Effects of High Temperature Pulsed Helium Implantation on Tungsten Surface Morphology

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November 2006

UWFDM-1317

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The durability and lifetime of thin tungsten or refractory metal coatings on the first walls of inertial and magnetic confinement fusion reactors is a key issue for the feasibility of such devices. Past studies at UW-Madison have indicated that tungsten, when subjected to He⁺ fluences in excess of 4x10¹⁷ He⁺/cm², shows extensive pore formation at 800 °C.¹,² The current study attempts to produce more realistic results by simultaneously irradiating tungsten samples with helium and hydrogen species and by investigating the effects of pulsed helium ion irradiation on tungsten.

I. MOTIVATION

Previous work by Cipiti, Kulcinski and Radel has shown extensive surface damage resulting from steady-state implantation of helium on tungsten.¹,² However, ICF reactors will face a simultaneous bombardment of helium and hydrogen isotopes, which could affect the way helium damage occurs. These reactors will also be operating in a pulsed mode, with pulse widths of ~10 µs and frequencies of ~5 Hz.³ This paper evaluates the effects of simultaneous helium and deuterium implantation and of performing helium implantation in a pulsed mode.

This research was performed as part of the High Average Power Laser (HAPL) program. HAPL scientists are currently focusing on tungsten as a potential material to protect the first wall from light ions, such as He, whose energy ranges from tens of keV to a few MeV. This study examines the lower portion of that spectrum.

The HAPL program also incorporates other experiments that are studying the effects of pulsed irradiation on tungsten surfaces, including the RHEPP facility at Sandia⁴, the XAPPER facility at Lawrence Livermore⁵, the Dragonfire facility at UCSD⁶, and an infrared facility at ORNL⁷. Figure 1 shows the pulse widths and frequencies for each of these experiments relative to the reference HAPL pulse characteristics. Initial IEC experiments at Wisconsin operated at 1 ms pulse width with a 20 Hz frequency. However, subsequent experiments have indicated that operation at 200 µs pulse widths with frequencies as low as 5 Hz are possible.

II. EXPERIMENTAL SETUP

II.A. Inertial Electrostatic Confinement (IEC) Device

The University of Wisconsin has been studying the performance of an Inertial Electrostatic Confinement (IEC) fusion device for more than a decade.⁸ It has been recently used to test the response of fusion related materials to high temperature bombardment from D and He. As seen in Figure 2, one of the UW IEC devices is an aluminum chamber 65 cm tall and 90 cm in diameter.⁵ A base pressure of ~10⁻⁶ torr is maintained in the device using a 1000 L/s turbo pump. Within this chamber are two conducting surfaces. The outer stainless steel anode grid is 50 cm in diameter and is kept at ground potential. The inner tungsten sample is connected to a 200 kV power supply with a high voltage feed thru.

![Fig. 1: Pulse capabilities of selected HAPL experimental facilities](image1.png)

![Fig. 2: IEC device with tungsten sample](image2.png)
During steady-state operation, helium and/or deuterium gas is fed into the chamber to produce a background pressure of 0.5 mtorr. This gas is then ionized via electron bombardment from hot tungsten filaments. A negative voltage is applied to the tungsten sample (shown in Figure 3), and the positively charged ions are attracted to it.

Fig. 3: Tungsten sample during irradiation

II.B. Pulsed Operation

The UW-IEC steady-state device was modified to allow pulsed operation. IEC current is nominally suppressed during pulsed operation by applying a positive bias to the electron filaments. Cathode current pulses are then generated by adding a large negative bias to the filaments. The cathode voltage is maintained constant during the pulse via a 100 nF parallel capacitor.

Although the ion current was pulsed, the sample temperature was calculated to be nearly steady-state during irradiation. This calculation was based on the semi-infinite solid surface radiation approximation found in Carslaw and Jaeger.\(^9\) This equation used to compute the temperature rise during a single pulse was:

\[
\Delta T = \frac{2P}{Ak} \sqrt{\frac{kt}{\pi \rho c_p}}
\]

where \(P\) is the total power into the sample, \(A\) is the total surface area, \(k\) is thermal conductivity, \(\rho\) is density, \(t\) is the pulse width, and \(c_p\) is the specific heat. Substituting in typical values for a pulsed implantation experiment yields a temperature change of only 8 °C during a pulse.

Fig. 4: High voltage circuit for pulsed IEC operation

The configuration shown in Figure 4 allows the creation of high-flux helium ion pulses at relatively constant voltages. The time-dependent current observed during the initial pulsed irradiation experiments is shown in Figure 5. Helium ion currents of 60 mA were pulsed at 25 Hz with a 1 ms pulse width. This resulted in a time-averaged current that was one-fourth of a typical steady-state irradiation, as shown in Figure 5.

Fig. 5: Pulsed vs. steady-state irradiation current

III. RESULTS

IIIA. Steady-State He\(^+\) and D\(^+\) Implantation

Simultaneous implantation of D\(^+\) and He\(^+\) was performed on tungsten samples at ~1100 °C. Previous experiments have indicated that deuterium irradiation alone does not induce pore formation.\(^1\) Figure 6 compares polycrystalline tungsten samples irradiated with helium alone and with a helium-deuterium mixture. At \(1 \times 10^{18}\) ions/cm\(^2\), there appears to be a slight reduction in the pore density from \(1.2 \times 10^9\) pores/cm\(^2\) on the helium-only sample to \(3.2 \times 10^8\) pores/cm\(^2\) on the sample run with He and D simultaneously. As the fluence is increased, however, this difference diminishes. At \(1 \times 10^{19}\) ions/cm\(^2\), there appears to be no significant difference between the samples with and without added deuterium.
This study indicates the addition of a simultaneous deuterium ion current has a minimal effect on the damage caused by helium irradiation in tungsten at fusion first wall-relevant temperatures. Therefore future experiments, including the pulsed implantation study discussed in this paper, can confidently be performed with helium ions alone. This simplification allows for more accurate measurement of helium fluence while still providing realistic results.

III.B. Pulsed Helium Implantation

Pulsed helium implantation of polycrystalline tungsten was performed at 1150 °C using the Wisconsin IEC device. Fluences of $1 \times 10^{18}$, $6 \times 10^{18}$, and $1 \times 10^{19}$ He$^+/cm^2$ were delivered to the samples in 1 ms pulses at 25 Hz. Micrographs of these samples were then compared to previous steady-state results at the same fluences and temperatures.

Figure 7 shows results for both pulsed and steady-state irradiation to $1 \times 10^{18}$ He$^+/cm^2$. When the implanted helium fluence was increased to $6 \times 10^{18}$ He$^+/cm^2$ at 1150 °C, the pore density of the steady-state sample increased dramatically, reaching $3.7 \times 10^9$ pores/cm$^2$. In contrast, the pore density on the $6 \times 10^{18}$ pulsed He$^+/cm^2$ sample did not significantly increase from the lower fluence, as shown in Figure 8. However, there does appear to be a change in the surface morphology at the grain boundaries. This change may indicate a shift towards more macroscopic damage mechanism as the pulsed helium fluence is increased.
When the steady-state implanted helium fluence was increased to $1 \times 10^{19}$ He$^+$/cm$^2$ at 1150 °C, the pore density decreased slightly to $1.9 \times 10^9$ pores/cm$^2$, as shown in Figure 9. However, the surface appears to have roughened in a similar fashion to the pulsed sample at $6 \times 10^{18}$ He$^+$/cm$^2$. The pulsed sample, however, has been damaged to the point of having a coral-like structure form in addition to the uniform pore density covering the surface.

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$$1 \times 10^{19} \text{ He}^+/\text{cm}^2$$

40 kV, 60 mA Pulsed (1140±20 °C baseline) 2 hour runtime
30 kV, 6 mA Steady-State (1150±20 °C) 30 minute runtime

**Fig. 9:** Pulsed and steady-state tungsten samples irradiated at ~1150 °C to $6 \times 10^{18}$ He$^+$/cm$^2$

Pulsed irradiation resulted not only in increased pore density on the surface, but also in an increased semi-porous layer beneath the surface. Figure 10 shows Focused Ion Beam (FIB) images of these surface layers at two fluences for both pulsed and steady state implantation. As either steady-state or pulsed fluence is increased, the additional helium bubbles create and extend a semi-porous surface layer.

In addition to the morphological changes, the samples pulsed at 1150 °C also experienced a measurable change in mass. Theoretical calculations based on physical sputtering rates predict that the sample would lose ~0.2 mg after $1 \times 10^{19}$ He$^+$/cm$^2$. However, the sample actually lost 4.2 mg, or roughly 1.1 µm uniformly from the surface, suggesting that other mechanisms of mass loss must be taking place. The mass loss for three samples subjected to pulsed helium implantation is summarized in Table 1 below.

<table>
<thead>
<tr>
<th>Pulsed (40 kV)</th>
<th>Steady-State (30 kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1150 °C baseline)</td>
<td>(1150 °C)</td>
</tr>
<tr>
<td>$1 \times 10^{18}$/cm$^2$</td>
<td>$6 \times 10^{18}$/cm$^2$</td>
</tr>
<tr>
<td>300 nm</td>
<td>90 nm</td>
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**Table 1:** Mass loss for pulsed samples (1 ms pulse width, 25 Hz, 1150 °C)

One possible explanation for the higher-than-expected could be increased sputtering coefficients for non-perpendicular ion incidences. However, this would not increase the physical sputtering loss enough to account for the observed mass loss, even assuming the forward-sputtered material is not re-deposited on the sample. Another possible explanation is the loss of the small protrusions during the irradiation process.
IV. CONCLUSIONS

The Inertial Electrostatic Confinement (IEC) fusion device at the University of Wisconsin is now able to perform both steady-state and pulsed irradiation experiments. This device is capable of generating 0.2-2 ms D+ or He+ pulses of up to 1 ampere at 10 Hz.

Pulsed helium implantation of polycrystalline tungsten was performed at 1150 °C using the Wisconsin IEC device. Fluences of 1x10^{18}, 6x10^{18}, and 1x10^{19} He+/cm² were delivered to the samples in 1 ms pulses at 25 Hz. Micrographs of these samples revealed increased surface damage at all fluences compared to steady-state irradiation. At 1x10^{18} He+/cm², the steady-state sample only exhibits pores collecting at grain boundaries with a pore density of 1.2x10⁹ pores/cm², while the pulsed sample appears close to a saturation density with larger pore size.

When the steady-state implanted helium fluence was increased to 1x10^{19} He+/cm² at 1150 °C, the pore density decreased slightly to 1.9x10⁹ pores/cm². The pulsed sample, however, has been damaged to the point of having a coral-like structure form in addition to the uniform pore density covering the surface.

Tungsten samples pulsed at 1150 °C at fluences ranging from 10^{18}-10^{19} He+/cm² experienced a measurable change in mass. Theoretical calculations based on physical sputtering rates predict that a tungsten sample would loose ~0.2 mg after 10^{19} He+/cm². However, the sample actually lost 4.2 mg, or roughly 1.1 µm uniformly from the surface, suggesting that other mechanisms of mass loss must be taking place.

ACKNOWLEDGMENTS

The authors would like to thank the Naval Research Lab, the Greatbatch Foundation, and the Grainger Foundation for financial support of this work. We also want to acknowledge Dr. Lance Snead and Dr. Steve Zinkle at ORNL for providing samples and the IEC team – Dr. John Santarius, Dr. Gil Emmert, Bob Ashley, Greg Piefer, Sam Zenobia, Dave Boris, Chris Seyfert, Brian Egle, and Eric Alderson – for their assistance and support during the helium implantation experiments.

REFERENCES