Dust Formation from Arc Spots on Nanostructured Tungsten Surface

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Arcing experiments were conducted in the linear plasma device Pilot-PSI, where a pulsed plasma was superimposed to a steady state plasma. The arcing was observed by a fast framing camera, and the sample was analyzed with a transmission electron microscope. Observations of glowing objects released from the sample in response to the arcing and destruction of the fuzzy layer at the edge of the arc trail without significant melting suggested that dust was formed and released from the surface in response to arcing.

Keywords: He irradiation, tungsten, arcing, metallic dust

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Arcing has been thought of as one of the major impurity sources in fusion devices [1]. However, it is difficult at the moment to predict the impact of the arcing in future fusion devices including ITER, because of the lack of sufficient data, in particular, its ignition frequency and erosion rate [2]. On nanostructured tungsten (W fuzz), which can be formed by exposure to helium (He) plasmas, arcing easily occurs in response to pulsed heat load [3]. The surface morphology changes induced by the He effects can be an important factor to change the ignition frequency, because they result in a decrease in the thermal conductivity [4] and an increase in the field electron emission [5]. A recent study suggested that the erosion rate increases with the fuzz thickness because of the dust formation [6]; until now there was no direct evidence to support the above speculation. In this study, we show dust releases from arc spots on fuzzy samples.

Pure W samples (Nilaco Co. Ltd.) with diameter and thickness of 30 and 1 mm, respectively, were used for the experiments. After polishing the samples, the nanostructures were prepared by exposure to a He plasma in the linear plasma device NAGDIS-II. The incident ion energy was ∼75 eV, and the surface temperature was ∼1330°C with an ion flux and fluence to the samples of 1.1×10^{22} m^{-2}s^{-1} and 8.0×10^{25} m^{-2}, respectively. The thickness of the fuzzy layer was estimated to be ∼1.2 μm from the fluence [7].

The prepared nanostructured W samples were exposed to hydrogen (H) plasmas in the Pilot-PSI device. The sample was at the floating potential. Figure 1 (a) shows a temporal evolution of the surface temperature measured with an infrared camera (FLIR SC7500-MB). In

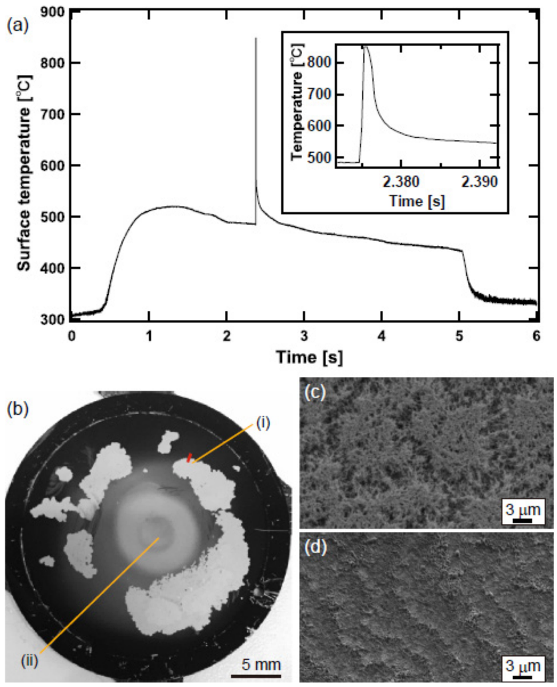

Fig. 1 (a) Temporal evolution of the surface temperature, and (b) a picture and (c, d) SEM micrographs of the sample at position (i) and (ii) shown in (b).

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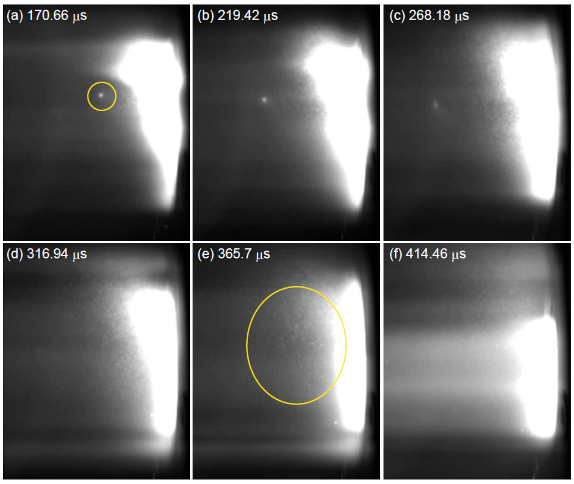

Fig. 2 Fast framing camera images in response to a plasma pulse. In yellow circled regions, glowing objects were identified.

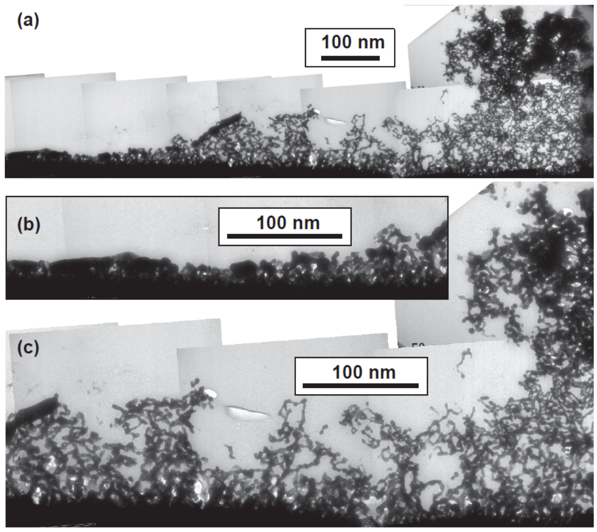

Fig. 3 TEM micrographs of the boundary of the arc trail on the sample. (b, c) Enlarged images of the left and right part of (a), respectively.

response to a pulse (~1 ms), where the density increased by two orders of magnitude to $\sim 10^{22}$ m^{-3}, which was measured by the laser Thomson scattering as changing the timing of the measurement trigger to the plasma pulse as was done previously [8], the surface temperature increased from 700 to 1400°C. The sample was exposed to 11 plasma shots, and arcing was ignited five times at 2nd, 5th, 6th, 7th, and 8th shots. Figures 1 (b) and (c, d) show a picture and SEM micrographs of the sample at different positions after the experiments. At position (ii) (Fig. 1 (c)), where arc trail was not identified, it was likely that the top of the fuzzy layer melted because of the high heat load of pulses, as was previously seen [9]. At position (i) (Fig. 1 (d)), the fuzzy layer was totally removed and ~5-μm-width wavy roughness was seen. This is a typical erosion trace by grouped arc spots [10]. Arcing occurred at the peripheral region of the plasma column, whose half maximum radius in the density was ~5 mm, because it has a well-shaped potential profile [11].

Figures 2 (a - d) shows several fast framing camera images in response to the plasma pulse. Bright emissions were identified in front of the material, probably from the emission of tungsten released from the surface. In addition, a bright spot from 170 μs and many small spots in the latter phase from the substrate were seen, suggesting that dust particles were released from the surface.

Figure 3 shows a cross sectional TEM micrograph of the boundary of the arc trail shown as a red line near the position (i). In Fig. 3 (a), the left part corresponds to the arc trail, where fuzzy layer was melted and totally removed. As seen in Fig. 3 (b), the layer where bubbles exist still remained in the bottom of the arc region. In the right part of Fig. 3 (a) (an enlarged view in Fig. 3 (c)), it is seen that a part of the fuzzy layer was destroyed without significant melting. Fiberform structures were agglomerated in some parts; it was likely that fragments of the fuzzy layer were removed by a mechanical shock from the arcing and were released from the surface.

The glowing objects which were released and the TEM observation of the trail suggest that a part of the fuzzy layer was removed in the form of dust in response to arcing. Concerning the amount of material erosion, it has been revealed that the amount can be well characterized in terms of the erosion per charge [12]. However, previous research revealed that the erosion per charge increased with the thickness of the fuzzy layer when the fuzz thickness was in the range of 1 - 3 μm; the ecton (explosive electron emission) model indicates that the erosion as ions did not play a major role, and mechanical destruction by momentum transfer from the explosive electron emission centre to neighbouring nanowires enhanced the erosion [6]. On fuzzy W, because the fiberform nanostructures were mechanically weak, the momentum transfer or mechanical shock from arc spots could lead to the formation of dust in addition to small droplets especially when a thick fuzzy layer existed. For future work, it is of interest to investigate the relationship between the dust release and fuzzy layer thickness including layers with a thickness of 3 μm or greater.

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[1] R. Behrisch, *Physics of Plasma-Wall Interactions in Controlled Fusion* (Nato ASI Series, Series B, Physics), (New York, NY, USA: Plenum Pub. Corp., 1986) pp. 495-513.

[2] G. Federici *et al.*, Nucl. Fusion **41**, 1967 (2001).

[3] S. Kajita *et al.*, Plasma Phys. Control. Fusion **54**, 035009 (2012).

[4] S. Kajita, T. Yagi, K. Kobayashi, M. Tokitani and N. Ohno, Results in Phys. **6**, 877 (2016).

[5] D. Hwangbo, S. Kajita, N. Ohno and D. Sinelnikov, IEEE Trans. Plasma Sci. **45**, 2080 (2017).

[6] D. Hwangbo, S. Kajita, S.A. Barengolts *et al.*, Contrib. Plasma Phys. **58** (6-8), 608 (2018).

[7] S. Kajita, N. Yoshida, R. Yoshihara, N. Ohno and M. Yamagiwa, J. Nucl. Mater. **418**, 152 (2011).

[8] T.W. Morgan, T.M. de Kruif, H.J. van der Meiden, M.A. van den Berg, J. Scholten, W. Melissen, B.J.M. Krijger, S. Bardin and G. De Temmerman, Nucl. Fusion **56**, 095004 (2014).

[9] S. Kajita, G. De Temmerman, T. Morgan, S. van Eden, T. de Kruif and N. Ohno, Nucl. Fusion **54**, 033005 (2014).

[10] S. Kajita, N. Ohno, S. Takamura and Y. Tsuji, Phys. Lett. A **373**, 4273 (2009).

[11] M. Yajima, N. Ohno, S. Kajita *et al.*, Fusion Eng. Des. **112**, 156 (2016).

[12] A. Anders, *Cathodic arcs: from fractal spots to energetic condensation* (Springer Science & Business Media, 2009).