Alleviation of Helium Holes/Bubbles on Tungsten Surface by Use of Transient Heat Load

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The alleviation effect of transient heat load on helium holes/bubbles has been demonstrated using ruby laser pulses for the transient heat source in the divertor simulator NAGDIS-II. It is shown that the holes and bubbles disappeared following the irradiation of the ruby laser pulses, while the surface roughness was significantly enhanced by the irradiation of the Nd:YAG laser pulses. Based on the numerically calculated temperature in the specimen, the physical mechanism causing this difference is discussed particularly in terms of pulse width (0.6 ms for ruby laser without a Q-switch and 5 ns for Nd:YAG laser with a Q-switch).

Keywords: tungsten, holes and bubbles, divertor simulator, heat conduction, laser irradiation, transient heat load

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The heat load accompanied by transient events in tokamaks, such as disruption and ELMs (Edge Localized Modes), pose serious problems to the divertor and first wall materials. Specifically for tungsten (W), which is one of the candidate materials for the divertor and first wall of fusion reactors, it has been pointed out that a part of the W target melts due to huge transient heat loads, and that the evaporation and the motion of the melted layer damages the W target materials, forming cracks and craters [1, 2]. These phenomena reduce the lifetime of the W material as well as deteriorate the performance of the core plasma.

Furthermore, holes/bubbles are formed in W by the exposure to low energy helium plasmas [3,4]. It is thought that the surface damages in the form of holes/bubbles intensify and complicate the problems accompanying transient heat load [5]. Our previous study found that a surface roughness was significantly enhanced by simultaneous irradiation by helium plasma and ns-laser pulses [6]. However, the pulse width of the laser is about five orders of magnitude shorter than the duration of ELMs, so that it is necessary to investigate the effect of transient heat load by use of a transient heat source having duration comparable to that of ELMs. In the present paper, the effect of transient heat load on damaged materials containing holes/bubbles is experimentally simulated using mainly a ruby laser without a Q-switch. Based on the experimental observation and numerical calculation of the temperature evolution in the material, the physical mechanisms causing the effects are discussed.

In the experiments, a ruby laser without a Q-switch (Nihon Koshuha: SLG-2018) and an Nd:YAG laser with a Q-switch (Continuum: SLII-10) were used for the transient heat source. The wavelength, pulse width, and pulse interval of the ruby laser are 694 nm, 0.6 ms and 30 s, respectively, and those of the Nd:YAG laser are 532 nm, 5-7 ns, 0.1 s, respectively. The pulse width of the ruby laser corresponds to that of typical type-I ELMs, and the heat load is also close to that of the type-I ELMs in ITER (International Thermonuclear Experimental Reactor) [1]. To investigate the effect of helium holes/bubbles, powder metallurgy W (PM-W) is pre-exposed to helium plasmas in the divertor simulator NAGDIS-II for 1800 s [6], then the PM-W specimen is irradiated by the laser pulses while it is exposed to the plasmas.

Figures 1 (a), (c) and (e) show SEM micrographs of PM-W specimens exposed to helium plasmas with ion fluence of 7×10^{26} m^{-2}, 3×10^{25} m^{-2} and 9×10^{24} m^{-2}, respectively. The irradiation temperatures were (a) 1700 K, (c) 1600 K, and (e) 1600 K. Since conditions necessary for the formation of sub-micron holes [7] were satisfied in all cases, many pinholes, which are the typical feature of the tungsten containing sub-micron holes [8], can be observed. Figure 1 (b) shows a SEM micrograph after the PM-W of (a) was irradiated by 18000 pulses of the Nd:YAG laser at a pulse energy of 2 kJm^{-2}. In addition to the surface cracks, possibly due to the repetitive transient temperature change in response to the laser irradiation, it was found from the SEM images of the cross section of the sample that the penetration depth of the holes became ~10 μm though the depth was 1-2 μm before the laser irradiation [6]. Figures 1 (d) and (f) show the PM-W after ten ruby laser pulses irradiated the sample of Fig. 1 (c) at a pulse energy of

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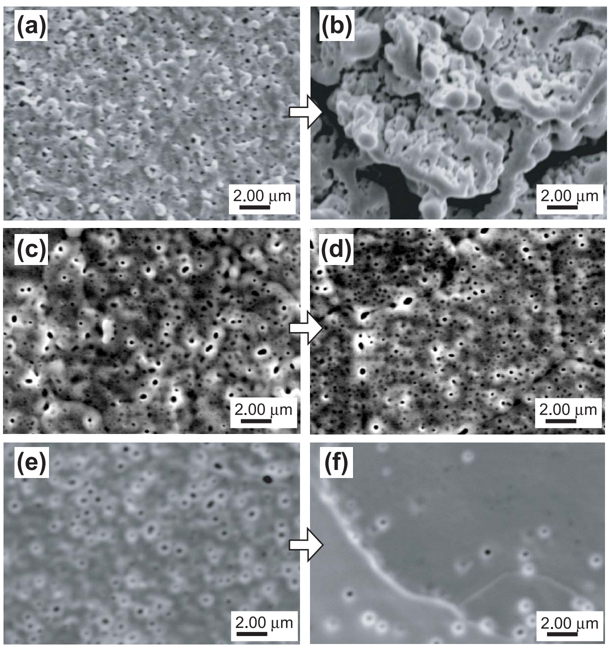

Fig. 1 The SEM micrographs of PM-W surface exposed to helium plasma taken before ((a), (c), and (e)) and after ((b), (d), and (f)) laser pulse irradiation. (b): Nd:YAG laser at a pulse energy of 2 kJm^{-2}. (d) and (f): Ruby laser at those of 70, and 580 kJm^{-2}, respectively.

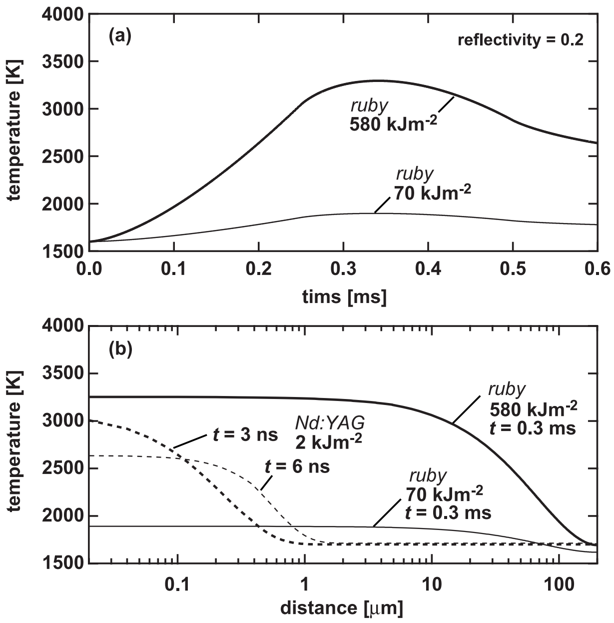

Fig. 2 Numerically calculated temperature in tungsten. (a) Temporal evolution of the surface temperature. (b) Depth dependence of the temperature at $t = 0.3$ ms for the ruby laser, and those at $t = 3$ and 6 ns for the Nd:YAG laser.

70 kJm^{-2} and (e) at a pulse energy of 580 kJm^{-2}. When the pulse energy was 70 kJm^{-2}, the surface showed no change. On the other hand, holes/bubbles disappeared when the pulse energy was 580 kJm^{-2}. It has been reported that the cracks appear on the tungsten surface due to the irradiation of the pulsed plasmas [9] in which the pulse width was several hundreds μs. Thus, the surface cracks may appear even when using the ruby laser if further pulses are irradiated. However, it is worth emphasizing that the structure of the holes/bubbles is alleviated due to the irradiation of the ruby laser pulses, contrary to the case of the *Q*-switch Nd:YAG laser shown in Fig. 1 (b). This raises the question regarding the mechanism that accounts for the difference between the effects caused by the ruby laser and those of the Nd:YAG laser.

Figure 2 (a) shows the temporal evolution of numerically calculated surface temperature obtained by solving a one-dimensional heat conduction equation [8]. In the calculation, the temporal evolution of the laser pulse was assumed to have a triangular shape and a rising and falling time of 0.25 ms for the ruby laser pulse and 2.5 ns for the Nd:YAG laser pulse. Concerning optical reflectivity, a value of 0.2 was used based on the fact that the surface reflectivity decreases due to the ion irradiation from ~0.4 [10]. It was found that the maximum surface temperature was ~ 1900 and 3400 K at 70 and 580 kJm^{-2}, respectively. The solid lines and dotted lines in Fig. 2 (b) show the depth profile of the temperature at $t = 0.3$ ms for the ruby laser and at 3 and 6 ns for the Nd:YAG laser, respectively. If we define length l_h as the depth in which temperature increase becomes ~1/e of that at the surface, l_h is about 100 μm for the ruby laser pulse, whereas $l_h < 1$ μm for the Nd:YAG laser pulse because $l_h \propto (\text{pulse width})^{1/2}$.

It has been found from three-dimensional heat conduction calculation [8] that the surface temperature can be anomalously increased due to the structure of the holes/bubbles when the pulse width is of a ns order. This is because the heat conduction length, l_h, is shorter than the depth of the damaged region due to holes/bubbles, l_d, which is typically ≤1-2 μm. This anomalous temperature increase in the surface of the bubbles/holes facilitates their bursting [8]. Moreover, it is likely that the holes remain after the holes/bubbles have burst because the surface temperature immediately drops. On the other hand, in the case of the ruby laser pulses, the effect of the structure of the holes/bubbles on the local temperature increase is negligible because $l_h \gg l_d$. Additionally, it is speculated that the structure of the holes/bubbles is modified when the surface is heated because the pulse width is much longer than that of the *Q*-switch Nd:YAG laser.

Though the detailed physical processes necessary to alleviate the hole structure have not yet been specified, transient heat load with a sub-ms duration has the potential to suppress the sub-micron structures such as helium holes/bubbles. In future studies, further investigations of surface damage including the formation of cracks are important. Moreover, we are planning to use spectroscopy to investigate the ejection of W atoms from target in response to the laser pulses.

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