the number of hydrogen plasma pulses of QSPA and helium and hydrogen plasma exposures in PPA. 1 – QSPA, 0.45 MJ·m^{-2}; 2 – QSPA, 0.75 MJ·m^{-2}; 3 – PPA, helium, 0.4 MJ·m^{-2}; 4 – PPA, helium, 0.2 MJ·m^{-2}; 5 – PPA, hydrogen, 0.4 MJ·m^{-2}. Dashed line 6 indicates the stress magnitude after 270 QSPA hydrogen plasma pulses of 0.45 MJ·m^{-2}.

formation, e.g. in the course of crack bifurcation, as it is demonstrated in Fig. 3b. Brittleness effects result in dust arising from major cracks. However, in addition, dust particles are able to be formed from the re-solidified melt bridges across micro-cracks. The bridges are caused by melt motion, capillary effects and significant viscosity of W melt. This mechanism is illustrated by Fig. 3a. It could not be responsible for μm-size dust due to very small crack thickness. But a lot of nanosize particles can be originated from the bridges.

Examples of nanosize dust particles that have been recognized on exposed W surface after multiple plasma exposures are presented in Fig. 4. These images illustrate one more possible mechanism of dust produc-

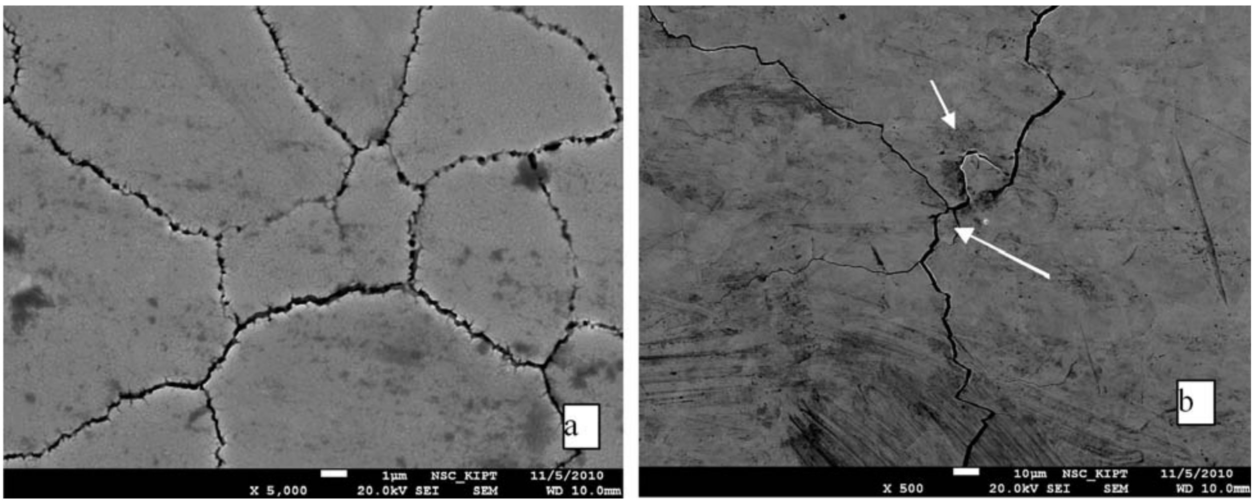

Fig. 3. W surface after QSPA exposures. Possible sources of nm-size dust particles (a) and μm-size dust particles (b).

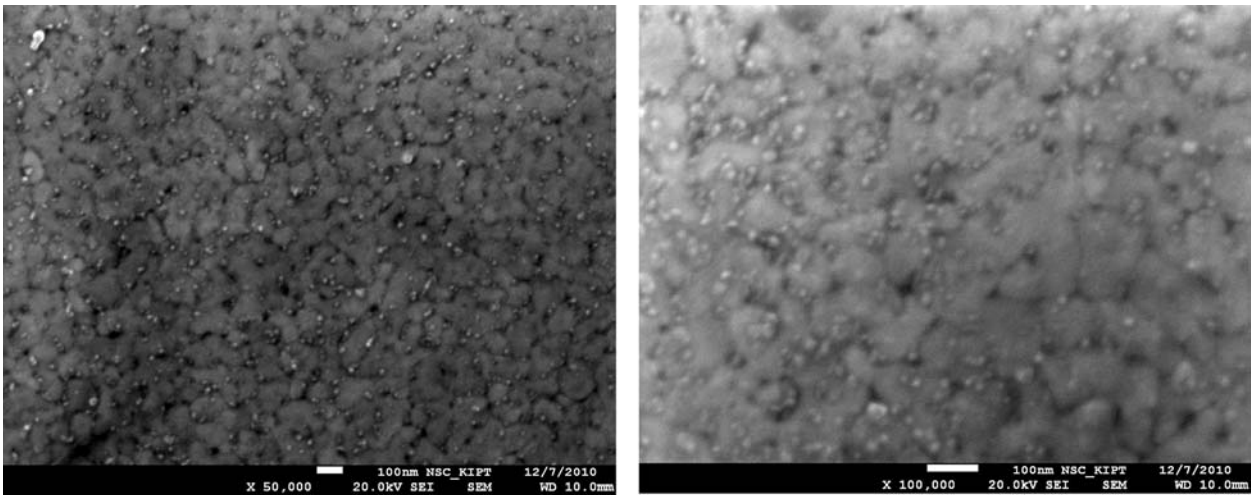

Fig. 4. Dust of nm-size collected on W surface.

tion, which is due to the material modification with the formation of fine cellular structure of the surface layer, e.g. [2, 9]. Typical size of the cellular structures is 100–500 nm. The origin of voids between fine cells can also be accompanied by a dust ejection. Then, edges of the ejected nm particles are able to be melted even for rather small heat loads below the surface melting threshold. This can be a reason for a ball shape of nm particles on a solid surface of the target. Such solid dust particles are deposited back to the target surface by plasma pressure in the pulse tail stage. Larger particles (tens of μm), in principle, have more chances to fly away irreversibly from the surface. Nevertheless, tungsten balls of nm and μm size were detected earlier inside the major crack voids in the regimes with pronounced melting [2]. Therefore, in those experiments the contribution of resolidified droplets to W balls population inside cracks was quite significant.

In IBIS experiments, spectroscopy studies of appeared WI and WII spectral lines of eroded tungsten in plasma provided a possibility for monitoring tungsten spectral lines and accurate measurement of W plasma density in front of the target. Information about dynamics of the W-ions production (mainly from the evaporation of dust particles in front of the surface) was obtained. On the basis of the space- and time-resolved spectroscopic measurements of the D_α line in RPI-IBIS, it was estimated that the highest electron density of the plasma layer in front of the target surface amounted to about $3.4–10^{16}$ cm^{-3} [5, 10]. Thus, the plasma pressure is quite sufficient to bring a small-size fraction of the ejected dust back to the exposed surface.

Summary and conclusions

Several mechanisms of dust generation under the transient energy loads to the tungsten surfaces have been recognized and identified in this study. Dust particles with sizes up to tens μm could be ejected from the surface due to the cracking development and major cracks bifurcation. This mechanism would be important for the first transient impacts when crack mesh is formed. The energy loads can be moderate and even could not result in melting. However, must be above the cracking threshold. Taking into account that for many repetitive pulses, the cracking threshold shifts to smaller energy loads and this mechanism can only be enfeebled by tungsten preheating above the ductile-to-brittle transition temperature. Fatigue cracks are still able to be developed after a large number of transient impacts to the preheated W surface.

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 nm-size dust. For this mechanism, the mass taken away by any single particle is much smaller, but the number of dust particles is considerable.

Furthermore, even in the case of mitigated cracking, the effects of surface modification of tungsten material after the repetitive plasma pulses with development of ordered submicron cellular structures [9] are able to contribute significantly to the dust generation. However, the obtained experimental results show that the majority of generated dust particles are deposited back to the surface by the plasma pressure. This result is confirmed by plasma parameter measurements in front of the surface (both in IBIS and in QSPA Kh-50). As a sequence, spectral lines of W atoms and ions in plasma are observed during the pulse in a very thin near-surface layer only.

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