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Laser energy absorption coefficient and *in-situ* temperature measurement of laser-melted tungsten

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HIGHLIGHTS

- High-speed 2D temperature profiles were obtained for laser melted W spots.
- Laser energy absorption coefficients above W melting point were measured.
- Several observations indicated the W surface bubbling at ~5000 K in UHV.

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ABSTRACT

The energy absorption coefficient of tungsten surface (W) for 1064 nm Nd:YAG laser was measured as a function of the induced energy. Result was confirmed by the reference spectral emissivity up to the melting point. Then, two non-contact surface temperature measurement diagnostics, a pyrometer measurement and a two-dimensional (2D) temperature measurement, were constructed for the laser-melted W spot. The 2D temperature profile was obtained by analyzing two-color images from a high-speed camera with an image splitter and a long-distance microscope. An OpenCV based program was developed for corrections on the tilted angle view and wavelength dependence of the captured intensities. W surface bubbling at the surface temperature near 5000 K was indicated by high-speed camera images, unstable temperature developments, asymmetric temperature profiles, and the postmortem surface observations.

1. Introduction

In regard to the plasma facing material, tungsten (W) is the major candidate at ITER (Ref. [1]) and DEMO reactors. In reactors, W divertor tiles will be exposed to high thermal loads repeatedly. A recent study showed that the transient thermal load such as ELM or disruption causes surface melting or evaporation of W [2]. In order to achieve a stable operation of the fusion reactor, the melting behavior of W divertor needs to be fully understood and predicted. However, the physical properties (energy absorption coefficient, thermal diffusion, viscosity) and behaviors of the W above the melting point have not been sufficiently known [3]. Plus, most of the previous studies are postmortem analyses [2,4]. Thus, a direct observation of molten W behavior by an *in-situ* observation system is important.

In case of a high-temperature measurement such as W above its melting point (3695 K), a non-contact measurement [5] should be taken. Observing optical emissions from the object, temperature was determined from the assumption of the Stefan-Boltzmann law. In this study, two non-contact measurement systems, a pyrometer for an entire laser spot temperature measurement and a high-speed camera with an image splitter and a long distance microscope for a 2D temperature measurement, were constructed and applied for a spot of laser melted W surface. In order to determine the temperature profile, the surface emissivity which is equal to the surface absorption coefficient should be examined. If the emissivity is a strong function of surface temperature, these effect must be taken into account for the temperature calculation. According to previous studies [6,7], the emissivity of W below the melting point decreases slightly as the temperature increases. However, no data above the melting point was provided. Thus, we first measured the laser energy absorption coefficient for different irradiation laser energies (Section 3.1). Then, a software was developed for the 2D temperature profile measurement. Corrections for wavelength dependent

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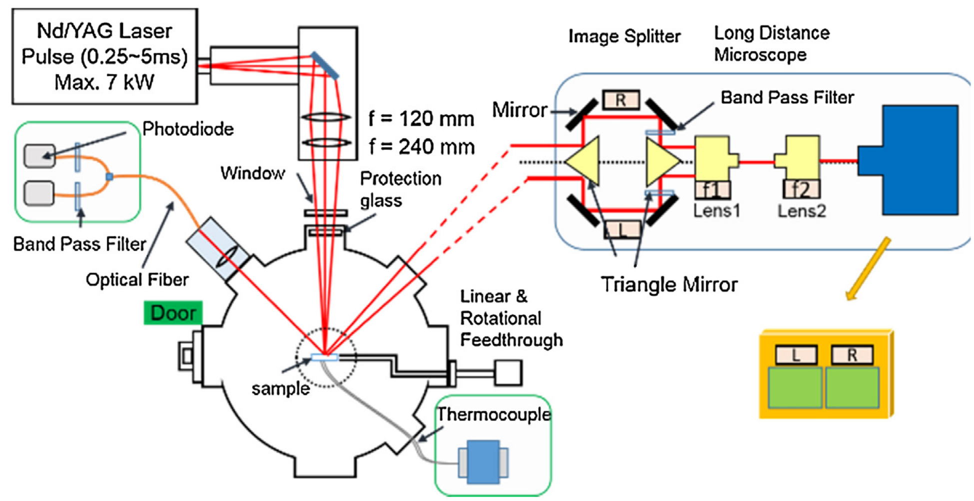

Fig. 1. Schematic view of experimental setups. The red lines represent the paths of light. Lens1 is single focus telephoto lens (focal length 200 mm by Nikon), lens2 is single focus wide-angle lens (focal length 28 mm by SIGMA), and lens attached to the camera is single focus lens (focal length 135 mm by Nikon). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

parameters and tilted angle views were taken for the entire image stacks automatically. A 2D temperature profile was obtained from intensity ratios of corresponding pixels (Section 3.2). Bubbling of the melted W surface near 5000 K was indicated from obtained 2D temperature profiles, high speed images and post mortem analyses (Section 3.3).

2. Experimental

A schematic diagram of experimental setup is shown in Fig. 1. A mirror-polished (surface roughness Ra 0.01 μ) W samples (by A.L.T.M. Corp.) were placed in an ultra-high vacuum (~10^{-7} Torr). A Nd:YAG laser (1064 nm, maximum pulse duration 5 ms, maximum power 7 kW) was used as a heat source. Sample stage was movable in the x-y direction (z direction is the laser path), and the laser irradiation was always done in a non-irradiated surface. By combining two lenses of f = 120 mm and f = 240 mm, the laser was focused to a diameter of 0.6 mm on the target surface. A flat-top power profile was achieved as intended. This flat-top profile is suitable for mimicking the ELM heat load effects compared to the typical Gaussian profile which produces a sharply peaking temperature profile. The profile of the laser power was measured by using a camera type beam profiler SP620U (by OPHIR), as shown in Fig. 2.

The surface temperature at the spot of the laser shots were measured by a pyrometer. The pyrometer spot included the whole (0.6 mm diameter) irradiated surface and the unirradiated surface. However, the photon emission from the unirradiated region is negligible. The laser energy absorption coefficient of the W surface for 1064 nm Nd:YAG laser was examined for various irradiation energy shots. The coefficient was determined by using the temperature rise (ΔT) of the entire sample ($10 \times 10 \times 1$ mm^3) during the laser irradiation. ΔT was measured by a thermocouple welded on a back surface of the specimen. Effects of the latent heats and the radiation cooling were examined.

In order to investigate the melting behavior in detail, a 2D temperature measurement system with a high speed camera (SA1.1 by Photron Limited) was constructed. In the system, a triangular mirror was used to divide the light from the same point into two optical paths. Band pass filters (450 nm & 600 nm, Transmittance >90%, 25 nm FWHM) were placed in the divided optical paths. Then, the beams were deflected by another triangle mirror and directed into one camera. This system works as an image splitter. In order to focus on the target surface with 0.6 mm diameter at approximately

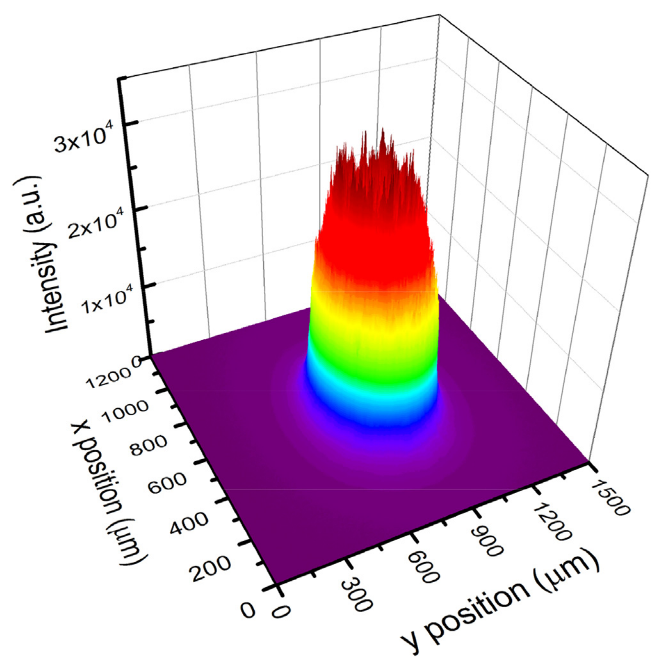

Fig. 2. 2D profile of the Nd:YAG laser power measured by the SP620U. Combining two lenses, a flat-top power profile, instead of a typical Gaussian-profile, was obtained.

1 m away, three lenses (a telephoto lens, a single focus wide-angle lens, and a camera-attached single focus lens) were combined. As a result, this system works as a long-distance microscope. Finally, two images of the laser spot through different band pass filters were captured by a high speed camera. The 2D temperature profile can be obtained by analyzing these two-color images.

3. Results and discussion

3.1. The laser energy absorption coefficient

When the W surface was irradiated by the Nd:YAG laser, the absorbed heat is balanced against the temperature rise, the radia-

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