Effects of transient heat load on tungsten surface having sub-micron helium holes and bubbles

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Tungsten, which has good thermal properties and a low sputtering yield, has been widely used where high heat flux is concentrated. Tungsten is a candidate for a divertor material in magnetic confinement fusion devices, and a candidate material for the first wall of inertial fusion reactors and future commercial fusion reactors [1]. However, recent experimental observations reveal that bubbles and holes are formed on the tungsten surface that is exposed to helium plasmas even when the incident ion energy is less than the threshold energy for physical sputtering [2]. The degradation of thermal properties may pose serious problems to melt tungsten owing to a pulsed heat flux accompanied by the following phenomena. Disruptions and Edge Localized Modes (ELMs) [3] provide a high heat load to a target material during a short time period in the operation of a tokamak. In Type-I ELMs of the ITER (International Thermonuclear Experimental Reactor), a heat flux of above several tens MWm^{-2} is expected during 0.1-1 ms [4]; moreover, in the disruption of ITER, a heat load of up to 100 GWm^{-2} is expected during a time period of the order of 10 ms. For inertial fusion reactor design, the heat load to the first wall is considered to be $\sim$ 500 Jm^{-2} (50 $mJcm^{-2}$) during 1 ns due to X-rays, and of $\sim$ 10 kJm^{-2} (1 Jcm^{-2}) during several μs due to burn ions [5].

In the present paper, the transient heat load on the tungsten surface with holes and bubbles due to helium plasmas are demonstrated using pulsed laser irradiation. Furthermore, heat conduction in the solid substrate and liquid melt is analyzed based on heat transfer models for investigating the physical processes in response to laser irradiations.

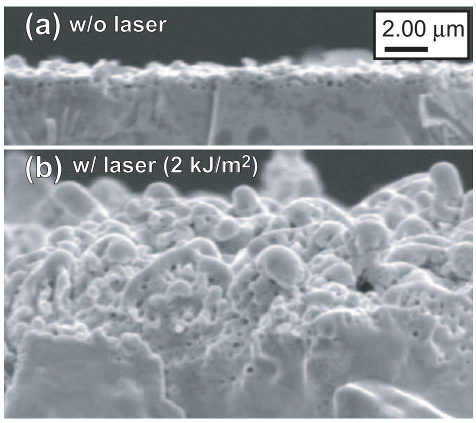

Figure 1: SEM images of tungsten cross sections. (a) w/o laser irradiation, (b) w/ laser irradiation.

The tungsten samples were exposed to high density helium plasmas in the divertor simulator NAGDIS (NAGoya university DIvertor Simulator) - II [6]. The typical plasma parameters, electron density and temperature, are 10^{19} m^{-3} and 5 eV, respectively. For transient heat source, two types of pulse lasers, a Nd:YAG laser

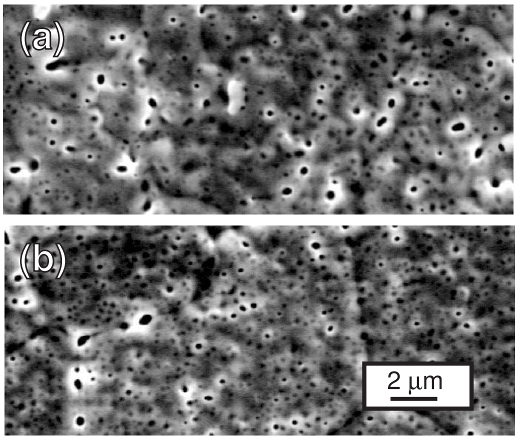

Figure 2: (a) SEM pictures of tungsten suraface exposed a helium plasma. Many pinholes are observed. (b) Ten ruby laser pulses were irradiated to the tungsten surface during the surface was exposed to helium plasmas. No significant modification cannot be seen.

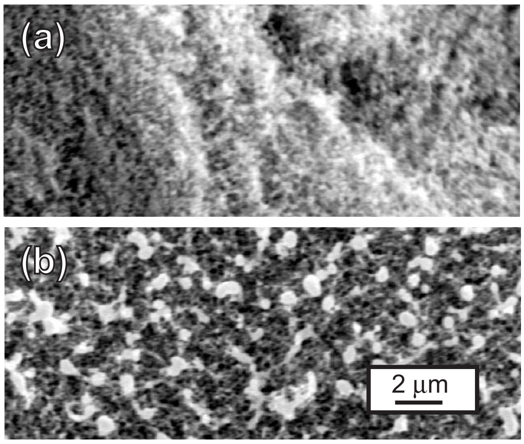

Figure 3: (a) SEM micrograph of tungsten coated graphite exposed to helium plasmas. (b) SEM micrograph of tungsten coated graphite surface of (a) after ruby laser irradiation in vacuum.

with a Q-switch and a ruby laser without a Q-switch, were used. The pulse width of the Nd:YAG laser and ruby laser are 5-7 ns and $\sim$ 0.6 ms, respectively. The typical laser pulse energies were 2 kJ/m^2 (Nd:YAG) and 100 kJ/m^2 (ruby), so that the ranges of the pulse energy for Nd:YAG and ruby lasers correspond to the heat load due to X-ray in inertial fusion reactors and that due to ELMs in tokamaks, respectively.

Figure 1(a) shows SEM micrographs of tungsten cross section (powder metallurgy tungsten, Nilaco Co. Ltd.) exposed to helium plasmas at the surface temperature of 1700 K for a period of 3600 s. We can observe holes and bubbles at sub-surface region. The penetration depth of the holes and bubbles was about 1-2 μm. On the other hand, after laser pulses (18000 pulses) were irradiated to the sample in the helium plasma, sizes of the bubbles and holes became much greater than those without laser pulses, and the penetration was much deeper as shown in Fig. 1(b) [7]. Assuming that the thermal property was that for virgin tungsten, the maximum surface temperature was estimated to be much lower than the melting point of 3700 K even if the reflection coefficient of light is assumed to be zero. For understanding the physical mechanisms to arise the phenomena, the heat conduction in the substrate having holes is modeled by solving a three-dimensional heat conduction equation. On the basis of surface temperature calculations by solving three-dimensional heat conduction equation and from an evaluation of the tensile stress put on the lids of the holes, repetitive explosions of the helium holes caused by heating the lids are considered to be the mechanism enhancing the surface roughness [8].

Figure 2(b) shows a tungsten surface after the surface was irradiated by ruby laser pulses. The pulse energy was $\sim$ 60 kJ/m^{-2}. Contrary to the experiments using Nd:YAG laser pulses, the surface modification can not be seen, even though the laser pulse energy was considerably (20 times) greater than that of Nd:YAG laser pulses. It can be said that the transient heat load in this range (0.6 ms, 60 kJ/m^2) was not sufficient to enhance the roughness.

Figure 3(a) shows a SEM micrograph of tungsten coated graphite exposed to a helium plasma at the surface temperature of 1600 K. This tungsten coated graphite was made of fine-grained graphite IG-430U (Toyo Tanso Co.) substrate coated by tungsten using a plasma spray [9]. The surface color was totally changed to black after the exposure. The surface appearance is quite different from that of bulk tungsten; it seems that materials having sub-micron fine structure cover the surface. Figure 3(b) shows the surface micrographs after the 10 ruby laser pulses were irradiated to the surface in vacuum at the surface bulk temperature of 300 K. We can see white spots, which are the melting traces, on the surface.

Figure 4 shows the temporal evolution of surface temperature calculated by solving one-dimensional heat conduction equation. The reflection coefficient was assumed to be zero, and time evolution of the heat pulse was assumed to be a triangular shape with 0.25 ms rising and falling time. If the thermal diffusion coefficient of bulk tungsten was used, the temperature increase due to the laser pulse of 100 kJ/m^2 is several hundreds K as denoted as 100 % in Fig. 4; thus, surface should not be melt. It is supposed that the thermal diffusivity of surface can be decreased due to the sub-micron structure near the surface, so that calculated surface temperature using decreased thermal diffusivity are shown in fig. 4 as 10% and 1%. It is estimated that the surface temperature may be sufficiently high to melt if the thermal diffusivity becomes lower than 1 % of the thermal diffusivity of bulk tungsten. Therefore, it can be said that sub-micron structure may lead a significant reduction of the thermal diffusivity, although hole structure may not lead drastic reduction of the thermal

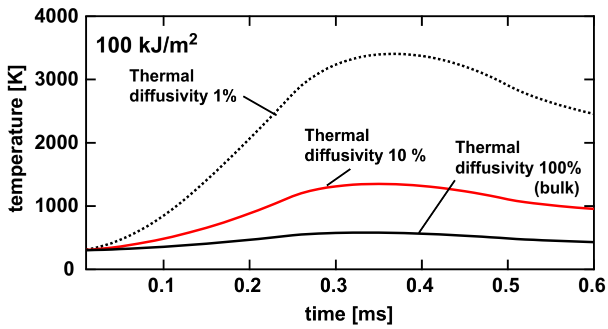

Figure 4: Calculated tungsten surface temperature in response to a laser irradiation. The calculated results with reduced thermal diffusivity (10%, and 1% of that for bulk tungsten) are also presented.

diffusivity.

As for future studies, investigations using higher heat load of the order of 1 MJ/m^2, which corresponds to the expected heat load in ITER operations, are necessary. Further, surface temperature calculation innovating the reduction of thermal diffusivity only around sub-surface region ($<10\ \mu$m) is remained.

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