Performance of Li- and Sn-filled CPS targets under the transient plasma loads in QSPA

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The divertor in a tokamak reactor will be subjected to extreme heat and particle loads during transient events such as edge-localized modes (ELMs) and disruptions. In addition to Tungsten (W), currently selected as the baseline material for plasma-facing components (PFCs), other alternative divertor designs incorporating liquid metals (LMs) are under comprehensive assessment. Liquid tin (Sn) and lithium (Li) are among the most prospective candidates due to their low melting points, high thermal resilience, and ability to form a vapour shield resulting in a significant decrease of the surface heat load during transient plasma events.

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). However, some critical issues, such as droplet ejection, material transport, and plasma contamination require dedicated simulations and experimental studies aimed at the qualification of liquid metal divertor concepts for the future DEMO fusion reactor. Previous experiments at the QSPA facility [1] 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 [2], 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. This paper presents comparative experimental studies of plasma-surface interactions during QSPA plasma exposures of 3D-printed Li- and Sn-CPS prototypes at normal and inclined plasma incidence, along with an analysis of the resulting damage to liquid metal prototypes as a function of the applied energy loads.

The 3D-printed CPS targets filled with either Li or Sn have been exposed to the plasma streams with an energy density varied in the range from 0.25 MJ/m^2 up to 3 MJ/m^2. The plasma loads above 1.1 MJ/m^2 typically cause strong melting and evaporation for pure tungsten samples in QSPA, while the smallest load applied is clearly below the W melting threshold. Other parameters of the QSPA hydrogen plasma streams were as follows: the ion impact energy of about 0.4 keV, the plasma stream diameter of 18 cm, and a maximum plasma pressure of 0.32 MPa. The plasma pulse shape was approximately triangular with a pulse duration of 0.25 ms. The 3D-printed Sn-filled CPS target, provided by DIFFER [2], was a cylindrical sample with a diameter of 24.5 mm and a height of 17 mm. The Li-CPS target had a cylindrical part with a plasma-facing surface (PFS) of 33 mm in diameter, a height of 9 mm, and a mounting platform with a diameter of 67 mm. A more detailed design description of the CPS targets is provided in [3]. The initial temperature of the sample (T_{base}) before plasma exposure remained at a room value (T_{base}=RT). A high-speed digital camera PCO AG (10bit CMOS pco.1200 s) was applied to observe PSI and monitor the dynamics of the ejected erosion products (droplets and dust particles) in the near-surface plasma. 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 nm to 1100 nm. To quantify the overall erosion, mass loss measurements of the targets were performed at regular intervals throughout the experiments.

Observations of plasma-surface interactions revealed the dynamics of particle ejection from the exposed targets, which strongly depended on the energy density of the incoming plasma stream. Examples of the results obtained for Li and Sn CPS targets are shown in Figs 1 and 2. The thresholds for particle ejection were analysed under the conditions of a gradually increasing energy density in the incident plasma stream (Fig.1,2 a-e). 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. Intense particle ejection was recorded in the camera frames corresponding to the range of $1.2 < Q \leq 3$ MJ/m^2. The highest bursts of droplets were observed at the maximum energy of the incident plasma flow ($Q = 3$ MJ/m^2). For the inclined Sn target exposures, the leading edge of the CPS sample was identified as the primary source of the ejected particles. A reduction in the 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 the conditions simulating transients in a fusion reactor was also performed.

Plasma exposure of the Li-filled CPS target also triggered the ejection of droplets and dust from the surface. The velocities of the ejected particles ranged from 1 to 33 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. For comparison, under normal irradiation of Sn CPS, the velocities of the ejected particles reached 17 m/s. An increase in the maximum velocity of the ejected particles compared to Sn CPS is consistent with the estimated mechanisms of particle ejection, including Kelvin-Helmholtz and Rayleigh-Taylor instabilities. The main series of 50 QSPA plasma impacts with an energy density of ~ 3 MJ/m^2 and a pulse duration of 0.25 ms on the Li-CPS target did not result in enhanced damage to the substrate. The mass loss rate obtained for Li-CPS was nearly an order of magnitude lower than that for Sn-CPS, fully consistent with the difference in material density. Nevertheless, for the highest heat load applied (3 MJ/m^2), the mass loss values obtained for both Sn and Li-CPS targets considerably exceed those observed for solid W targets.

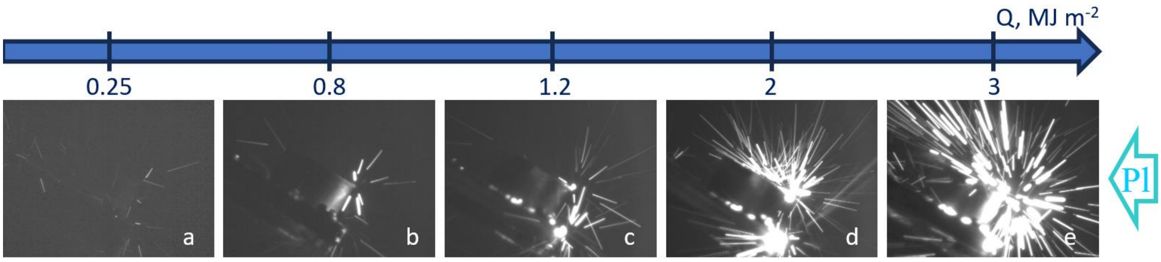

Fig. 1. Energy density of incoming plasma and corresponding images of PSI for inclined exposures of Sn-filled CPS (a –0.25 MJ m^{-2}; b –0.8 MJ m^{-2}; c –1.2 MJ m^{-2}; d –2 MJ m^{-2}; e –3 MJ m^{-2}). The images correspond to 1.2…2.4 ms after the start of the PSI ($t_{exposure}$=1.2 ms)

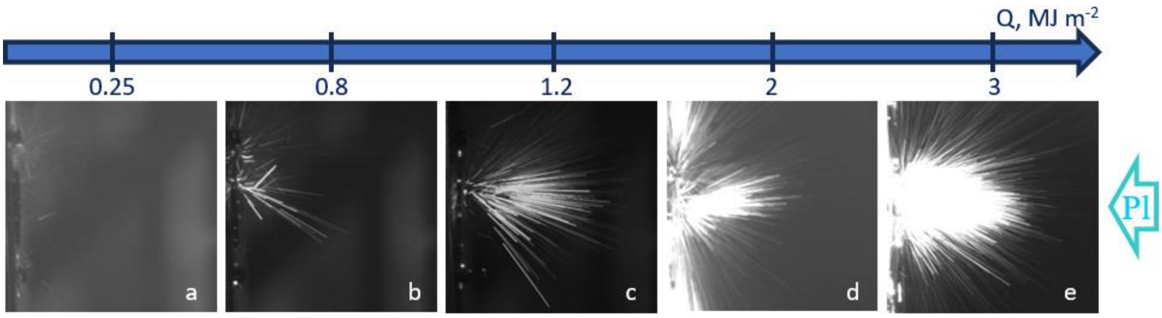

Fig. 2. Energy density of incoming plasma and corresponding images of PSI for normal exposure of Li- filled CPS (a – 0.25 MJ m^{-2}, b – 0.8 MJ m^{-2}, c – 1.2 MJ m^{-2}, d – 2 MJ m^{-2}, e – 3 MJ m^{-2}). The images correspond to 1.2-2.4 ms after the start of the PSI ($t_{exposure}$=1.2 ms).

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