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Enhanced erosion of tungsten plasma-facing components subject to simultaneous heat pulses and deuterium plasma

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ABSTRACT

When an ELM occurs in tokamaks, up to 30% of the pedestal energy can be deposited on the wall of the tokamak causing heating and material loss due to sublimation/evaporation and melt layer splashing of plasma-facing components (PFCs) and expansion of the ejected material into the plasma. A short-pulse laser system capable of reproducing the thermal load of an ELM heat pulse has been integrated into the existing PFC research program in PISCES, a laboratory facility capable of reproducing plasma-materials interactions expected during normal operation of large tokamaks. An Nd:YAG laser capable of delivering up to 1 J of energy over a 7 ns pulsewidth is used for the experiments. Laser heat pulse only, H^+/D^+ plasma only, and laser plus plasma experiments were conducted and initial results indicate enhanced erosion of tungsten exposed to simultaneous plasma and heat pulses, as compared to exposure to separate plasma-only or heat pulse-only conditions.

1. Introduction

Off-normal events such as edge-localized modes (ELMs) can occur in tokamaks at varying frequency and amplitude levels, resulting in a large thermal transient load on plasma-facing components. When an ELM occurs, up to 30% of the pedestal energy can be deposited on the plasma-facing boundary of the tokamak in the form of a heat and particle load [1,2]. There are two main consequences of these ELMs. First, heating and material loss from the divertor and first wall due to sublimation of CFCs, or evaporation and melt layer splashing of metals can occur. Secondly, subsequent to this event, the expansion of the ejected material into the outer region of the plasma, known as the scrape off layer (SOL), and even penetration to the core plasma, can occur. Simulation of the heat pulse and particle load of such ELMs in laboratory devices is desirable to identify the processes that occur and their effect on plasma-facing materials and the plasma. A moderate-energy laser can be used to develop diagnostics necessary to study these phenomena and determine the heat and particle sources necessary to simulate the effect of ELMs in the laboratory environment. We have integrated a laser system into the existing plasma-facing materials research program in PISCES [3,4], a laboratory facility capable of reproducing plasma-materials interactions expected during normal operation of large tokamaks, and report initial results from this work are reported in this paper.

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2. Experiment

2.1. Tungsten samples

Several mechanically polished tungsten samples measuring 25 mm in diameter and 2 mm thickness were generated in house by EDM cutting of tungsten rod. The rod, purchased from Goodfellow Corporation, has a quoted purity of 99.95% with the main impurities being Mo (150 ppm), Si (50 ppm), and O (30 ppm). The samples were mechanically polished on a wheel with grit sizes down to <1 μm until the surface was smooth and free of large defects under SEM analysis (Fig. 1). Further polishing was not necessary for the experiments that were conducted. All samples were weighed on a high precision microbalance before and after exposure to laser and/or plasma irradiation.

2.2. Plasma exposure

Deuterium or hydrogen ion species were generated in the PISCES-A plasma device [3,4] (Fig. 2), which has parameters similar to the edge plasma in tokamaks. The 7.5 cm diameter plasma is generated by electron emission from a large area LaB_6 disc cathode and is transported along the 1–2 kG magnetic field to produce a high density ($\sim 10^{13}$ cm^{-3}), low energy (5–15 eV) deuterium plasma. The ions can be accelerated to the sample by biasing the sample to produce 50–250 eV ion energy at a flux on the order of a few 10^{18} cm^{-2} s^{-1}. Samples in this experiment were held near 50–100 °C and subjected to a fluence of 10^{26} D^+/m^2. The ion energy

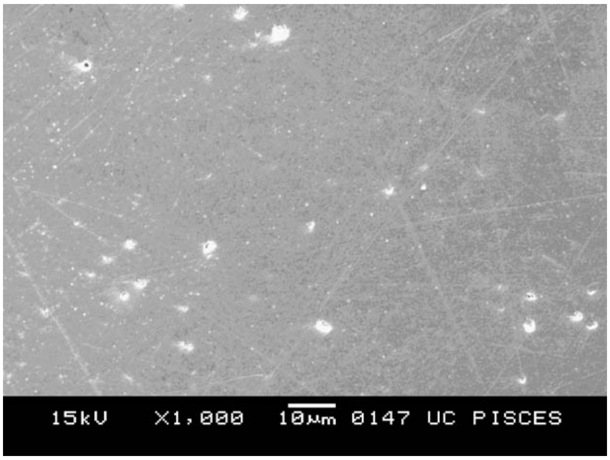

Fig. 1. SEM image of W surface as prepared by mechanical polishing.

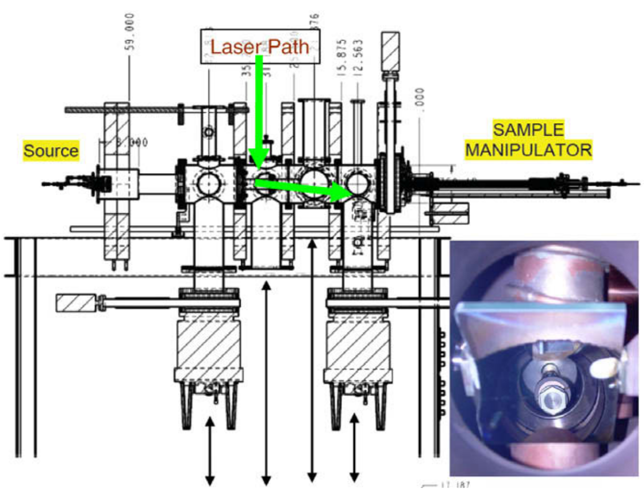

Fig. 2. Drawing of the PISCES-A System and the laser beam path utilized for heat pulse experiments. A photo of the sample holder as viewed by the laser system is included.

distribution function at the surface is non-thermal, with energy dispersion that is small compared to the mean ion energy.

2.3. Laser heat pulse

A Q-switched Continuum Surelite Nd:YAG laser capable of delivering up to 850mJ of energy has been acquired and installed at the PISCES facility. The pulsewidth of the laser is ∼5 ns and the primary wavelength of 1064 nm is used for the experiments. The beam divergence of this system is <1 mrad and the beam diameter is ∼9 mm. A holographic beam sampler is utilized at the laser output to monitor the laser in real time – laser energy and pulsewidth can be evaluated for every shot. Exterior optical systems prior to the final vacuum mirror can be used to modify the laser spot size at the target (Fig. 2).

The laser energy and spot size used for these experiments were determined by calculating the energy density required to reproduce the surface temperature that is anticipated during ELM events in the International Thermonuclear Experimental Reactor (ITER). During type-I ELMs in ITER an energy flux of at least several MJ/m^2 is expected to be deposited during a 0.1–1 ms transient event. [1,2,5]. As this pulse duration is several orders of magnitude longer

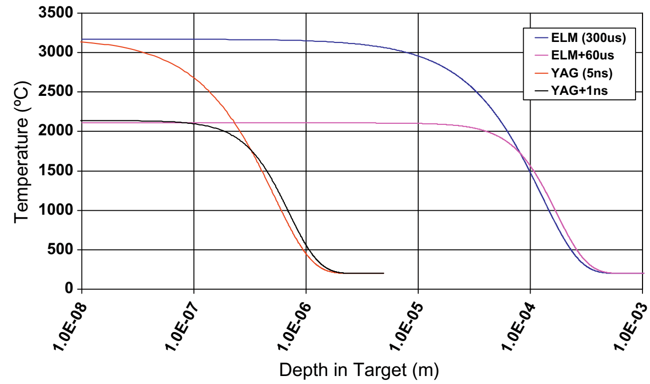

Fig. 3. Comparison of calculation of temperature rise in surface and bulk from predicted ITER ELMs and pulses from the laser heat pulse system.

than the laser pulse, we calculated the surface temperature rise expected from an ELM of 1 MJ/m^2 (pulsewidth of 300 us) and determined the laser energy and spot size to achieve the same surface temperature increase, albeit for a much thinner surface heating area. In these calculations we assumed that 30% of the laser energy is absorbed, consistent with other measurements [6], to allow for reflection from a normal tungsten surface, and then used Eq. (1), which is the solution to a time-dependent one-dimensional heat diffusion equation with a step function heat input, to calculate the temperature profile near the surface of the W plasma-facing component (PFC) (Fig. 3). Temperature curves at a delay of 1/5 the incident pulse duration are also shown to illustrate how rapidly the near-surface layer cools. The incident laser pulse energy density (E/A) equivalent to the relevant ELM impact energy (58MJ/m^2 s$^{1/2}$) [5] was calculated to be ∼15 kJ/m^2 (∼4.5 kJ/m^2 absorbed) for the laser duration used. The laser was fired at a frequency of 0.5 Hz for all experiments discussed here and about 1000 pulses were delivered to each of the samples.

$$\Delta T(z,t) = \frac{2H}{k}\sqrt{\alpha t}\left\{ \mathrm{ierfc}\left[\frac{z}{2\sqrt{\alpha t}}\right] - \mathrm{ierfc}\left[\frac{\sqrt{z^2+a^2}}{2\sqrt{\alpha t}}\right]\right\}. \quad (1)$$

Temperature rise of surface from laser irradiation from Carslaw and Jaeger [7] In this equation H is the absorbed laser irradiance, k is the thermal conductivity, α is the thermal diffusivity, t is time and z is the distance below (into) the surface.

3. Results and discussion

Scanning electron microscope (SEM) images from the initial tests of the plasma and laser heat pulse system described above are shown in Figs. 4–8. From prior work on tungsten at room temperature in the PISCES devices, we know that the plasma alone (Fig. 4) has little effect on the surface for the exposure conditions used in these experiments ($n_e \sim 1.5 \times 10^{12}$ cm^{-3}, $T_e \sim 10$ eV, Flux $\sim 2.5 \times 10^{18}$ cm^{-2} s^{-1}, Ion Energy $\leqslant 130$ V). The onset of some blistering is visible but no measurable mass loss occurs. Prior laser ablation work has shown that one can expect surface damage similar to that shown in Fig. 5 when it is exposed to laser irradiances in the range of those utilized in these experiments, which is sufficient to melt the surface and form reflow regions. As only the near-surface region is heated (Fig. 3) cooling occurs quickly and surface cracks develop as shown in Fig. 5. When the surface is subjected to the same heat pulse under plasma irradiation (Fig. 6), one can see that the surface shows additional roughening as compared to the heat pulse-only scenario. This is similar to the result obtained by other researchers utilizing He plasmas and simultaneous laser irradiation [8,9]. It is difficult to discern visually if the craters

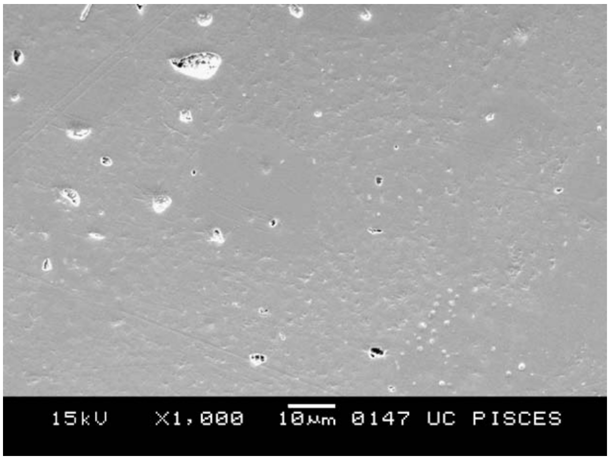

Fig. 4. SEM image of W surface when exposed to deuterium plasma only (Fluence $\sim 10^{26}\ \mathrm{m}^{-2}$).

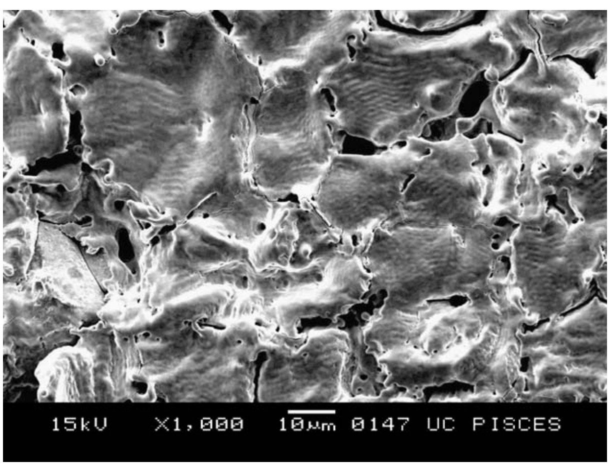

Fig. 5. SEM image of W surface within the laser pulse area exposed only to laser pulses (E/A_{laser} = 15 kJ/m^2).

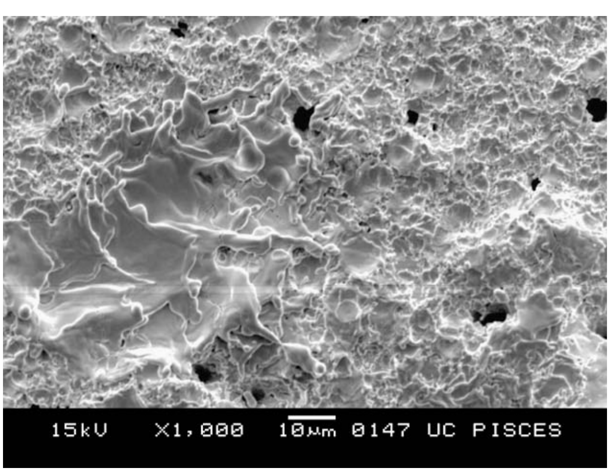

Fig. 6. SEM image of W surface within the laser pulse area exposed to deuterium plasma and simultaneous heat pulses (E/A_{laser} = 15 kJ/m^2 , Fluence $\sim 10^{26}\ \mathrm{m}^{-2}$).

are deeper or if there is any difference in mass loss from this region. This is not the case adjacent to the laser-material interaction location where one can easily observe a change in the surface. Figs. 7 and 8 are SEM images of the surface of the tungsten sample

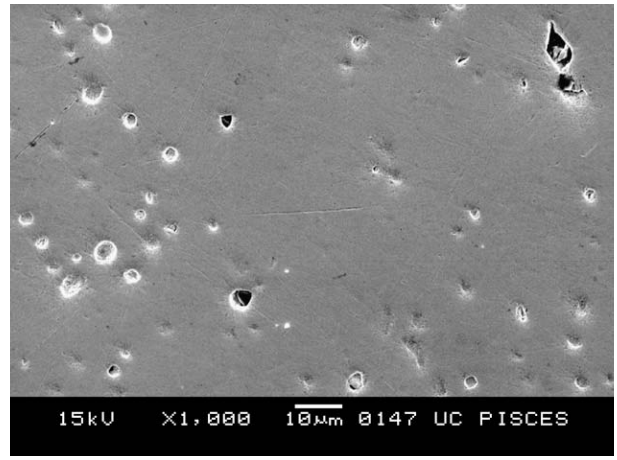

Fig. 7. SEM image of W surface outside the laser pulse exposed only to laser heat pulses.

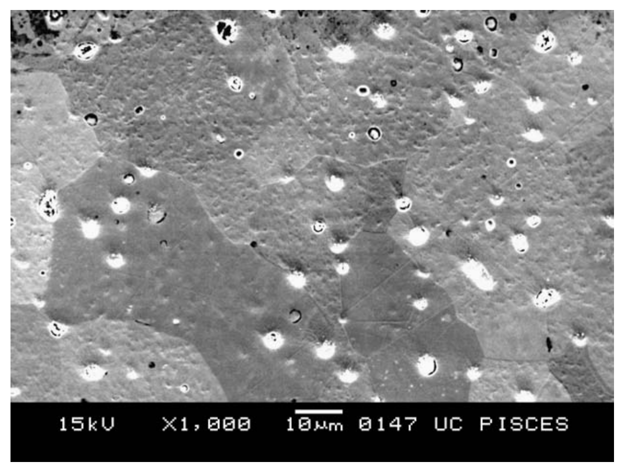

Fig. 8. SEM image of W surface outside the laser pulse exposed to deuterium plasma and simultaneous heat pulses.

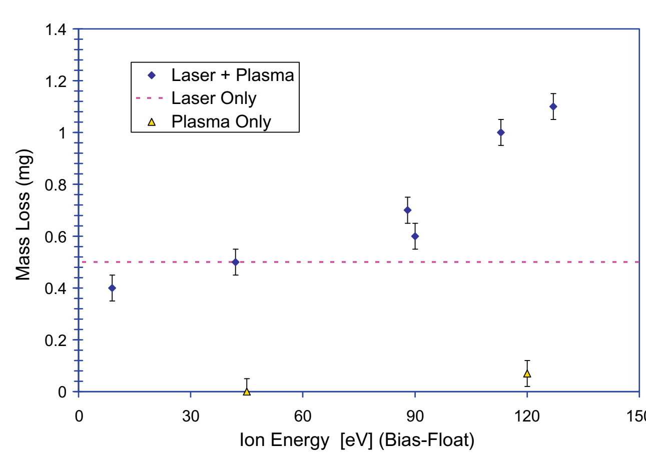

Fig. 9. Mass loss from W targets exposed to plasma only, laser heat pulses only, and plasma plus simultaneous laser at various surface biases.

$\sim$1 cm away from the laser interaction location. Fig. 7 shows features similar to those seen in the polished sample (Fig. 1), where only blemishes from cutting and sanding can be seen. The large divots in the surface stem from the bulk material used and the

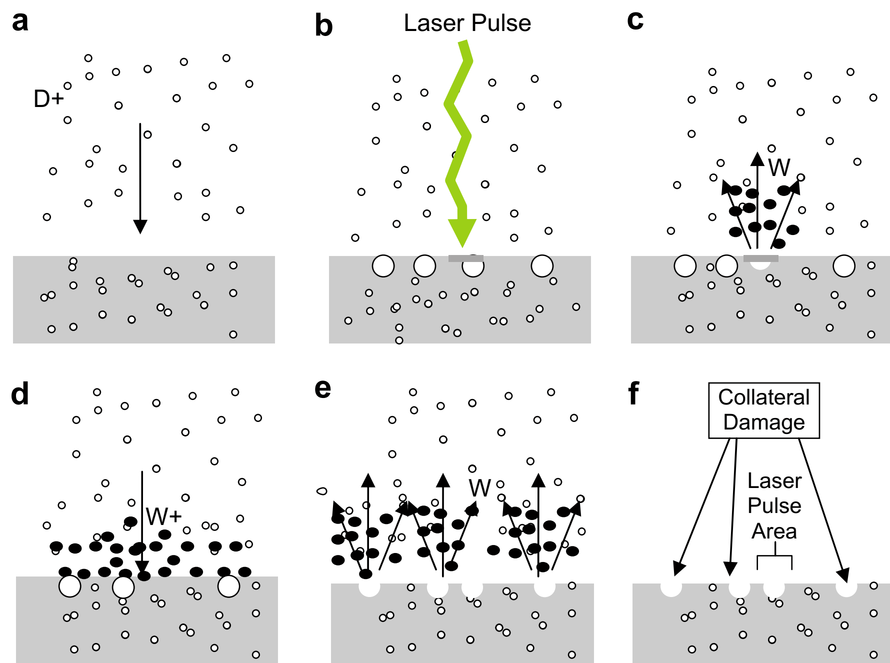

Fig. 10. Cartoon of proposed process occurring when W PFC is exposed to D^+ plasma and simultaneous laser heat pulse. (a) Tungsten surface is exposed to D^+ plasma and retains some of the deuterium. (b) Saturated near-surface region forms blisters, (c) blisters rupture when hit with a laser heat pulse resulting in the ejection of tungsten clusters and particles. (d) Some ejected atoms and clusters are ionized by the surrounding plasma and return to other surface locations. (e) If the ion energy is high enough, the W ion flux can heat and sputter additional material outside the laser pulse area resulting in (f) changes in surface morphology in the surrounding area.

method of sample preparation for these experiments. Further polishing was not done in order to more closely mimic the surface of actual tokamak PFCs. In Fig. 8 there are some features similar to plasma-only exposures (Fig. 4) as some blisters are evident throughout the surface. However, grain boundaries can also be seen in the combined laser plus plasma exposure conditions; no such boundaries are observed in the plasma-only experiments.

Tungsten atoms when released into the plasma by heat pulses do not travel far due to their low energy (which is assumed to be at the thermal energy of the surface). We calculate the range of mean free path for such tungsten atoms in PISCES-A plasmas using electron impact ionization cross-sections from Auburn–Rollins–Strathclyde Ionization Data [10] to be <1 cm. Therefore, a significant fraction of the atoms released from the surface are ionized within the plasma and can return with a distribution across the sample face.

Fig. 9 shows the mass loss of the W samples exposed to the plasma-only, laser-only, and simultaneous plasma bombardment and laser heating conditions of these experiments as a function of bombarding ion energy. Each sample was exposed for a fluence of 10^{26} m^{-2} at a steady-state surface temperature of 50–100 °C and for $\sim$1000 laser pulses. Plasma-only exposure does not result in any measurable weight loss, consistent with expectations for negligible physical sputtering at these ion energies. The expected weight loss in the laser-only condition due to evaporation of material from a liquid W surface, multiplied by the number of laser pulses on each sample of W in vacuum, is of the order of 0.1 mg [11]. The actual laser-only exposure results in a 0.5 mg mass loss, which exceeds the estimate for evaporation discussed above, suggesting that the laser produces some additional mass loss from e.g. droplet and cluster formation as has been observed in other laser ablation experiments [12]. As the ion energy is increased to 90 eV and higher during combined laser plus plasma exposures an enhanced mass loss, defined as the difference between the laser heat pulse-only mass loss and plasma plus laser mass loss, is observed. Recall that there was no measurable change in mass of samples exposed to plasma only at ion energies up to 120 eV. This result suggests that a new mechanism is leading to a significantly larger mass loss under combined plasma and thermal transient conditions.

Preliminary work on PISCES indicates that this combined effect depends upon the total plasma fluence, suggesting that the quantity of deuterium in the near-surface region plays a role in the enhanced mass loss. In addition, careful examination of the SEM photographs shown above indicate that something in the heat pulse plus plasma exposure mass loss process influences the entire surface of the sample, and is not isolated to the laser focal spot. Fig. 10 is a cartoon of a proposed process that may be occurring when W PFCs are exposed to D^+ plasma and a simultaneous heat pulse. A saturated W surface forms microscopic bubbles in the near-surface region, which then are heated and ruptured during laser heating. This then causes the release of the trapped gas, tungsten clusters and particles from the surface, which is subsequently ionized in the plasma and can interact elsewhere on the surface. There is potentially a large amount of gas trapped in the blisters and this may cause additional heating of the surface. If these ions have enough incident energy, then can also cause additional material removal. The net result is a synergistic effect between heat pulse and deuterium plasma causing greater surface roughening and material removal due to formation of clusters and microparticles from rupturing of near-surface bubbles.

4. Conclusions and future work

A study of laser-material interaction was conducted in vacuum and in a low-pressure gas environment at laser energies below the ablation threshold. We then studied the effect of laser heat pulses on PFCs that are simultaneously irradiated by plasma. Initial results indicate that an enhanced erosion of tungsten surfaces can occur during exposure to plasma and ELM-like thermal transients. Materials that have been irradiated with energetic plasma ions ($E > 90$ eV) for times sufficient to saturate the near-surface layer with deuterium (a fluence of $10^{26}/m^2$ was used in these experiments) can experience an explosive release of material. This enhanced erosion could lead to significant increases in estimated mass loss for ITER relevant ELMs. More research will be conducted to determine the threshold for damage and to compare this result to longer (more ELM-like) heat pulses using a laser system with a pulse length and energy flux comparable to ITER ELMs.

Acknowledgement

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