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Interaction of adhered metallic dust with transient plasma heat loads

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The first study of the interaction of metallic dust adhered on tungsten substrates with transient plasma heat loads is presented. Experiments were carried out in the Pilot-PSI linear device with transient heat fluxes up to 550 MW/m² and in the DIII-D divertor tokamak. The central role of the dust-substrate contact area in heat conduction is highlighted and confirmed by heat transfer simulations. The experiments provide evidence of the occurrence of wetting-induced coagulation, a novel growth mechanism where cluster melting accompanied by droplet wetting leads to the formation of larger grains. The remobilization activity of the newly formed dust and the survivability of tungsten dust on hot surfaces are documented and discussed in the light of implications for ITER.

Despite the recent progress in the understanding of dust transport in fusion devices [1–3] and the successful design and implementation of relevant diagnostics [4–10], many aspects of dust physics have remained unexplored, especially those related to metallic droplets and dust formation. The ITER nuclear licensing agreement requires that the quantity of dust in the vacuum vessel remains below given limits [11]. The most stringent safety limit concerns dust residing on hot surfaces due to the explosion hazard in case of loss-of-coolant accidents [12]. Dust accumulation depends on the local balance between the deposition and remobilization rates. To date, no study focused on the effect of transient events, in particular edge-localized modes (ELMs), on dust remobilization.

In this Letter, we present the first experimental and theoretical study of metallic dust behavior under ELM-like conditions. W and Al dust has been deposited on planar W substrates with a controlled adhesion technique [10] and exposed to transient plasmas. W-on-W samples were exposed in the Pilot-PSI linear plasma device [13] under ITER-relevant transient heat fluxes up to 550 MW/m² and varying magnetic field inclination. W-on-W and Al-on-W samples were exposed to ELMing H-mode discharges in the lower DIII-D divertor [14], where, due to the weaker transient heat fluxes, Al dust was also employed, having a much lower melting point.

A consistent picture emerged from exposures in both machines: dust grains can melt under much lower heat loads than bulk materials, especially as clusters or multilayers, due to poor heat conduction through the small contact area. This interpretation is supported by heat transfer simulations including a mechanical model for the contact radius of adhesive elastic-perfectly plastic impacts [15]. A novel result concerns the observed wetting-induced coagulation of dust that leads to the formation of larger grains. This unique paradigm of dust growth via coagulation stems from the interplay between the wetting properties of metal droplets and the short ELM duration. The remobilization activity of the newly-formed dust is found to be low. The overall remobilization activity is not enhanced compared to the steady-state case [10], implying that adhered W dust can survive ELMs.

Linear device experiments. Pilot-PSI allows the superposition of a transient heat/particle pulse to its steady-state plasma [13]. Here ELM-replicating pulses (∆t = 1 ms) were produced by the cascaded arc plasma source connected in parallel to a capacitor bank. The discharge parameters were: steady state current 190 A, capacitor charging voltage 1200 – 1800 V, magnetic field 1.2 – 1.6 T, hydrogen flow 7 slm (standard liters per minute). The pulse repetition rate in experiments with periodic transient heat fluxes [16] was 10 Hz. Planar W disks (Ø = 30 mm, t = 1 mm) with pre-adhered dust were mounted either directly on the endplate (∠B = 90°) or on a specially designed oblique holder (∠B = 10°). Highly spherical W dust with a nominal size distribution 5 – 25 μm was supplied by TEKNA Advanced Materials Inc and a nearly monodisperse 8 – 10 μm sub-population was generated with high-pressure electroformed metal meshes. Controlled adhesion was achieved with the aid of gas dynamics methods in a manner that realistically mimics dust sticking as it occurs in fusion devices [10].

For ∠B = 90° in absence of dust, the steady-state and transient plasma parameters were measured by a Thomson scattering system, 17 mm in front of the endplate [16]. The peak transient electron density and temperature were in the range (4 – 5) × 10^{21} m^{-3}, 13 – 20 eV and the steady state in the range (4 – 11) × 10^{20} m^{-3}, 0.8 – 1.8 eV. The combination of a multi-wavelength pyrometer and a fast 2D infrared (IR) camera enabled measurements of the sample surface temperature profile [13]. The IR camera was calibrated against the pyrometer on a pristine W sample [17]. The incident heat flux q norm to the surface was calculated from the temperature profile with the THEODOR code [18].

Melting of W clusters. The heat flux parameter \( q\sqrt{\Delta t} \) is typically 6 (maximum 17) MWm^{-2}s^{1/2}, which is much lower than the threshold for bulk W melting [13]. We
TABLE I: Exposure statistics for W dust adhered to W planar samples under Δτ = 1 ms ELM-like plasma pulses in Pilot-PSI, \( \dot{q} \) denotes the heat flux at the center of the plasma column averaged over Δτ. Nearly all samples have 4 dust spots of 0.5 mm diameter each. “High” spot density implies multi-layers, “medium” - isolated grains and clusters, “low” - mostly isolated grains. In the oblique set-up, the heat flux is calculated by the geometric approximation \( \dot{q} = q_0 \sin(10^\circ) \).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Dust</th>
<th>Spot</th>
<th>( \angle B )</th>
<th>( B )</th>
<th>( \dot{q} )</th>
<th>Cluster</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1-1\textsuperscript{st} exp.</td>
<td>5 – 25</td>
<td>medium</td>
<td>90(^\circ)</td>
<td>1.2</td>
<td>200</td>
<td>Yes</td>
</tr>
<tr>
<td>#1-2\textsuperscript{nd} exp.</td>
<td>5 – 25</td>
<td>medium</td>
<td>90(^\circ)</td>
<td>1.2</td>
<td>200</td>
<td>Yes</td>
</tr>
<tr>
<td>#1-3\textsuperscript{rd} exp.</td>
<td>5 – 25</td>
<td>medium</td>
<td>90(^\circ)</td>
<td>1.6</td>
<td>550</td>
<td>Yes</td>
</tr>
<tr>
<td>(10 ELM-pulses)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#2-1\textsuperscript{st} exp.</td>
<td>8 – 10</td>
<td>medium</td>
<td>10(^\circ)</td>
<td>1.2</td>
<td>( \approx 35 )</td>
<td>Yes</td>
</tr>
<tr>
<td>#2-2\textsuperscript{nd} exp.</td>
<td>8 – 10</td>
<td>medium</td>
<td>10(^\circ)</td>
<td>1.2</td>
<td>( \approx 35 )</td>
<td>Yes</td>
</tr>
<tr>
<td>#2-3\textsuperscript{rd} exp.</td>
<td>8 – 10</td>
<td>medium</td>
<td>90(^\circ)</td>
<td>1.6</td>
<td>550</td>
<td>Yes</td>
</tr>
<tr>
<td>#3-1\textsuperscript{st} exp.</td>
<td>5 – 25</td>
<td>medium</td>
<td>90(^\circ)</td>
<td>1.2</td>
<td>( \approx 35 )</td>
<td>Yes</td>
</tr>
<tr>
<td>#3-2\textsuperscript{nd} exp.</td>
<td>5 – 25</td>
<td>medium</td>
<td>10(^\circ)</td>
<td>1.2</td>
<td>( \approx 35 )</td>
<td>Yes</td>
</tr>
<tr>
<td>#4</td>
<td>5 – 25</td>
<td>low</td>
<td>90(^\circ)</td>
<td>1.2</td>
<td>200</td>
<td>Yes</td>
</tr>
<tr>
<td>#5</td>
<td>8 – 10</td>
<td>low</td>
<td>90(^\circ)</td>
<td>1.2</td>
<td>200</td>
<td>Yes</td>
</tr>
<tr>
<td>#6</td>
<td>8 – 10</td>
<td>low</td>
<td>10(^\circ)</td>
<td>1.2</td>
<td>( \approx 35 )</td>
<td>No</td>
</tr>
<tr>
<td>#7</td>
<td>8 – 10</td>
<td>low</td>
<td>10(^\circ)</td>
<td>1.2</td>
<td>( \approx 35 )</td>
<td>No</td>
</tr>
<tr>
<td>#8 (9 disch)</td>
<td>5 – 25</td>
<td>high</td>
<td>90(^\circ)</td>
<td>1.2</td>
<td>200</td>
<td>Yes</td>
</tr>
<tr>
<td>#9-1\textsuperscript{st} exp.</td>
<td>5 – 25</td>
<td>high</td>
<td>10(^\circ)</td>
<td>1.2</td>
<td>( \approx 35 )</td>
<td>Yes</td>
</tr>
<tr>
<td>(3 discharges)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#9-2\textsuperscript{nd} exp.</td>
<td>5 – 25</td>
<td>high</td>
<td>90(^\circ)</td>
<td>1.2</td>
<td>200</td>
<td>Yes</td>
</tr>
<tr>
<td>#9-3\textsuperscript{rd} exp.</td>
<td>5 – 25</td>
<td>high</td>
<td>90(^\circ)</td>
<td>1.6</td>
<td>550</td>
<td>Yes</td>
</tr>
</tbody>
</table>

never observed any evidence of melting of isolated W dust but consistently observed melting of W clusters. In a total of 16 exposures under varying conditions, cluster melting took place in all but two cases, see Table I. These two are characterized by the lowest cluster occurrence and lowest incident heat fluxes. Fig.1 shows an example of cluster melting under \( \dot{q} \approx 35 \) MW/m\(^2\); the adhered dust population consists of both clusters and isolated grains. Isolated grains are not affected by the ELM-like pulse, whereas most clusters melt and form larger grains. This pattern persists also in exposures to repetitive pulses of 550 MW/m\(^2\) and exposures of samples with dust multi-layers, the main difference lies in the larger size of the newly-formed grains.

Wetting-induced coagulation. Liquid metals are known to exhibit excellent wettability on their own solids due to strong interfacial bonding [19, 20]. This can be demonstrated by the Young-Dupré equation [19] and has been verified by experiments [21]. Good wettability implies that a spherical W droplet residing on a W substrate will tend to spread out due to the surface tension imbalance [22], which vanishes when the dynamic contact angle reaches the equilibrium Young angle [23], at most equal to few tens of degrees [20]. In general, spreading dynamics are driven by capillary forces (the combination of cohesive forces within the droplet and adhesive droplet-solid forces) and limited by viscous friction [24, 25]. In our case, due to the short heat pulse duration, there is a strong competition between wetting and re-solidification, hence spreading dynamics cannot fully develop. Wetting is less inhibited only for clusters, where the physical connection of the top grains to the substrate is realized through the bottom grains. The top grains receive most heat flux and melt, since heat conduction to the cooler substrate is poorer, being mediated by at least two contacts. Thus, droplets form which first efficiently wet the bottom grains, then re-solidify (Fig.2). This process generates larger dust that can even have a spherical shape. To our knowledge it has not been documented in the literature, we shall refer to it as wetting-induced coagulation. Fig.3 shows post-exposure SEM images displaying a characteristic signature of spreading dynamics in the
FIG. 3: Frozen capillary waves at the bottom of a nearly spherical (a) and a non-spherical W grain (b) formed by wetting-induced coagulation. Events from sample #1, exposed to a Pilot-PSI ELM-like pulse of $q = 200 \text{MW/m}^2$. The inserts show the spot regions prior to and post exposure.

Form of capillary waves [22, 25], visible as ripples essentially frozen by re-solidification.

From the original $5 - 25\ \mu\text{m}$ population, wetting-induced coagulation led to the formation of dust with sizes from several tens of $\mu\text{m}$ on samples with clusters to a fraction of mm on samples with multi-layers. The question arises whether these grains can get detached by plasma forces [10]. This is an important issue, since larger grains can penetrate deeper into the core plasma and release performance-degrading high-Z impurities [9, 26].

From a theoretical perspective, the answer is not straightforward due to the competition between the enhanced remobilization tendency of larger dust [10] and the increased contact area of re-solidified dust. By multiple re-exposures under ELMs, we have observed that the newly-formed grains can get detached (Fig.4) but the remobilization activity is very low, only $\sim 20$ events in the 4 multiply exposed samples. Sticky tape collection followed by SEM has allowed us to image areas previously in contact with the substrate (Fig.5). The results confirm that melting leads to an increased contact area, hence to stronger adhesive forces acting against detachment. Adhesion is so strong that, in sample #1, only 9% of the newly formed grains could be collected by adhesive tape.

Simulations. Heat transfer for W dust adhered to a W substrate in the perpendicular configuration has been simulated with finite element solvers implemented

FIG. 4: Events from sample #1, multiply exposed to ELM-like Pilot-PSI pulses (two single pulses of $q = 200 \text{MW/m}^2$ and ten repeated pulses of $q = 550 \text{MW/m}^2$), displaying wetting-induced coagulation of adhered W dust followed by remobilization in subsequent discharges. During these events, all the isolated grains visible in the spots remained unaffected. In (a,b,c), the remobilized newly-formed grains were not totally removed but strongly displaced by $\sim 300$, $\sim 130$ and $\sim 200 \mu\text{m}$, respectively. In (d), only one of the newly-formed grains is remobilized, and displaced by $\sim 450 \mu\text{m}$. The sizes of the newly formed dust grains after the 1st pulse are (a) 35, (b) 28, (c) 32 and (d) 25 and 30 $\mu\text{m}$.

FIG. 5: SEM images of the contact area of newly-formed W grains collected by adhesive tape (double-sided conductive carbon tape) after various exposures. (a) sample #8, multiple $q = 200 \text{MW/m}^2$ pulses, non-molten grains are attached at the bottom and frozen capillary waves are visible; (b) sample #1, repetitive $q = 550 \text{MW/m}^2$ pulses; (c,d) sample #3, single $q = 35 \text{MW/m}^2$ pulse, with a zoom-in of the contact with the substrate. We note that the contact region can have a much more intricate structure due the effect of roughness, which for our substrates is characterized by the measures $R_q = 0.52 \mu\text{m}$, $R_a = 0.43 \mu\text{m}$. In sample #1, only 9% of the newly formed grains could be collected by adhesive tape. On the contrary, in sample #3 that was exposed to a single weaker ELM-like pulse, 75% could be collected.
in COMSOL Multiphysics, using an axisymmetric geometry consisting of a 1 mm thick cylindrical plate whose surface lies on the \( z = 0 \) plane and a spherical grain of radius \( R_{\text{d}} \) placed on the top of the plate, with its center located at \( z = \sqrt{R_{\text{d}}^2 - a^2} \), where \( a \) is the sphere-plate contact radius. The initial system temperature is chosen to be uniform, matching the IR camera data of Pilot-PSI. In addition to the incoming heat flux from the plasma, the upper surface is subject to temperature-dependent cooling fluxes due to thermal radiation and thermionic emission [3]. Active cooling at the bottom of the plate is neglected since the characteristic heat diffusion time across 1 mm of W is of the order of a few tens of ms, that is much longer than the 1 ms pulse duration.

The contact radius \( a \) is calculated from theoretical models of adhesive elastic-perfectly plastic impacts [15]. Complexity arises from the onset of plastic deformation during sticking impacts [10, 27, 28] that leads to a dependence on the contact radius for zero impact energy \( a_0 = \left( \frac{9\pi R_{\text{d}}^2 \Gamma}{2E^*} \right)^{1/3} \), where \( \Gamma \) is the interface energy, \( E^* \) the reduced Young’s modulus. For W-on-W impacts, \( a_0/R_{\text{d}} \) lies between 6%-3% for diameters between 5 - 25 \( \mu \)m. Inclusion of the dust deposition speed in the range 0.6 - 4 m/s for the experiments reported here and - plasticity leads to \( a/R_{\text{d}} \) between 8%-5% for the same sizes.

Assuming perfect thermal contact through the contact area and cooling by unimpeded thermionic emission, simulations for \( q = 550 \text{MW/m}^2 \), \( \Delta T = 1 \text{ms} \) and isolated grains show that only large sizes, \( \geq 21 \mu \text{m} \), can melt. On the other hand, simulations for \( q = 550 \text{MW/m}^2 \) and clusters consisting of two equal-sized grains (with only the top one absorbing the incident heat flux) reveal that the top grain can melt already for diameters \( \geq 9 \mu \text{m} \). These are upper limit estimates, since the imperfection of the thermal contact [29] and the thermionic flux suppression (due to space charge effects and / or prompt return via gyration) [3] would allow melting to occur under lower heat fluxes. The simulation results are clearly consistent with the experimental evidence that clusters are more susceptible to melting than isolated grains.

**Divertor tokamak experiments.** Planar W disks (\( \varnothing = 6 \text{mm}, t = 1.6 \text{mm} \)) with pre-adhered dust (4 spots of 0.5 mm diameter each) were exposed flush with the target surface near the outer strike point (OSP) in the lower DIII-D divertor during ELMy H-mode discharges using the DiMES manipulator [30]. Spherical 5 - 25 \( \mu \text{m} \) W dust and irregular 2 - 6 \( \mu \text{m} \) Al dust were employed, the latter due to its low melting point and as a beryllium proxy. The plasma parameters were measured by the divertor Thomson scattering (DTS) system, the heat fluxes were deduced from the DTS data and crosschecked with IR camera data. One Al-on-W sample was exposed for 4.9 s in discharge \#161565 with detached OSP, inter- (intra- ) ELM \( \eta_e = 8.0(8.4) \times 10^{20} \text{m}^{-3} \), \( T_e = 1.5(5.4) \text{eV} \), \( \eta = 0.3(1.0) \text{MW/m}^2 \) and ELM frequency \( f_{\text{ELM}} = 130 \text{Hz} \). Other experiments were in discharges with attached OSP. One W-on-W sample was exposed for 10.2 s to discharges \#162318 - 20, \( \eta_e = 1.5(3.7) \times 10^{19} \text{m}^{-3} \), \( T_e = 30(75) \text{eV} \), \( \eta = 0.5(4.8) \text{MW/m}^2 \), \( f_{\text{ELM}} = 100 \text{Hz} \). One Al-on-W and one W-on-W sample were exposed for 4.9 s in discharges \#163712, -14, \( \eta_e = 1.3(1.5) \times 10^{19} \text{m}^{-3} \), \( T_e = 24(66) \text{eV} \), \( \eta = 0.4(1.6) \text{MW/m}^2 \), \( f_{\text{ELM}} = 80 \text{Hz} \). The intra-ELM values were obtained by averaging DTS and IR data over many ELMs, whose duration varied between \( \sim 1 - 2 \text{ms} \).
Both Al-on-W and W-on-W samples exhibited a similar behavior to the W-on-W samples exposed in Pilot-PSI, albeit under much lower heat fluxes. Namely, wetting-induced coagulation was observed in most Al clusters (Fig.6, left panel). On the other hand, the spot density of the W-on-W sample was low due to restrictions consisting of only a few grains, whereas isolated grains were unaffected (Fig.6, last two panels). The overall remobilization was low, \( \leq 5\% \) of the grains were gone. Only 5\% of the newly formed Al grains (but 100\% of the W grains) could be collected by adhesive tape.

**ITER implications.** (i) Safety & removal: Dust removal in ITER will be performed by vacuuming of PFCs using the Multi-Purpose Deployer [31]. In addition, a dust monitoring endoscope is foreseen for regular collection of dust samples below the divertor. The specific collection method is currently under consideration (brush, gas flow, electrostatic). Dust formed by wetting-induced coagulation is typically strongly adhered, rendering sampling even by adhesive tapes ineffective. Such sticking properties would strongly reduce the chances for remobilization during loss-of-vacuum accidents, which reduces the risk of radioactive or toxic dust release. However, this needs to be verified in dedicated setups [32]. Moreover, since wetting-induced coagulation converts clusters to single grains, it reduces the available reactive area in case of loss-of-coolant accidents and thus also the risk of hydrogen and dust explosions. On the other hand, the strong adhesion can increase the dust inventory on hot divertor surfaces beyond expectations. (ii) Performance: In the full-W ASDEX Upgrade the most probable W dust size is 1\,\mu m [8]. Such small dust promptly vaporizes once released in the edge plasma. Via wetting-induced coagulation, small grains become the building blocks of much larger grains capable of deeper plasma penetration, also due to the formation of an ablation cloud partly shielding them from the plasma heat fluxes [33]. Thus, the newly formed grains can either cross the separatrix or inject impurities to the core by means of high-Z ion transport [34]. Our results indicate that the remobilization activity of the newly formed grains is very low, but it increases with the size. Quantification of the remobilization activity and modelling of the penetration depth, as well as extrapolations to ITER, will be subjects of future work.

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