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Tungsten melt layer erosion due to $\mathbf{J} \times \mathbf{B}$ force under conditions relevant to ITER ELMs

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Abstract

The behavior of tungsten under repetitive hydrogen plasma impacts causing surface melting in conditions of an applied $\mathbf{J} \times \mathbf{B}$ force of up to 20 MN/m^3 is studied with the plasma accelerator QSPA Kh-50. Tungsten samples of EU trademark have been exposed to up to 100 pulses simulating ITER ELMs of the energy load 0.7 MJ/m^2 and the duration 0.25 ms. An electric current **J** flows across the magnetic field **B** of 1.4 T, and the resulting $\mathbf{J} \times \mathbf{B}$ force produces a displacement of the melt with formation of an erosion crater and an inclination of the surface profile along the force. Surface morphology and the damage by surface cracks are discussed. Comparisons of experimental results with numerical simulations of the code MEMOS-1.5D are presented.

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Keywords: ITER; ELM; Tungsten; Surface analysis; Erosion and deposition

1. Introduction

Divertor armor erosion caused by ELMs is an important issue for ITER performance. In particular, high heat loads on the tungsten surfaces of the ITER divertor may form a melt layer subjected to different forces such as plasma pressure gradient and surface tension. Since ELM heat loads correlate with the electric currents, **J**, crossing the divertor plate, melt motion driven by the $\mathbf{J} \times \mathbf{B}$ force in the applied magnetic field **B** (the Lorentz force) can also be an erosion factor for the divertor [1].

For energy loads relevant to ITER disruptions, experimental studies with the powerful plasma accelerator QSPA-Kh-50 and numerical simulations of material response showed that the dominant force for the tungsten melt motion is a considerable plasma pressure gradient [1,2]. Droplet splashing and formation of craters with rather large edge ridges of displaced material have been investigated.

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For ITER ELM relevant loads of $Q_{\mathrm{ELM}} \sim 1$ MJ/m^2 at $t = 0.25$–0.5 ms, the simulation experiments on exposure of tungsten plates at QSPA Kh-50 and macro-brush targets at QSPA-T demonstrated a much smaller effect of the pressure gradient [3,4]. In this case the Lorentz force can be one of the main mechanisms of melt layer erosion.

Although the erosion caused by the $\mathbf{J} \times \mathbf{B}$ force is an important issue of plasma wall interactions [5,6], up to now it has not been studied experimentally because of its complexity in ITER relevant conditions. Simultaneous control of high heat loads and extreme electric currents, separation of the influence of plasma pressure gradient effects, difficulties in creation of controllable distribution of electric currents through the surface and monitoring melt motion of tungsten are among the main obstacles to adequate experiments. Therefore the influence of $\mathbf{J} \times \mathbf{B}$ force on the melt motion was analyzed mostly within numerical simulations [6,7].

This paper presents experimental investigations at QSPA Kh-50 on the behavior of molten tungsten under pulsed energy loads of 0.7 MJ/m^{2}and Lorentz force up to 20 MN/m^{3}due to electric currents crossing the melt in a magnetic field of up to 1.5 T.

2. Experimental setup

Plasma exposures were performed with repetitive pulses of the quasi-steady-state plasma accelerator QSPA Kh-50, described elsewhere [8]. The exposed targets had a surface of 50×10 mm^2 and a thickness of 50 mm. The magnetic field along the target surface was created by a magnetic system consisting of a solenoid supplied by direct current and a U-shaped magnetic flux concentrator. The target was flush mounted onto the electromagnet gap of 10 mm as it is shown in Fig. 1. The magnetic field is concentrated mostly in the target bulk, $B_{\mathrm{surface}} = 1.4$ T, and it decreases considerably with distance from the surface: down to 0.2 B_{surface} at 1 cm from the surface. A molybdenum diaphragm of 16×24 cm size with a rectangular hole of 5×1 cm was inserted to protect the magnetic circuit from plasma impact and also to simulate the case when the target size exceeds the diameter of the plasma stream. Protective tungsten strips cover 5 mm of the surface at both edges, providing a reference line for profilometry measurements. The target was electrically insulated from the magnetic system and the diaphragm to avoid redistribution of the currents among these elements.

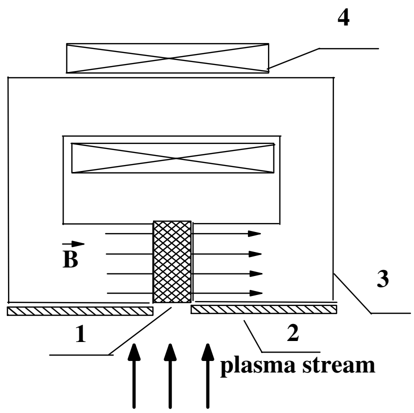

Fig. 1. Scheme of magnetic system: 1– tungsten target, 2 – molybdenum diaphragm, 3 – magnetic flux concentrator, 4 – solenoid.

In earlier studies with QSPA Kh-50 [2,3] the tungsten targets had been exposed to a current-free hydrogen plasma. However, generally the plasma streams generated by QSPA can transport both heat and electric fluxes. The creation and control of the plasma currents and their distribution in the plasma stream are analyzed in [9]. In order to provide electric current into the surface of the target at the distance 2.3 m from the accelerator output, 30% of the discharge current was redistributed to the plasma stream.

The main plasma parameters are as follows: the ion energy is about 0.4 keV, maximum plasma pressure 3.2 bar, and the plasma stream diameter 18 cm. The plasma pulse shape is triangular with a pulse duration of 0.25 ms. The surface energy load in the presence of a magnetic field measured with a calorimeter is 0.675 ± 0.25 MJ/m^2, which resulted in a melting below the evaporation threshold. The time interval between pulses was 5 min. Thus the target temperature before each plasma pulse was kept at room temperature level.

The forces at the exposed tungsten surface are presented in Fig. 2. The advantage of this experimental geometry is that the Lorentz force direction is the same for the whole exposed area. The electric currents across the melt layer can be measured in situ, during the pulse. The small magnetic field at the periphery does not influence substantially the plasma energy transfer to the surface. Due to relatively large diameter of the plasma stream in comparison with the exposed target surface, the influence of the plasma pressure gradient on the melt motion is neglected, which was confirmed by

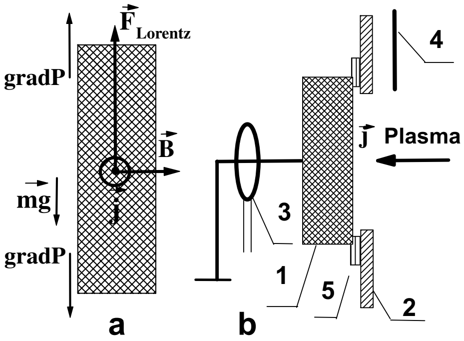

Fig. 2. Configuration of the forces: (a) at the target surface (view from the front) and the measurement scheme and (b) for electric currents (view from the side): 1– tungsten target, 2 – molybdenum diaphragm, 3 – Rogowski coil, 4 – magnetic probe, 5 – Rogowski coil.

measurements of plasma pressure distribution in the plasma stream with a movable piezoelectric detector.

3. Experimental results

The electric currents in the plasma stream and their distributions in front of the tungsten target surface as well as the currents through the target bulk have been measured in situ with the Rogowski coils and a set of magnetic probes shown in Fig. 2.

Fig. 3(a) demonstrates the electric current through the exposed area of 4 cm^2 as a function of time. In spite of the good reproducibility of the heat load in repetitive exposures, the currents through the melt vary about 25% of magnitude from pulse to pulse, which follows from regular comparisons of current traces. The current shape is peaked in time and differs from the heat load profile. However, the temporal behavior of the current measured simultaneously with the Rogowski coil is in good agreement with the signal of the magnetic probe in front of the target surface. The maximum total current through the tungsten surface is approximately 6.5 kA. This corresponds to an averaged current density of 1.6 kA/cm^2, shown in Fig. 3(b) with a dashed line.

The radial distributions of electric current density j in front of the target have been obtained from magnetic probes measurements. It was found that j is not constant in space. The maximum of j is at least 2 kA/cm^2at the center of the exposed surface. It drops down to 1.2 kA/cm^2 2 cm from the axis, which corresponds to the edge of exposed surface.

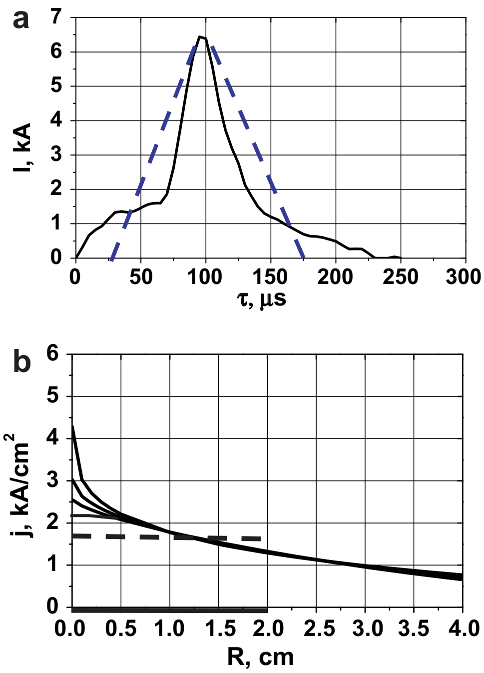

Fig. 3. Electric current through the exposed surface (a) and radial distributions of current density in the plasma stream in front of the target (b). Assumptions for numerical modeling are shown with dashed lines.

In the axis region the measurement accuracy is worse than at large radii. Fig. 3(b) indicates the measured electric currents near the axis region with large error bars.

The tungsten surface was prepared for the plasma exposures with surface roughness and flatness below 1 μm. After the exposures to 20, 50, 75 and 100 plasma pulses, the tungsten surface was respectively examined with microscopy and profilometry techniques.

Fig. 4 demonstrates the surface profiles after plasma exposures in conditions of predominant action of the Lorentz force. After 20 pulses the surface was marked with a special marker, which is necessary for accurate comparison of the profiles after different exposure numbers and for microscopic analyses of the melt motion (the marker looks like an indentation on the profile contours).

The Lorentz force produces a displacement of the melt forming an erosion crater and an inclination of surface in the direction of the force. After 20 pulses the continuous region of profile maximum due to displaced material reaches a height of 2 μm. For a large number of impacts the profile rises nonlinearly with the number. This is attributed to the variations

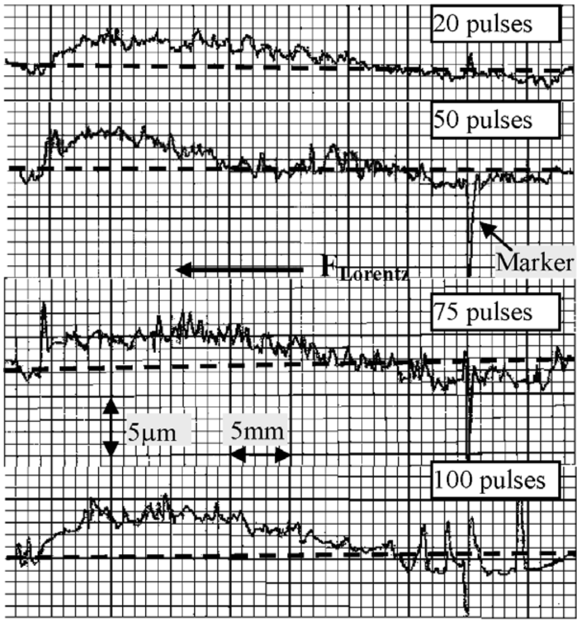

Fig. 4. Evolution of tungsten surface profile after 20, 50, 75 and 100 pulses of 0.7 MJ/m^2.

of electric current distribution over the exposed surface, mentioned above.

Fig. 5 illustrates the changes in surface morphology after 20 pulses for different areas of the exposed target. A rather smooth surface (1) with meshes of fine intergranular cracks corresponds to the edge of the melt surface, where the $\mathbf{J} \times \mathbf{B}$ force is directed from the periphery to the center (the crater area on the profile). The second region with the 'footprints' of the melt motion is typical for the central area, and the third one is the displaced material corresponding to the profile maximum where the force is directed to the edge of melt pool.

The experiments showed that the exposures to a tungsten target with width of 1 cm produce less pronounced surface cracking in comparison with those to the plates of 5×5 cm^2 investigated in [3]. Large cracks ('macro-cracks') are formed in some surface regions, but the exposures did not reproduce a mesh of macro-cracks like in [3].

Aiming also at investigation of different materials and visualization of melt motion and estimation of melt velocities driven by the Lorentz force, repetitive exposures to a composite Cu target with embedded W, SS and Al rods of a diameter 3 mm were performed. The melt displacements in result of exposures were measured using a microscope. The melt velocities caused by the Lorentz force for tungsten, steel and aluminum were found to be of the order of 5–6 cm/s, 16 cm/s and 0.5 m/s, respectively.

4. Comparison of experimental results with numerical simulation

The melt layer erosion of tungsten at the conditions corresponding to QSPA Kh-50 was numerically simulated using the fluid dynamics code MEMOS [1]. The computer modeling employs the 'shallow water' approximation and accounts for surface tension, viscosity and radiative losses from the hot surface of the tungsten melt. The calculated

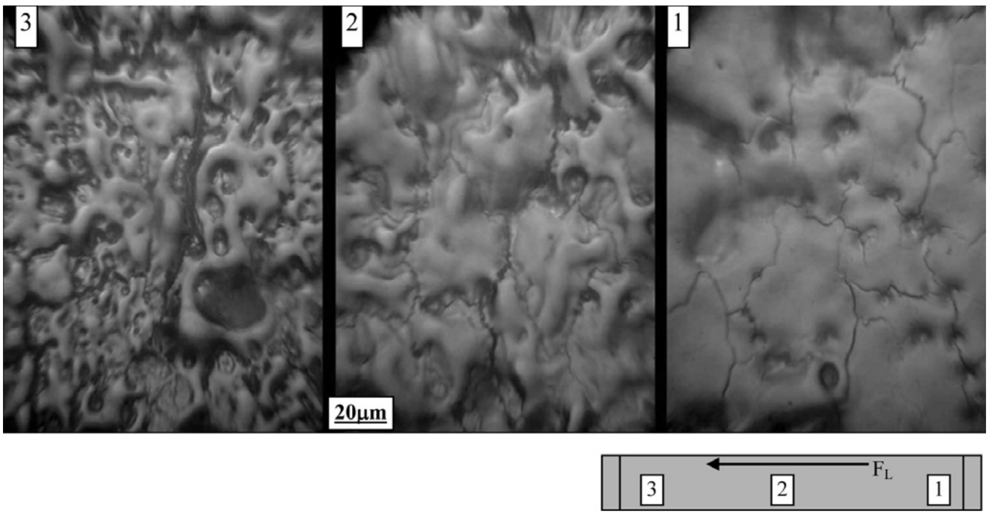

Fig. 5. Microscope images of different areas on exposed surface. Three regions could be distinguished, which is shown schematically.

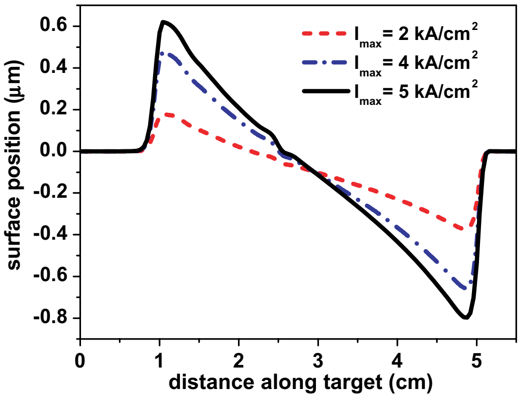

Fig. 6. The displacement of the melt layer due to the Lorenz force calculated for the conditions of QSPA Kh-50.

displacement of the melt due to the Lorentz force is presented in Fig. 6. The constant heat load along the surface and a triangular pulse shape with 0.2 ms duration were taken into account. The calculations were performed at $B = 1.4$ T for uniform distribution of the current across the heated area and with triangular pulse shape of the current during 0.15 ms, as it is assumed from Fig. 3(a).

The numerical simulation reproduces the characteristic continuous inclination of the experimental resolidification profile confirming it as a result of melt displacement caused by the Lorentz force. For the maximal electric current in the melt of $2\,kA/cm^2$ the profile grows with the rate 0.15–0.18 μm/pulse. The calculations confirmed that the applied heat load produces a pronounced surface melting with negligible evaporation: the evaporation thickness during the pulse of 1.6×10^{-3} μm is numerically obtained. Melt velocity of about 4–9 cm/s after 0.14 ms is calculated.

Thus, the numerical results showed good agreement with obtained experimental data. A broader maximum in experimental profiles is likely caused by a decrease of electric current density from the center to the periphery of the exposed surface, which results in decreased magnitude of the $\mathbf{J} \times \mathbf{B}$ force at the edge region (see Fig. 3(b)). It should be mentioned that after many exposures some variation of electric currents distribution from pulse to pulse may also influence the resulting profile.

5. Conclusions

Tungsten erosion under repetitive plasma heat loads of $0.7\,MJ/m^2$ lasting 0.25 ms, which are relevant to ITER Type I ELMs, has been investigated in the conditions of the $\mathbf{J} \times \mathbf{B}$ force action on melt layer.

The force resulted in a significant displacement of the melt, with formation of erosion crater and surface profile inclination along the force.

Surface morphology due to the melt motion and tungsten damage caused by surface cracks are analyzed. After the plasma exposures, mainly fine meshes of intergranular cracks have developed on the tungsten surface. Separated macro-cracks formed also, but they did not result in a complete mesh on exposed surface. This can be an indication of advantage of macro-brush geometry over the monolithic surface from the point of minimization of the stresses induced by plasma exposures.

The experimentally measured surface profiles and the melt velocities due to the Lorentz force are in agreement with the first numerical simulations by the code MEMOS of the melt motion dynamics for irradiation conditions of QSPA Kh-50.

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