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Complex interactions between high flux plasma and materials

高熱流プラズマー固体材料複合相互作用

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Complex interactions occur between plasmas and materials in the divertor condition of nuclear fusion reactor. Morphology changes occur on surface of tungsten, which will be used for divertor materials, by the plasma irradiation. One of the serious issues for divertor materials is the interaction with transients accompanied by edge localized modes (ELMs). The morphology change by the plasma irradiation essentially alters the interaction between the material and transients.

1. Introduction

In ITER, divertor material will be fully tungsten from the start-up phase. In nuclear fusion reactors, helium atoms are produced by a nuclear reaction process, and helium plasma irradiation of tungsten leads to the surface morphology changes. It is known that the fibreform nanostructures are formed on the surface [1].

As a consequence of the morphology changes, various material properties are altered such as optical reflectance, secondary electron emission, field electron emission, sputtering yield, energy reflection coefficient and thermophysical properties. Materials will be exposed to transients heat load; the type-I edge localized modes (ELMs) in ITER will provide the heat load of 0.5 MJm^{-2} for less than 1 ms even in mitigated cases. Considering the interaction between material and ELMs, the above-mentioned variations could lead to serious problems.

One is the initiation of arcing [2]. When nanostructures are formed on the surface, it was found that arcing could be much easily initiated on the surface. Another issue is an enhancement of tungsten release by melting and vaporization [3]. In this study, we presents the interaction between the He irradiated tungsten and transients.

2. Nanostructure formation

Figure 1 shows a cross sectional TEM micrograph of He irradiated tungsten. The experiments were performed in the linear plasma device NAGDIS (Nagoya Divertor Simulator)-II. The electron density was on the order of 10^{18}-10^{19} m^3 and the temperature was ~ 5 eV. The surface temperature was 1400 K and the incident ion energy was 50 eV. Growth of helium bubbles beneath the nanostructured layer is an important process to form the nanostructures. Swelling of material by absorbing He particles during the plasma irradiation is likely to be of importance as well.

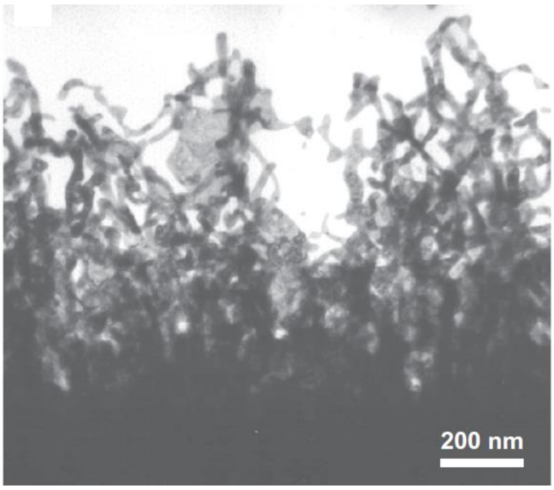

Fig.1: Cross sectional TEM micrographs of helium irradiated tungsten with the helium fluence of $5.5x10^{25}$ m^2.

3. Initiation of free running arcing

Demonstration of transients heat load to materials in plasmas was conducted in the divertor simulator NAGDIS-II using laser pulses for pulsed heat source. A fast framing camera was used to observe the behavior of arc spots. Figure 2 shows consecutive CCD images of the emission WI from arc spots triggered by a laser pulse. The angle between the magnetic field and the sample was 45 degree. The frame rate was 125 000 fps (frame per second), and the corresponding time interval between the image is 8 μs. The direction is determined by the ratio of the axial to transverse magnetic field strength. When the magnetic field is parallel to the surface, the spot moves to retrograde, namely $-j \times B$, direction. In Fig. 2, the direction is consistent with the one which is determined by the so-called acute angle rule or Robson angle [4].

When arcing is initiated on W, tungsten is released from the surface. The amount of erosion was estimated to be ~10 mg/s for single arc spot [5], and it could increase when spots forms grouping [6].

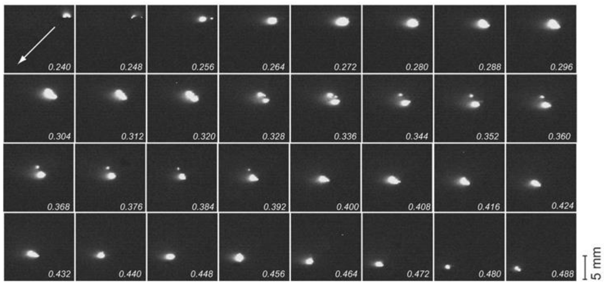

Fig. 2: Consecutive CCD images of the emission WI. The angle between the magnetic field and the sample was 45 degree. The frame rate was 125 000 fps (frame per second), and the corresponding time interval between the image is 8 μs.

4. Thermal response of nanostructured W

The thermal response of nanostructured tungsten, which was fabricated in the linear divertor simulator NAGDIS-II, was investigated using pulsed plasma in the MAGNUM-PSI device and by using high powered laser pulses.

Figure 3(a) and (b) shows the temporal evolutions of the surface temperature measured with an IR fast camera during pulsed plasma irradiation experiments for pristine and nanostructured W samples, respectively. The pulse energy was 430 J and the frame rate of the camera was 13 kHz. The surface temperature started to increase after the plasma irradiation and reached ~700–800 K. In response to the pulse plasma irradiation, the surface temperature promptly jumped. On the pristine sample, the increase was less than 100 K, while on the nanostructured sample, the increase was much greater and was 400–500 K. It was also interesting to note that the surface temperature was sufficiently less than the melting point even though melting traces were formed on the surface after exposing to the pulsed heat loads. It was likely that nanostructure matrix formed a thermally isolated part near the surface, and non-uniformity in the temperature increase would have been taken place. That is, it was suggested that the averaged surface temperature was less than the observed temperature; the locally heated part would increase the thermal radiation and increase the measurement temperature. When nanostructured tungsten was exposed to type-I ELMs in ITER, the present experiments suggested that the vapourization will occur locally even in mitigated cases.

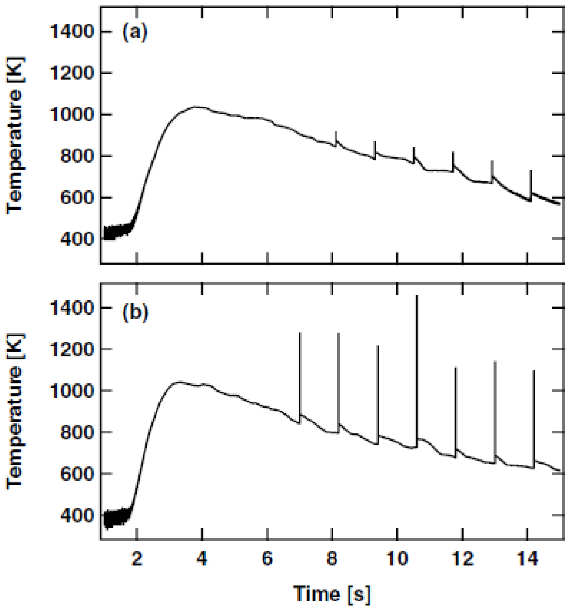

Fig. 3: Temporal evolutions of the surface temperature measured with an IR fast camera during pulsed plasma irradiation experiments. (a) and (b) show the cases for pristine and nanostructured W samples, respectively.

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