Crack Formation Inside Plasma-Facing Materials Irradiated by Pulsed Laser to Simulate Heat Load in Inertial Confinement Fusion System*)

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(Received 12 January 2022 / Accepted 6 October 2022)

The first wall in an inertial confinement fusion (ICF) reactor is eroded by charged particles, neutrons, and X-rays as the nuclear fusion output within an extremely short period. Because damage to plasma-facing materials (PFMs) determines the lifetime of a nuclear fusion system, it is crucial to examine the internal state of PFMs. We irradiated a pulsed laser to simulate the heat load generated by the ICF output using tungsten as the wall material. No cracks were observed on the surface of the sample using an optical microscope, whereas cracks appeared near the surface inside the sample manufactured in the depth direction using a focused ion beam device. The observed cracks were formed in deeper locations than in previous studies. The cracks were generated owing to the temperature difference between the surface and the interior generated by the thermal load within an extremely short period.

Keywords: inertial confinement fusion, plasma-facing material, crack, pulsed heat load, pulsed laser, focused ion beam

DOI: 10.1585/pfr.17.2405108

1. Introduction

Plasma-facing materials (PFMs) are heavily exposed to energy loads, such as fusion output, edge-localized modes (ELM), and disruption in magnetic confinement fusion [1, 2]. The first wall of an inertial confinement fusion (ICF) system is eroded by charged particles, neutrons, and X-rays as the nuclear fusion output within a very short time. In particular, charged particles and X-rays have a short range of materials and cause local energy deposition in a shallow region around the surface of PFMs compared with neutrons. Thermal loading is expected to generate cracks on the surface [3, 4]. While the surface changes of damaged PFMs have been investigated, the effect on the depth direction is unclear. In particular, the effects of internal conditions by extremely short-time heat loads have not been investigated extensively. Because the damage to PFMs determines the lifetime of a nuclear fusion system, it is necessary to examine the internal state of the PFMs.

In this study, we irradiated a pulsed laser to simulate the heat load generated by the ICF output on tungsten (W) and observed the internal state of the sample. The tungsten sample was irradiated with a pulsed laser by adjusting the energy fluence absorbed by the sample to 1 $\mathrm{J\,cm^{-2}}$. The energy fluences were lower than the ablation threshold, which was approximately 2 $\mathrm{J\,cm^{-2}}$ for a solid metal under a pulsed load [5]. The heat flux parameter was 77 $\mathrm{MJ\,m^{-2}\,s^{-0.5}}$. Optical microscopy was performed to observe the surface of the sample. In addition, the sample was manufactured in the depth direction using a focused ion beam (FIB) device, and the internal state of the sample was observed. No cracks were observed on the surfaces using optical microscopy. However, it was confirmed that cracks were generated near the surface inside the sample using the FIB device.

2. Experimental Setup

We used an Nd:YAG laser (wavelength of 532 nm) to simulate the pulsed thermal load in the PFMs. The energy per shot was E_L = 265.5 mJ, and the pulse duration was 17 ns. Figure 1 shows the experimental setup for the laser irradiation of the sample. A tungsten plate (99.95%, Nilaco) was used as the sample in a vacuum chamber (7~9 Pa).

First, we demonstrated pulsed laser irradiation of the sample surface as a preliminary experiment to obtain the absorption ratio α_W of the laser energy into the sample. The sample was irradiated using a pulsed laser with several shots, and the sample temperature was measured using a radiation thermometer. The laser was weakly focused onto the sample surface to prevent ablation of the sample. The

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*) This article is based on the presentation at the 30th International Toki Conference on Plasma and Fusion Research (ITC30).

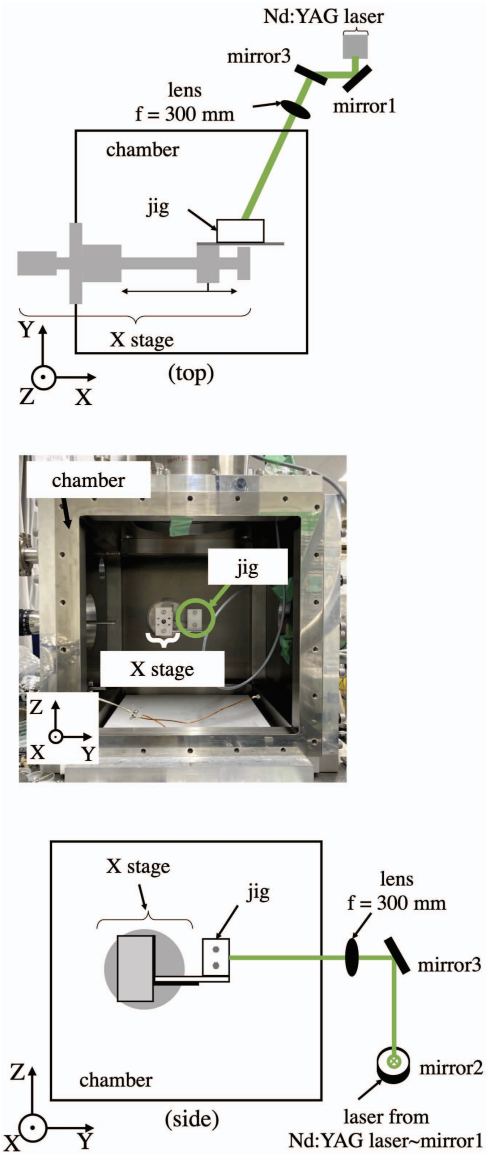

Fig. 1 Experimental setup for pulsed laser irradiation.

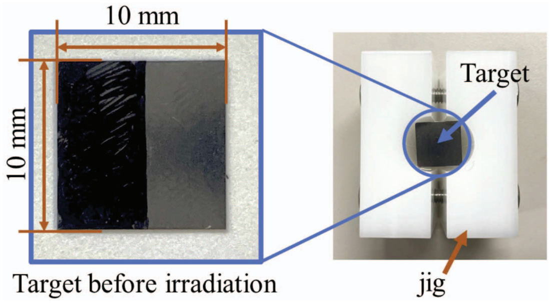

Fig. 2 Target sample with support.

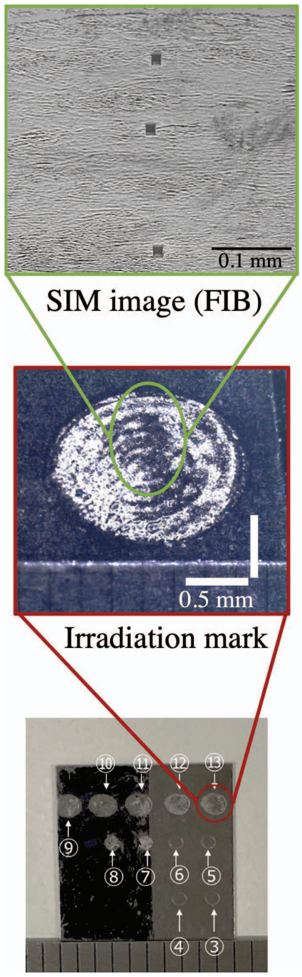

Fig. 3 Sample surface irradiated using pulsed laser.

laser intensity was 5.5×10^7 W cm^{-2} for a spot diameter of 6 mm. The absorption ratio α_W was 0.05 in this study.

Next, we performed pulsed laser irradiation of the target sample to simulate the pulsed thermal load at the PFM. Figure 2 shows the tungsten plate (10 mm × 10 mm × 0.2 mm) was used as the W sample. The left half of sample surface was colored with an oil-based pen (black) to observe the irradiated part. The energy fluence absorbed by the W sample was set as 1 J cm^{-2} based on the results for the absorption ratio in the preliminary experiment because a fluence of 1.85 J cm^{-2} was obtained for a wall in a laser fusion reactor. Therefore, the pulsed laser was focused onto a spot diameter of 1.3 mm.

3. Irradiation Experimental Results

Figure 3 shows a sample surface irradiated using a pulsed laser in a single shot. The laser-irradiated marks were captured using a digital camera (Fig. 3 (bottom)). One of the laser-irradiated marks was observed using an optical microscope, as shown in Fig. 3 (middle). A part of the surface of the laser-irradiated mark is shown in Fig. 3 (top) as a scanning ion microscope (SIM) image using the FIB device.

4. Measurements for Irradiated Samples

The FIB device was used to observe the interior of the

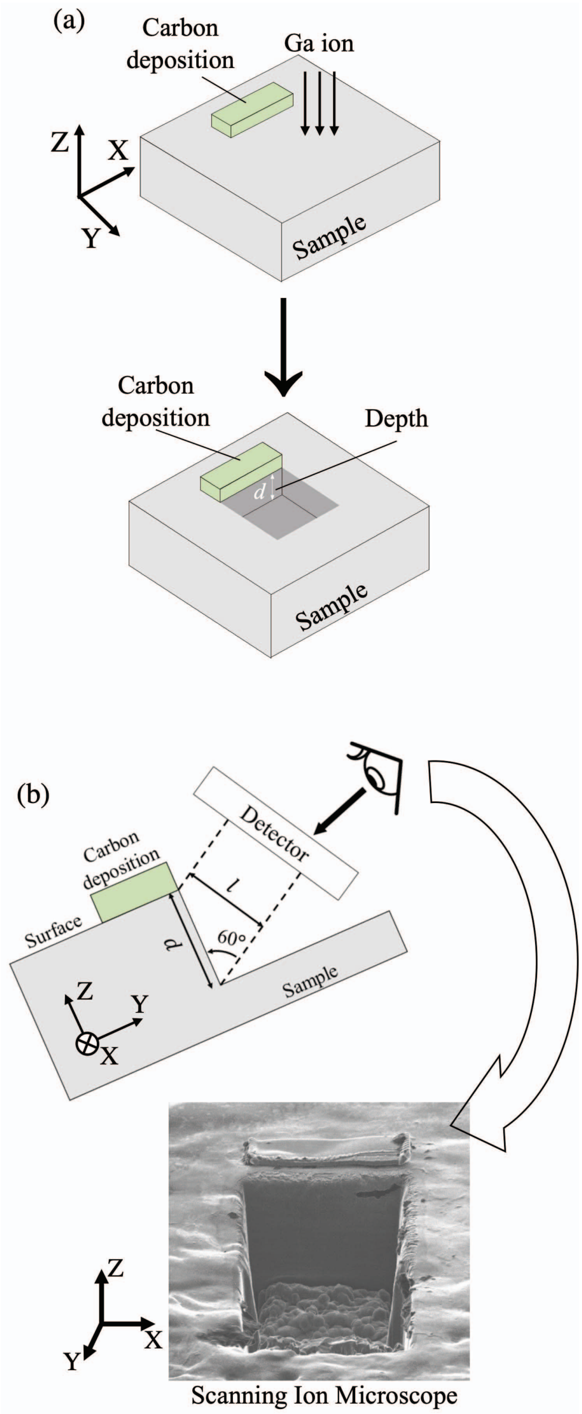

Fig. 4 Measuring method with cross-section processing and observation using FIB device; (a) sample processing via irradiation of Ga ions, and (b) observation of cross-section processed using SIM.

sample after irradiation by the pulsed laser. The procedure, from cross-section processing to observation, is shown in Fig. 4. As shown in Fig. 4 (a), Ga ions sputtered the irradiated surface of the W sample for cross-section processing with the FIB device. After processing, the W sample was tilted to observe the cross-section, as shown in Fig. 4 (b).

The SIM images of a sample surface and a cross-section processed using the FIB device are shown in Fig. 5. The interior of the area irradiated with a fluence of 1 J cm^{-2} was observed, as shown in Fig. 6. Two cracks were observed near the surface around the upper right (yellow circle) and the lower left (red circle) positions, as shown in Fig. 5. The crack in Fig. 6 (a) corresponds to the crack for the yellow circle shown in Fig. 5. It was formed at a depth of 0.4~1.9 µm from the sample surface and a width of 3.9 µm. The crack in Fig. 6 (b) corresponds to the crack for the red circle in Fig. 5. It was formed at a depth of 0.7~2.9 µm from the sample surface and a width of 7.3 µm.

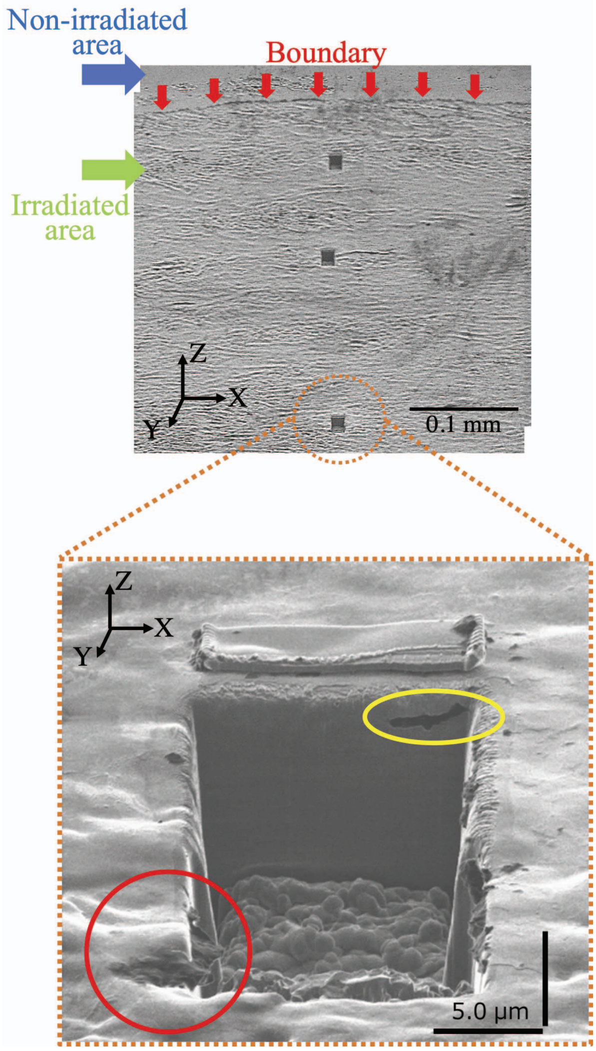

Fig. 5 SIM image on sample surface and cross-section processed using FIB device.

5. Discussion

In this section, we discuss the cause of cracking as reported in the previous section. From the viewpoint of porosity owing to laser welding [6], the reason for the crack formation was not porosity owing to laser welding because the laser irradiation duration was somewhat different. During the reduction of yield stress owing to the

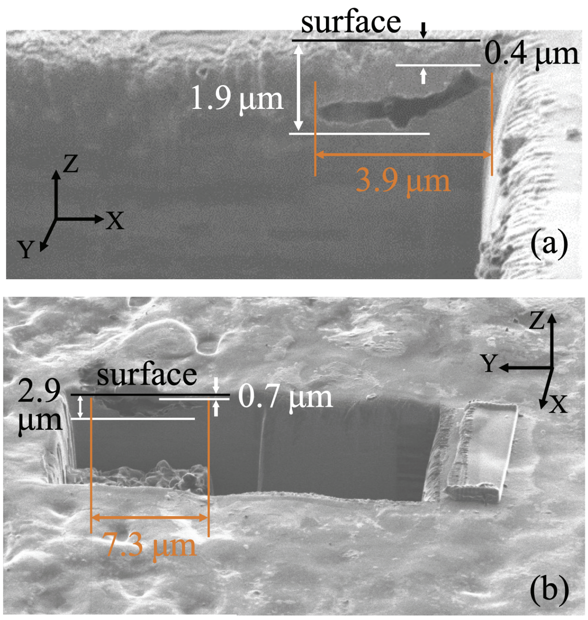

Fig. 6 Images showing cracks near surface of sample observed using SIM; (a) crack observed from y-direction for yellow circle in Fig. 5, and (b) crack observed from x-direction for red circle in Fig. 5. The SIM image of Fig. 6 (b) was synthesized based on three images.

increase in temperature of the sample, there was almost no possibility of internal cracking because the temperature on the sample surface was higher than that inside the sample. In a previous study [2], although the cracks were formed via laser irradiation with lower heat flux parameters (41.8 $MJ\,m^{-2}\,s^{-0.5}$ and 46.2 $MJ\,m^{-2}\,s^{-0.5}$) than that in this study (77 $MJ\,m^{-2}\,s^{-0.5}$), the cracks appeared on the sample surface in the previous study. In thermal shock, the cracks may have been caused by the temperature difference between the surface and the interior owing to the thermal load in an extremely short time.

6. Conclusion

In this study, we investigated the internal state of PFMs irradiated with a pulsed laser to simulate the thermal load in an ICF reactor system. The tungsten sample was irradiated with a pulsed laser by adjusting the energy fluence absorbed by the sample to the ablation threshold (1 $J\,cm^{-2}$). An optical microscope was used to observe the sample surface, and no cracks were observed on the surface. However, the sample was manufactured in the depth direction using the FIB device. The cracks were generated near the surface of the sample using the FIB device. The observed cracks were formed in deeper places in comparison with observations from previous studies. The cracks were formed by the temperature difference between the surface and interior owing to the thermal load within an extremely short time.

In a previous study, blisters were generated via 4-MeV-helium-ion beam irradiation for 5 hours to the tungsten sample at room temperature with an energy fluence of 640 $kJ\,cm^{-2}$ and a heat flux parameter of 9.4 $MJ\,m^{-2}\,s^{-0.5}$ [7]. Although the energy fluence in this study (1 $J\,cm^{-2}$) was somewhat low compared with the experimental parameters in a previous study [7], cracks were observed in this study. For this reason, cracks were generated inside owing to the heat load within a short time in the pulsed laser case, even under the low fluence condition. However, gas bubbles-induced stress resulted in cracking in the helium irradiation case.

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