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Experimental validation of 3D simulations of tungsten melt erosion under ITER-like transient loads

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ABSTRACT

Tungsten in form of a macrobrush structure is foreseen as one of two candidate materials for the ITER divertor. The main mechanisms of metallic target damage are surface melting and melt motion erosion, which determines the lifetime of plasma facing components (PFC). The damage to W-macrobrush targets under repetitive ELM-like heat loads corresponding to the conditions of the plasma gun QSPA-T and ITER is numerically investigated with the three-dimensional melt motion code MEMOS. The calculations revealed a significant damage to brush edges caused by the interaction of impacting plasma with the lateral surfaces. In addition, experimentally observed overlapping of brush gaps by molten tungsten was numerically confirmed. These 3D effects of the repetitive transient loads may significantly influence the PFC lifetime.

1. Introduction

Operation of ITER is assumed to be the H-mode. A characteristic feature of this regime is the transient release of energy from the confined plasma onto plasma facing components (PFCs) after the transient events (TE) such as multiple ELMs (about 10^3–10^4 per discharge) and the disruptions, which can play a determining role in the erosion rate and the PFC lifetime. The expected fluxes on the ITER divertor during the transients are: Type I ELM energy fluxes of 0.5–4 MJ/m^2 in timescales of 0.3–0.6 ms [1].

Tungsten macrobrush armour (W-brush) is foreseen as one of PFC for the ITER divertor and the dome. During the intense loads, melting, melt motion, melt splashing, surface cracking, exfoliation and evaporation are seen as the main mechanisms of metallic armour damage. The damage to PFCs after each TE leads to significant changes of surface shape, which substantially influence the plasma impact dynamics and the erosion rate for a subsequent TE. This accumulated damage ultimately determines the lifetime.

The expected erosion of ITER PFCs under transient energy loads can be properly estimated by numerical simulations using codes validated against target erosion of the experiments at the plasma gun facilities, in which most important peculiarities of the plasma-PFC interaction expected in ITER can be modeled. The experimental data on PFCs erosion under repetitive ELM-like plasma loads for satisfactory numerical modeling were obtained mostly at the plasma gun QSPA-T [2] within the collaboration established between the EU fusion programme and the Russian Federation. The measured material erosion of W-brush targets was used to validate the code MEMOS which was then applied to model the erosion of ITER divertor and main chamber under expected TE [3–6].

Earlier algorithms incorporated in the code MEMOS take into account the macrobrush geometry in a simplified way being based on 2D heat transport and 1D melt motion models. Moreover, the code MEMOS was applied mainly for the damage simulations of single transient events. For the repetitive TE loads only a few simplified studies were carried out [3] based on the assumption that the total erosion is the linear composition of the erosion after single transient loads applied to the undisturbed surface.

However, for multiple heat loads the QSPA-T experiments [2] discovered new important three-dimensional and non-linear accumulative features. The 3D effects include a melting of brush edges and melt layer displacement along the surfaces directed parallel to the impacting plasma stream. The non-linear accumulative effect of repetitive TE loads is bridging between brushes. The analytical estimations [7] demonstrated that for the bridging the

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Rayleigh–Taylor instability caused by the centrifugal force at the brush edges is responsible. The critical radius of brush edge of bridge growth was determined.

For the adequate numerical simulations of the macrobrush armour damage the code MEMOS was significantly upgraded. To investigate the non-linear accumulative effect of multiple TE loads on the PFCs the model was generalized in order to take into account the change of surface profile after each transient event. Now each next TE load changes the target surface. The centrifugal force at brush edges is accounted for. Also the extension of the code MEMOS to 3D geometry was done: 3D thermal transport solver to the Stefan problem is implemented. The 2D melt motion model based on the 'shallow water' approximation was developed. The driving forces, which are the plasma pressure, the surface tension gradient, the tangential pressure of inclined impact, are also adjusted to the 2D model. The appropriate 2D boundary conditions at the diverse involved surfaces (including the rare surface, the melt surface and the water cooled surface) are implemented.

The numerical simulations were carried out for the multiple ELM-like heat loads with the reference energy density $Q = 1.6$ MJ/m^2 and the timescale $\tau = 0.5$ ms, for which the experimental data on the target erosion are most complete. The influence of the brush edge radius R_e on the bridging under repetitive plasma action is analyzed. The numerical simulations for the ITER ELM-like repetitive heat loads with the plasma pressure below 0.01 MPa were done. The 3D numerical simulations carried out for the single brush under QSPA-T experimental conditions showed an additional significant damage to the brushes caused by the interaction of impacting plasma with the lateral surfaces.

2. W-macrobrush target erosion under repetitive ELM-like plasma heat loads

2.1. Experiment

The W-macrobrush targets (19.5 × 19.5 × 3 mm^3) consisted of separate tungsten elements of sizes (9.5 × 9.5 × 3 mm^3) with 0.5 mm gaps between brushes was exposed to repeated plasma pulses ($N = 100$) with energy density in a range of 0.35–1.6 MJ/m^2 and 0.5 ms duration. The targets were preheated up to 500 °C. The plasma stream has Gaussian profile with half-width of 8 cm along a target and was inclined under angle of $\alpha = 30°$ to the target surface. The maximum of plasma pressure varied in range of 0.2–0.9 MPa [2].

The damage of tungsten brushes was determined mainly by melt layer movement (Fig. 1): The main experimental results to be important for us are: $Q > 1.3$ MJ/m^2 bridges were formed already after 10 exposures. After 50 pulses all the gaps are melt-filled. The surface profile measurements along the plasma stream for target exposed with $Q = 1.6$ MJ/m^2 demonstrated that the surface roughness exceeds 0.2 mm after 100 shots. Target metalography across the target demonstrated large erosion of the brush edges, being parallel to the plasma stream, difference between brush center and brush edges achieves 1 mm.

Experimental results on melt layer erosion can not be directly extrapolated to ITER conditions because the plasma pressure at ITER target is expected to be at least by one order of value less than it is in QSPA-T.

2.2. Numerical simulations

The numerical simulations of repetitive ELM-like heat load were carried out for the W targets preheated up to 500 °C and heat load with the reference energy density $Q = 1.6$ MJ/m^2, $\tau = 0.5$ ms having Gaussian profile with half-width of 8 cm was applied. Two sets of the plasma pressure at the target were used, $p = 0.1$, 0.2 MPa (QSPA-T conditions) and $p = 0.005$, 0.01 MPa (ITER-like). The brush target is similar to experimental one: brush size $D = 1$ cm, distance between brushes 0.05 cm, radius of the brush edge rounding was varied $R_e = 0.1$, 0.15, 0.2 cm. Inclination of the plasma stream is 30°. Heating of the frontal and lateral sides of brushes are determined by the inclination angle and the gap width in accordance with the expressions given in [4]. After each pulse distributions of the pressure and heat load at the brushes surface are recalculated accounting real surface profile obtained after previous pulse. The melt motion is described in the 'shallow water' approximation. The tangential friction force is the main driving force for given heat load conditions. The tangential friction force p_S can be derived in assumption of the stochastically roughening surface (below α – inclination angle of plasma stream)

$$p_S = \frac{p}{\sqrt{1 + 8\sin^2\alpha}} \quad (1)$$

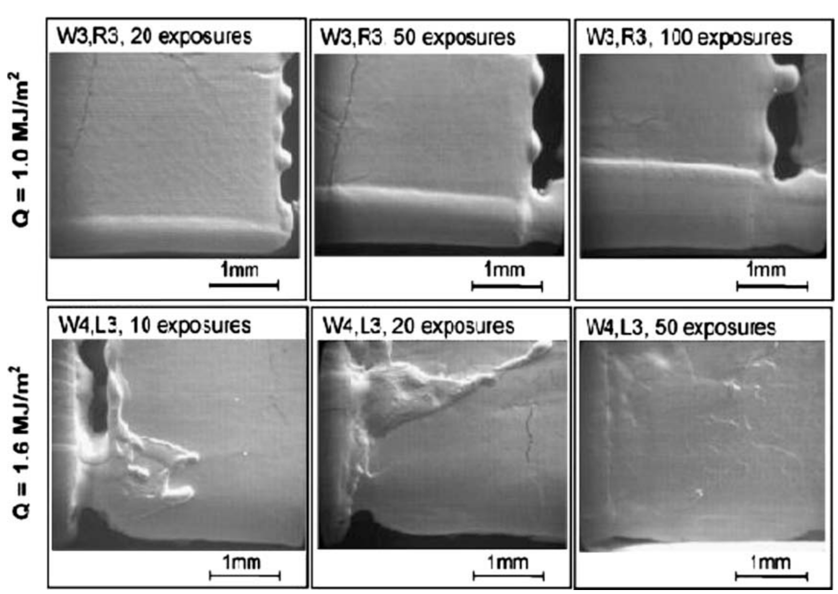

Fig. 1. The SEM view of the tungsten tile surface.

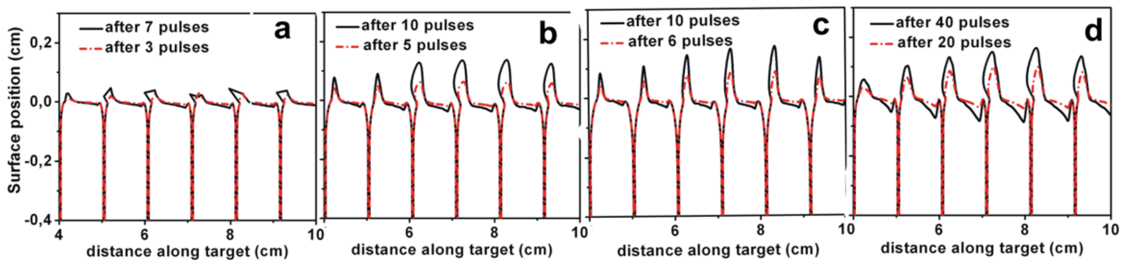

Fig. 2. Final erosion profile after repetitive heat loads (QSPA-T). (a) $R_e = 0.1$ cm, $p = 0.2$ MPa (b) $R_e = 0.15$ cm, $p = 0.2$ MPa (c) $R_e = 0.2$ cm $p = 0.2$ MPa (d) $R_e = 0.15$ cm, $p = 0.1$ MPa.

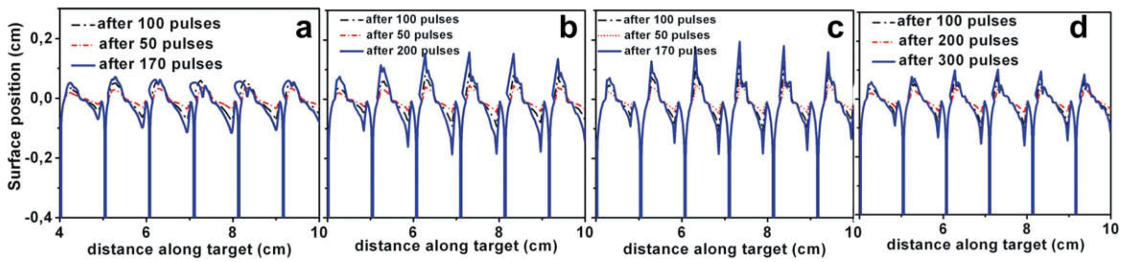

Fig. 3. Final erosion profile after repetitive heat loads (ITER). (a) $R_e = 0.1$ cm, $p = 0.01$ MPa (b) $R_e = 0.15$ cm, $p = 0.01$ MPa (c) $R_e = 0.2$ cm, $p = 0.01$ MPa (d) $R_e = 0.15$ cm, $p = 0.005$ MPa.

Centrifugal force is implemented into the 'shallow water equations' as correction to the plasma pressure

$$\tilde{p} = p - \frac{\rho h u_m^2}{R_e} + \frac{2\sigma}{R_e} \quad (2)$$

with u_m melt motion velocity along the brush edge, h thickness of melt layer and σ surface tension.

For given QSPA-T conditions calculated depth of melt pool below 36 μm (per pulse) and the negligible evaporation depth was obtained. Tangential friction force generates melt motion along the brush surface with melt velocities up to 1.3 m/s for $p = 0.2$ MPa and up to 0.7 cm/s for $p = 0.1$ MPa. Numerical simulations demonstrated evidently non-linear accumulative effect of repetitive TE heat loads, namely fast formation of the bridges between brushes (Fig. 2). Results obtained for different radius of the brush edge rounding R_e and plasma pressures showed that the centrifugal force at the brush edges is responsible for the bridge formation and the gap overlapping. The rate of the bridge growth is proportional to the melt velocity (the melt velocity is proportional to the applied plasma pressure) and reverse proportional to the R_e [8]. Thus for $R_e = 0.1$ cm ($p = 0.2$ MPa) visible bridges appears after seven pulses (Fig. 2(a)) whereas for $R_e = 0.2$ cm ($p = 0.2$ MPa) bridges were not observed even after 10 pulses (Fig. 2(c)). Brush edge radius $R_e = 0.15$ cm is too small to prevent bridge formation: bridging appears after 10 pulses for $p = 0.2$ MPa and after 40 pulses for $p = 0.1$ MPa. Numerical simulations demonstrate a rather good agreement with the QSPA-T experiments on the bridge formation. Simulation results lead to the conclusion. It should be expected existence of the critical R_e^{cr} so that for $R > R_e^{cr}$ bridging would be prevented. This confirms the earlier analytical estimation of the edge critical radius [7]

$$R_{cr} \geqslant \frac{0.53 u_m^2 \rho^{1/3} \tau_m^{4/3}}{\sigma^{1/3}} \quad (3)$$

with τ_m mean time of intense melt motion. For QSPA-T experimental conditions $\tau_m \sim 1$ ms and $R_{cr} \sim 0.13$–0.17 cm.

Numerical simulations for repetitive heat loads (up to 200 pulses) for expected ITER plasma pressures [1,2] ($p = 0.005$, 0.01 MPa) demonstrated that for the chosen R_e brush roughness linearly increases with number of pulses (Figs. 3 and 4). Formation of the bridges was observed for case $R_e = 0.1$ cm (Fig. 3(a)) that can be also seen in Fig. 4 for which sharp curve is obtained instead of linear curve for others R_e. Calculated melt motion velocities (up to 0.15 m/s for $p = 0.005$ MPa and up to 0.3 cm/s for $p = 0.01$ MPa) are much less than that obtained for QSPA-T. Due to less velocity of melt motion the critical edge radius becomes smaller (Eq. (3)) that prevents bridging. Thus the results demonstrated that it is possible to avoid gap filling for expected ITER-like TE loads by optimizing properly macrobrush target design.

3. W-brush erosion QSPA-like heat loads 3D effects

Additional brush damage caused by the plasma action on the lateral brush surfaces; being parallel to the plasma stream; was simulated for reference QSPA-T scenario (see above). The code MEMOS upgraded to 3D geometry was applied. The top brush surface is exposed uniformly with the reference energy density

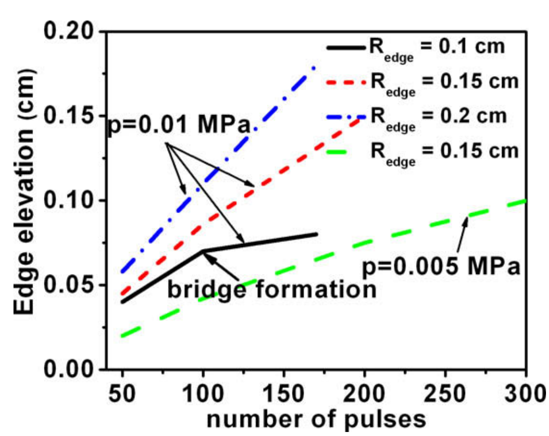

Fig. 4. Maximum mountain height vs pulse numbers.

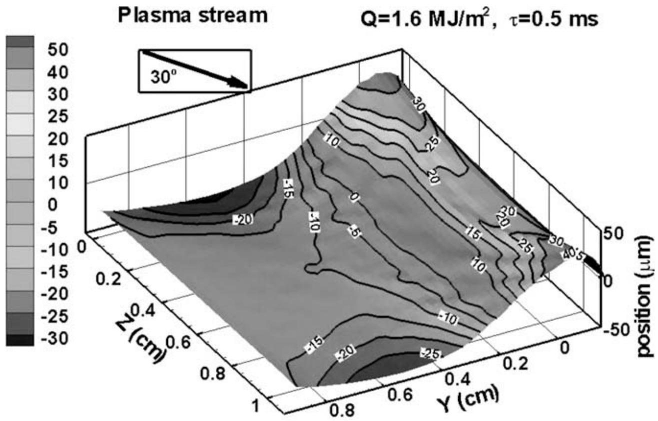

Fig. 5. Final surface profile of a single brush after QSPA heat load.

Q = 1.6 MJ/m^2, τ = 0.5 ms and plasma pressure p = 0.2 MPa. Heating the lateral brush surfaces was omitted. Tangential friction force as main driving force (Eq. (1)) is applied along Y-direction at the top and both lateral surfaces.

As previously the calculated depth of melt pool below 36 μm and the negligible evaporation depth were obtained. Tangential friction forces accelerate the melt layer along the surface with non-uniform distribution of melt layer velocity across plasma stream. The highest velocities are observed at the brush edges, being parallel to the plasma stream. This leads to formation of the non-uniform erosion profile (Fig. 5) across the brush with large erosion of the lateral brush edges. Difference between brush center and brush edges can achieve about 15–20 μm per pulse. This result well agrees with experimental results obtained in QSPA-T experiments – difference observed in experiments was about 1 mm after 100 shots.

Similar scenario calculated without accounting the plasma action at the lateral surfaces demonstrated uniform erosion across the brush. Damage deepness at the edge faced to the plasma stream about 12 μm and mountain height at the opposite edge about 20 μm were calculated. Such values correspond to the erosion along brush center obtained in the previous scenario.

4. Conclusions

The numerical simulations carried out for the QSPA-T repetitive heat loads demonstrated that the erosion monotonically increases with the number of ELMs. The melt mountain height is proportional to the ELM number. For the bridge formation and the gap overlapping the centrifugal force at the brush edges is responsible. Bridge formation time depends on the brush edge rounding.

The numerical simulations for the ITER ELM-like repetitive heat loads with the expected plasma pressure below 0.01 MPa demonstrated that in the case of brush edge radius larger than a critical radius the melt motion does not lead to the bridge formation.

The 3D MEMOS calculations revealed an additional significant damage to the brushes caused by the interaction of impacting plasma with the lateral surfaces.

The simulation results on the damage under the repetitive heat loads are in rather good agreement with the QSPA-T experiments on W targets.

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