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EXPERIMENTAL STUDIES OF PLASMA-SURFACE INTERACTIONS DURING INCLINED QSPA PLASMA IMPACTS ON Sn-FILLED CPS

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A 3D-printed tungsten Sn Capillary Porous Structure (CPS) sample was exposed to oblique high-power plasma in the QSPA facility. The experiment aimed to analyze the damage to a liquid metal prototype, a potential component of the divertor in fusion tokamaks. Observations of plasma-surface interactions revealed particle ejection from the exposed target, which depended on the energy density of the incoming plasma stream. The leading edge of the CPS sample was identified as the primary source of the ejected particles. A reduction in mass loss rate of the plasma-treated sample over the course of the experimental series was demonstrated. The W substrate of the CPS target did not sustain significant damage. A comparative analysis of the damage to Sn-CPS and castellated W samples exposed to inclined and normal plasma streams under conditions simulating transients in a fusion reactor was also performed.

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INTRODUCTION

The divertor in tokamak reactors endures significant thermal and particle loads, particularly during transient events such as edge-localized modes (ELMs) and disruptions. These extreme conditions can lead to the degradation of plasma-facing components (PFCs) through erosion, sputtering, and neutron-induced embrittlement [1]. Such damage not only affects the structural integrity of the divertor but also risks the contamination of the plasma core, thereby reducing overall reactor efficiency.

Tungsten (W) has been adopted as the baseline material for divertor PFCs in reactors like ITER and DEMO due to its high melting point, thermal conductivity, and low sputtering yield [2]. However, tungsten faces challenges such as brittleness, and limited resistance to neutron damage which limits its operational lifespan. Although advanced W-based materials, such as fiber-reinforced composites, are being developed, they are still in the early stages of research and may not fully address the limitations [3]. These challenges highlight the need to explore alternative divertor solutions.

To address these limitations, alternative divertor designs incorporating liquid metals (LMs) have been proposed. Liquid tin (Sn) and lithium (Li) are the leading candidates due to their low melting points, high thermal resilience, and ability to form vapor shielding during transient plasma events [4, 5]. LM divertors offer several advantages, including reduced mechanical stress due to their liquid state and the ability to replenish eroded material through capillary porous structures (CPS) [5, 6]. However, challenges such as droplet ejection, material transport, and plasma contamination remain critical areas of research.

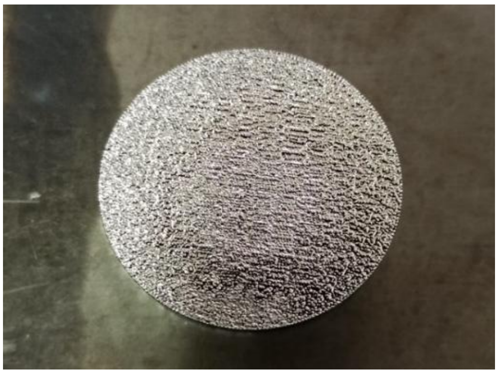
Previous experiments at QSPA [7] have shown that irradiation of Sn-filled CPS targets at a 90-degree angle to the plasma flow is accompanied by a strong shielding effect. In disruption simulation experiments [8], the energy density absorbed by the Sn CPS target was nearly half of that absorbed by W targets. Furthermore, experiments with 3D-printed W-Sn CPS demonstrated that the target could withstand 100 plasma impacts with an energy density of ~ 3 MJ/m^2 without significant damage to the W substrate.

To mitigate the heat flux on the divertor target plate, the divertor configuration is designed to ensure that plasma flows impact the divertor surface at an oblique angle [1].

Using fast camera imaging and calorimetric measurements, the properties of plasma-surface interaction (PSI) under oblique target irradiation were investigated [9]. It was demonstrated that a transient layer of dense plasma forms in front of the target, with its thickness varying along the surface. This layer reduces the absorbed energy density of the incoming plasma stream in the central part of the target by more than half compared to a target oriented at 90 degrees.

A study on castellated 3D W targets under oblique pulsed power plasma irradiation [9, 10] has shown that the primary erosion feature of the target is the damage to the leading edge and sharp edges facing the plasma. These areas are the main contributors to intense droplet erosion. Therefore, the features of PSI and erosion of 3D CPS targets filled with liquid metal require detailed investigation under the conditions of inclined high-power plasma loads.

This paper is devoted to a comprehensive study of the features of PSI for 3D-printed W-Sn CPS under oblique plasma exposures simulating transient events in a tokamak reactor.



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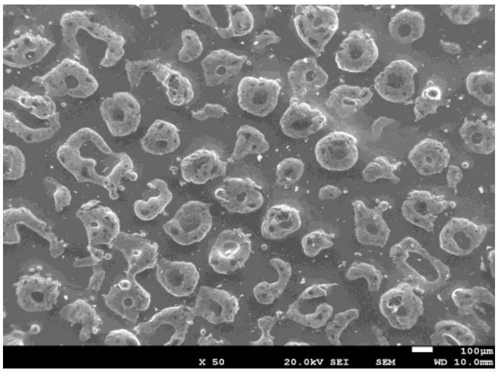

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Fig. 1. General view (a) and SEM image (b) of the CPS sample surface in its initial state

1. EXPERIMENTAL SETUP AND DIAGNOSTICS

Experimental simulations of fusion reactor transient conditions, including relevant surface heat load parameters such as energy density, pulse duration, and particle loads, were performed using the quasi-stationary plasma accelerator QSPA Kh-50 [7-12]. The 3D-printed tungsten CPS target filled with Sn was exposed to the plasma streams with an energy density of up to 3 MJ/m^2, a load that typically causes strong melting and evaporation in pure tungsten samples [11, 12]. The other parameters of the hydrogen plasma streams were as follows: the ion impact energy of about 0.4 keV, the stream diameter of 18 cm, and a maximum plasma pressure of 0.32 MPa measured using a piezodetector. The plasma pulse shape was approximately triangular with a pulse duration of 0.25 ms.

CPS target was a cylindrical sample of 24.5 mm in diameter (considerably smaller than the QSPA plasma stream diameter) and a height of 17 mm, provided by DIFFER (a more detailed design described in [13]). A general view and an SEM image of the CPS sample surface in its initial state are shown in Fig. 1, respectively. To protect the holder during the experiments, a molybdenum diaphragm was used, as depicted in Fig. 2,a. The initial temperature of the sample (T_{base}) before plasma exposure remained at a room value (T_{base}=RT). The target surface was oriented at an angle of 30 degrees to the plasma stream direction (see Fig. 2,b). The number of plasma irradiations during the main experimental series reached 30 pulses.

A high-speed digital camera PCO AG (10bit CMOS pco.1200 s) was employed for observing PSI and the ejections of erosion products. The camera had an exposure time ranging from 1 µs to 1 s, a spatial resolution of 12×12 μm^2, and operated within a spectral range from 290 to 1100 nm [8]. For clear monitoring of erosion product ejection from the affected surfaces, an exposition of 1.2 ms was selected.

To quantify the erosion, mass measurements of the targets were carried out during the experiment. The mass loss after the pulses (ΔM) was determined with an accuracy of ± 15 µg.

2. RESULTS OF EXPERIMENT

2.1. PLASMA-SURFACE INTERACTION PHENOMENA

The observation of PSI using a high-speed camera during the experiment provided data on the relationship between the energy density of the incident plasma (Q) and the behavior of the particle ejection process (Fig. 3,a-e). The thresholds for particle ejection were analyzed under the conditions of a gradually increasing energy density in the incident plasma stream.

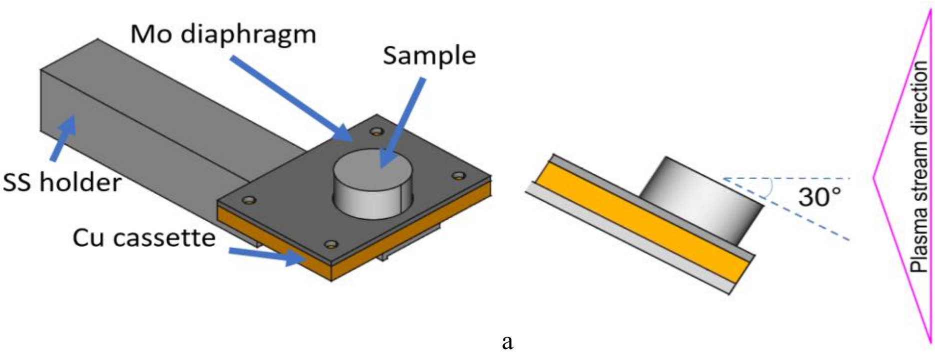

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Fig. 2. The design of the holder used in the experiment (a) and the schematic view of the plasma exposure (b) in the QSPA facility

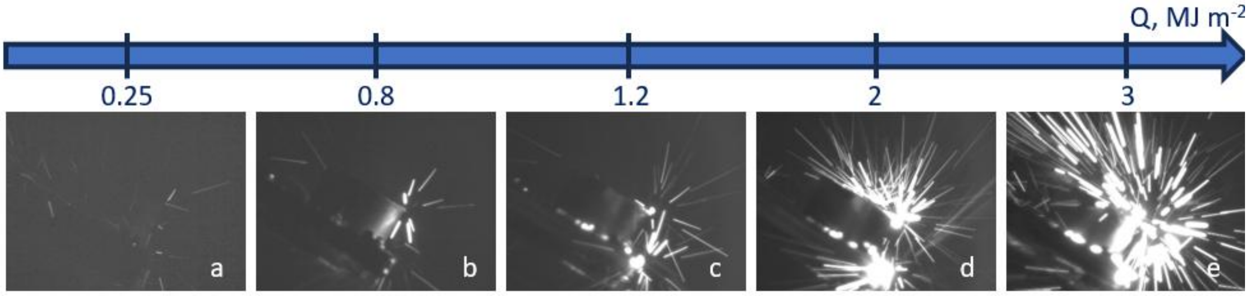

Fig. 3. Energy density of incoming plasma and corresponding images of PSI (a – 0.25 MJ m^{-2}; b – 0.8 MJ m^{-2}; c – 1.2 MJ m^{-2}; d – 2 MJ m^{-2}; e – 3 MJ m^{-2}). The images correspond to 1.2…2.4 ms after the start of the PSI ($t_{exposure}$=1.2 ms)

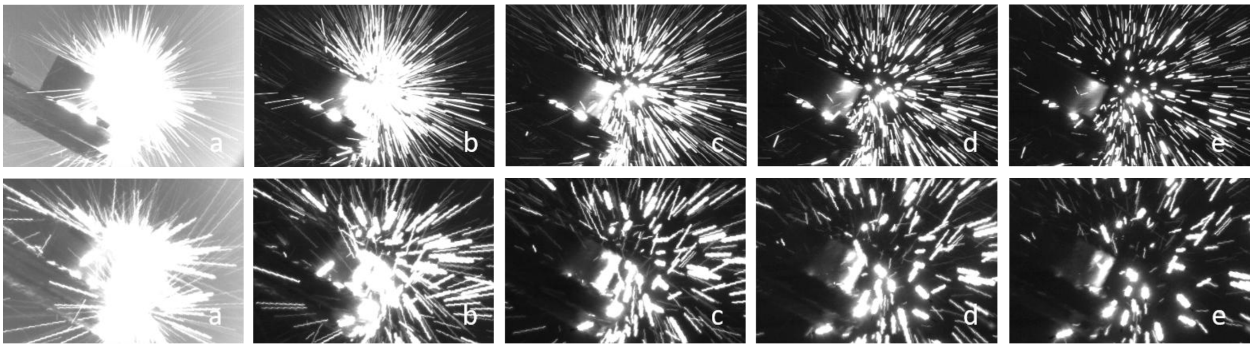

Fig. 4. Images of PSI during the first (top line) and after 30 (bottom line) plasma impacts on CPS target (with an incoming plasma energy density of 3 MJ·m^{-2}). The images correspond to 1.2…2.4 ms (a); 2.4…3.6 ms (b); 3.6…4.8 ms (c); 4.8…6 ms (d); 6…7.2 ms (e) after the start of the PSI ($t_{exposure}$=1.2 ms)

The first plasma pulses with an energy density of Q < 0.25 MJ/m^2 did not cause any ejection of particles from the target material surface. Plasma exposure in the range of 0.25 < Q < 1.2 MJ/m^2 resulted in up to 20 particles being ejected from the surface per pulse. Intense particle ejection was recorded in the camera frames corresponding to the range of 1.2 < Q ≤ 3 MJ/m^2. The highest bursts of droplets (more than 300 particles) were observed at the maximum energy of the incident plasma flow (Q = 3 MJ/m^2).

Intense particle ejection was observed throughout the entire main experimental series (Fig. 4,a-e), with the number of ejected particles varying from pulse to pulse. The particle ejection was observed to occur in a nearly semi-spherical pattern, covering an area close to a 2π solid angle. The velocities of the ejected particles ranged from 1 to 20 m/s, with the start-time from the exposed surface occurring within 0…1 ms. It is worth noting that the particles were still observed for more than 7 ms after the onset of PSI.

Fig. 5 illustrates the number of ejected particles as a function of the number of plasma pulses. The data for the target under inclined plasma exposure was obtained in the current experiment (see Fig. 5,a). These results were compared to earlier studies [8] examining a target without pre-heating under normal plasma exposure (see Fig. 5,b). The average number of particles ejected from the surface of the inclined target was 137.

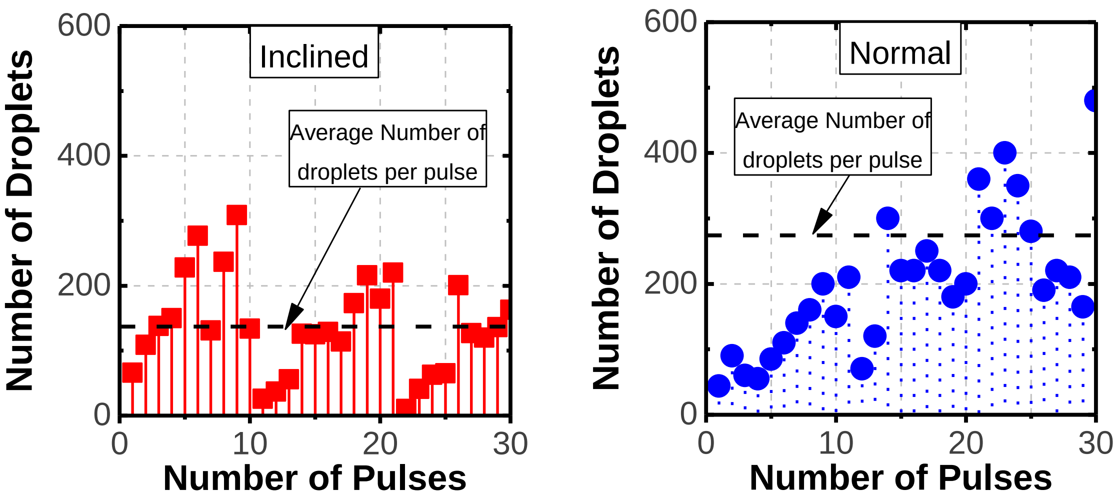

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Fig. 5. Number of ejected particles versus the number of plasma pulses for targets without pre-heating under inclined (a) and normal (b) [8] plasma exposure

2.2. SAMPLE MASS LOSS AND SURFACE ANALYSIS

The detachment of particles from the CPS target surface during PSI led to a reduction in the mass of the exposed target. To track the mass loss, the target was weighed after every 10 plasma pulses. The results of the mass loss measurements during the experiments ($\Delta m = m_{initial} - m_{measured}$) are presented in Fig. 6, where $m_{initial}$ represents the mass of the CPS sample before the main experimental series, and $m_{measured}$ is the mass measured after the corresponding number of plasma pulses. The first recorded mass loss was 8.6 mg, corresponding to a mass loss rate of 0.182 mg cm^{-2} per pulse. The second measurement was 6.25 mg, equivalent to 0.132 mg·cm^{-2} per pulse, and the final measurement was 4.5 mg, i.e. 0.095 mg·cm^{-2} per pulse. It can be concluded that the mass loss of the CPS sample decreases with an increasing number of applied plasma pulses. As an overall result of the entire main experimental series, the exposed target lost 18 mg, which corresponds to an average mass loss rate of 0.128 mg·cm^{-2} per pulse.

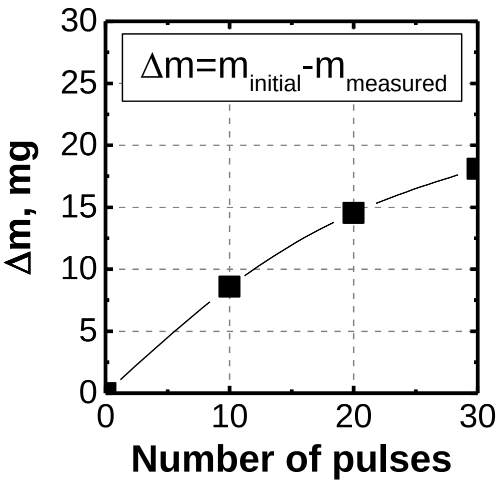

Fig. 6. Mass loss dependencies on the number of exposition plasma pulses. Accuracy of the measurements: ±15 μg

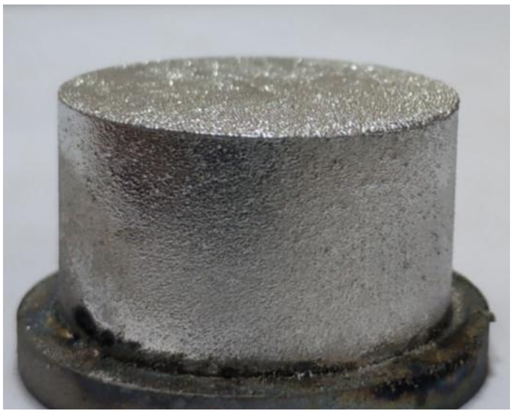

Fig. 7. General view of the CPS target surface exposed to inclined plasma. Images obtained after 30 plasma pulses

Surface analysis revealed that the pulsed high-power QSPA plasma exposures caused the motion of molten Sn across the plasma-facing surface (PFS) and the side surface of the sample, as shown in Fig. 7. Nevertheless, after the experimental series, the remaining amount of Sn was sufficient to sustain the PFS for subsequent plasma exposures. It is noteworthy that surface analysis did not reveal any visible changes in the W substrate.

3. DISCUSSION AND CONCLUSIONS

The experiment demonstrated that inclined QSPA plasma stream exposures, simulating transient events, induced the motion of molten Sn from inside the CPS target to the PFS. From there, part of the molten Sn detached from the target as flying particles, while another portion moved across the side surface of the sample. Intense particle ejection was registered for incoming plasma pulses with the energy density above the Q > 1.2 MJ/m^2 and persisted throughout the main experimental series. The particle velocities and start-up times from the target surface are within the same range as those observed for the CPS target under normal plasma exposures. Consequently, the main mechanisms of molten particle ejection remain the Kelvin-Helmholtz and Rayleigh-Taylor instabilities at the plasma-liquid interface [7–10]. Additionally, solid dust could detach from the exposed surface due to cracking processes.

The camera frames obtained during the experiment show that intense particle ejection primarily occurred from the leading edge, which was also observed in experiments involving the inclined exposures of the castellated W [9, 10]. The average number of particles per pulse for the inclined CPS target was lower than that for the CPS target exposed to normal plasma flow. This result is supported by the mass loss rate values: 0.128 mg·cm^{-2} per pulse (and have a tendency to subsequently decrease) for the inclined CPS target and 0.9 mg·cm^{-2} per pulse [8] (the rate of linear increase in the mass loss coefficient) for the normally irradiated cold target. This can be explained by the formation of a non-uniform shield across the target, resulting in an inhomogeneous distribution of the plasma flow energy on the target surface. In particular, the energy density absorbed by the surface of the leading edge of the inclined target is similar to that absorbed by the central part of the target under normal plasma flow [9].

The erosion of a 3D-printed W Sn-CPS prototype was studied under oblique high-power plasma exposure in the QSPA. The main series of 30 QSPA plasma impacts with an energy density of ~ 3 MJ/m^2 and a pulse duration of 0.25 ms on the inclined CPS did not result in enhanced damage to the W substrate. The plasma-facing surface of the CPS, as in the case of normal irradiation, remained wetted by the liquid Sn during subsequent exposures.

The experiment showed that the plasma impacts with energy densities below 1.2 MJ·m^{-2} caused only a small number of particles to eject from the target surface. With higher plasma loads, the number of ejected particles increased significantly.

The particle ejection was predominantly observed from the leading edge of the CPS target. Similar behavior was noted in experiments involving oblique irradiation of castellated W target due to the formation of a non-uniform shielding layer over the target surface.

The study revealed that both the average number of ejected particles and the mass loss rate during 30 inclined plasma exposures of Sn CPS were lower compared to those observed under normal irradiation.

Further experiments are required to analyze the damage of CPS prototypes filled with liquid metals under inclined high-cycle pulsed plasma loads.

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ЕКСПЕРИМЕНТАЛЬНІ ДОСЛІДЖЕННЯ ВЗАЄМОДІЇ ПЛАЗМИ З ПОВЕРХНЕЮ ПІД ЧАС ПОХИЛОГО ОПРОМІНЕННЯ КПС, ЗАПОВНЕНОЇ ОЛОВОМ, ПЛАЗМОВИМИ ІМПУЛЬСАМИ КСПП

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Зразок вольфрамової 3D-друкованої капілярно-пористої структури (КПС) з оловом піддавався впливу похилої потужної плазми в установці КСПП. Метою експерименту був аналіз пошкоджень рідкометалевого прототипу, який розглядається як потенційний компонент дивертора в термоядерних токамаках. Спостереження за взаємодією плазми з поверхнею виявили викид частинок з опроміненої мішені, залежний від густини енергії падаючого потоку плазми. Встановлено, що основним джерелом відлітаючих частинок є передня кромка зразка КПС. Продемонстровано зменшення втрати маси зразка, опроміненого плазмою протягом серії експериментів. W-основа КПС мішені не зазнала значних пошкоджень. Також було виконано порівняльний аналіз пошкоджень зразків Sn-КПС і зубчастих W під впливом похилих та нормальних потоків плазми в умовах, що моделюють перехідні події в реакторі термоядерного синтезу.