# Further Roughing of Tungsten Surface due to Transient Heat Load by Laser Irradiation during Helium Plasma Exposure

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The influence of a transient heat load on the formation of hole and bubble structures on tungsten surfaces exposed to helium plasmas is demonstrated using pulsed laser-beam irradiation in divertor simulator NAGDIS-II. SEM (scanning electron microscope) micrographs of the tungsten surface revealed that the formation of the holes and bubbles was dramatically enhanced due to a transient temperature increase in response to the laser irradiation.

**Keywords:**
tungsten, holes, bubbles, laser irradiation, ELM

Tungsten is one of the candidates for divertor materials because of its high thermal property and low sputtering yield. However, recent experimental observations have revealed that bubbles and holes are formed on the surface by helium plasma exposure even with an incident ion energy less than the threshold energy of sputtering [1]. The formation of holes and bubbles may lead to degradation of the superior properties of tungsten, especially, its thermal diffusivity. If the thermal diffusivity is degraded, transient heat loads owing to the ELMs (Edge Localized Modes) [2] and disruption may pose serious problems, such as the melting of high-Z materials. In this paper, the transient heat load to the tungsten target during exposure to helium plasmas was demonstrated using pulsed laser irradiation. Although the heat pulse duration was several ns, which is much shorter than the characteristic time of the ELMs ($\lesssim 10^{-4}$ s), the experimental observations indicate the effect of transient temperature increases on the surface modification.

Experiments were performed in the divertor simulator NAGDIS-II (NAGoya university DIvertor Simulator-II). A schematic view of the experimental setup is shown in Fig. 1. The helium plasma was irradiated to a W sample situated at about a 45-degree angle to the magnetic field line. The specimen was powder metallurgy W 0.2 mm in thickness. Second-harmonic pulses of an Nd:YAG laser (Continuum: SLII-10), with a wavelength of 532 nm, were used for the photon source. The pulse duration was 5–7 ns, and the pulse interval was 0.1 s, sufficiently longer than the characteristic thermal relaxation time. The laser beam was injected through a quartz viewing port at a 90-degree angle to the magnetic field line. The laser-pulse energy was measured before the viewing port, and the energy per unit area at the target was deduced by taking into account the transmission rate of the viewing port and the angle of the laser beam to the tungsten sample.

SEM images of the tungsten sample exposed to helium plasmas without laser irradiation are shown in Fig. 2 (a) (from top) and Fig. 3 (a) (cross section). The ion flux was $\Gamma_i = 1.7 \times 10^{23}$ m$^{-2}$/s, and the incident ion energy was 27 eV. The exposure time to the helium plasma was 1800 s; the tungsten surface temperature measured with a radiation pyrometer was ~1700 K.

Micron-bubbles and holes are observed on the surface, and the penetrating depth of the surface modification was 1– 2 $\mu$m. Figure 2 (b) shows SEM images of the laser irradiated tungsten surface exposed to the helium plasma under the same

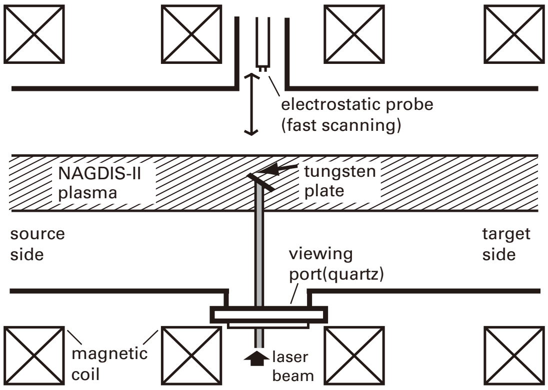

Fig. 1 Experimental setup for laser irradiation experiments to tungsten surface in helium plasmas.

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*author's e-mail: kajita@ees.nagoya-u.ac.jp* plasma condition as in Fig. 2 (a). The laser-pulse energy was 200 mJ/cm$^2$ per pulse, and 18000 pulses were irradiated. The sizes of the bubbles and holes were much larger than those in Fig. 2 (a). Furthermore, the surface is cracked, maybe due to the transient temperature increase in response to the laser irradiation. Figure 3 (b) is a cross section of the sample shown in Fig. 2 (b), showing that the hole depth was 13 $\mu$m, significantly greater than that without laser irradiation shown in Fig. 3 (a). We also analyzed a virgin tungsten surface irradiated by laser pulse in vacuum at the laser-pulse energy of 600 mJ/cm$^2$, three times the pulse energy used in the above experiments. However, surface modification at a depth of ~ 10 $\mu$m was not observed.

Because the surface modification of a tungsten surface exposed to helium plasma was significantly enhanced by laser irradiation, we speculate that the surface temporarily reached melting point due to the laser irradiation. The surface temperature was estimated by solving the one-dimensional heat conduction equation assuming that the temporal evolution of the laser pulse is triangular, and using the standard thermal diffusivity of bulk tungsten [3,4]. Even if we assumed that the reflection coefficient of light on the tungsten surface was 0%, and all laser energy was deposited to the tungsten surface, the estimation shows a maximum surface temperature of ~ 3150 K, which is sufficiently lower than the melting point of 3700 K. However, the surface temperature can reach the melting point if the surface thermal diffusivity is assumed to be 50% of that for virgin tungsten and the heat capacity is assumed to be that for virgin tungsten. These results indicate that poor thermal diffusivity of the tungsten surface due to hole/bubble formation by He plasma exposure causes the tungsten surface to melt even with a transient heat load by laser irradiation smaller than that required for the melting of bulk tungsten.

Further investigation with spectroscopy of WI or the 'strange' electron/ion current that was observed recently due to laser irradiation to a tungsten probe tip in helium plasmas [5] will provide detailed information of this phenomena. These are currently underway.

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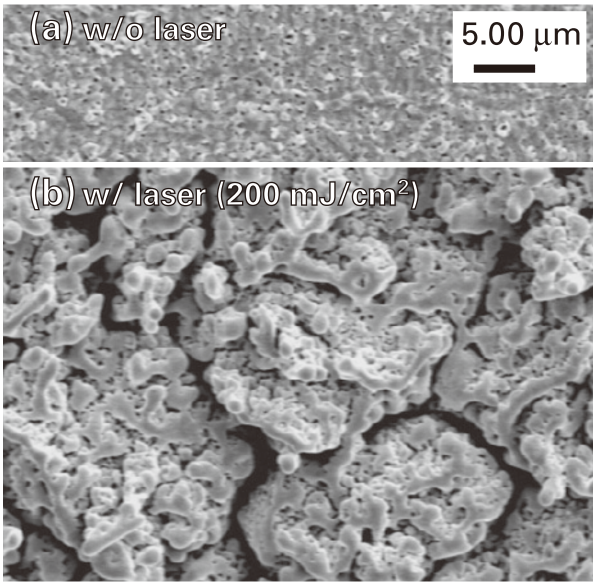

Fig. 2 SEM images of tungsten surfaces. (a) without laser irradiation, (b) with laser irradiation.

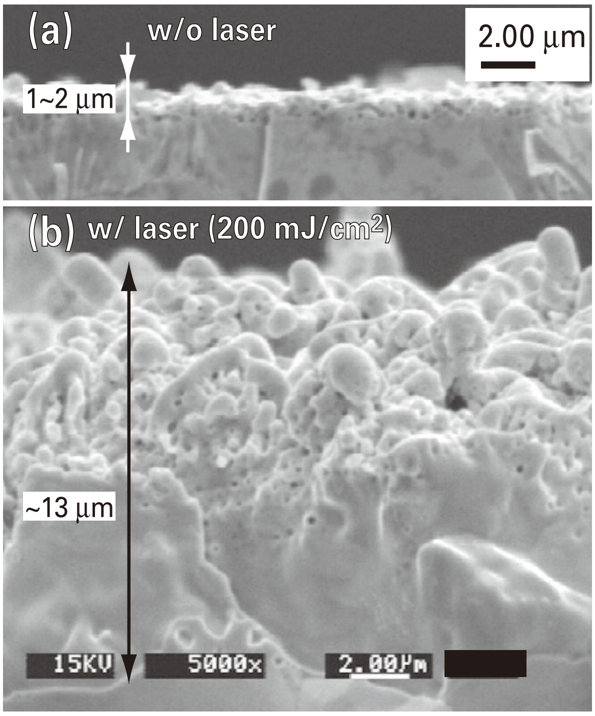

Fig. 3 SEM images of tungsten cross sections. (a) without laser irradiation, (b) with laser irradiation.